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# The LHCspin project: A polarized target experiment at LHC

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**Summary.** — A polarized target, operated in combination with the high-energy, high-intensity LHC beams and a highly performing LHC particle detector, has the potential to open new physics frontiers and to deepen our understanding of the intricacies of the strong interaction in the non-perturbative regime of QCD. Specifically, the LHCspin project aims to perform spin physics studies in high-energy polarized fixed-target collisions using the LHCb detector. Being designed and optimized for the detection of heavy hadrons, the LHCb spectrometer, in combination with the LHCspin setup, will provide a complementary access to the nucleon structure, *e.g.*, by studying inclusive production of c- and b-hadrons, which represent an ideal tool to access the essentially unexplored spin-dependent gluon TMDs. Furthermore, fixed-target collisions with 7 TeV proton beams, corresponding to center-of-mass energies ranging from 115 GeV in pp interactions to 72 GeV per nucleon in collisions with ion beams, will allow to cover a wide backward rapidity region, corresponding to the poorly explored high $x$-Bjorken and high $x$-Feynman regimes. The status of the LHCspin project is presented along with a selection of physics opportunities.

## 1. – Introduction

Among the experiments running at the Large Hadron Collider (LHC), LHCb is presently the only one that can be operated also in fixed-target mode. The LHCb detector [1, 2] is a general-purpose forward spectrometer specialized in detecting hadrons containing $c$ and $b$ quarks. It is fully instrumented in the $2 < \eta < 5$ region with state-of-the-art particle detectors including a Vertex Locator (VELO), a tracking system, two Cherenkov detectors, electromagnetic and hadronic calorimeters and a muon detector. Fixed-target measurements at LHCb are possible since the installation of the SMOG (System for Measuring the Overlap with Gas) device [3] in 2011, enabling the injection of some noble gases at a pressure of $\mathcal{O}(10^{-7})$ mbar in the beam pipe section crossing the VELO. In particular, p-He, p-Ar, p-Ne as well as Pb-Ar and Pb-Ne collisions have been performed at different beam energies, paving the way to a diverse physics program at unique kinematic conditions. During the LHC Long Shutdown 2, the SMOG system has

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been upgraded with the installation, in front of the VELO, of an openable storage cell for the target gas. The use of the storage cell ensures target areal densities higher by up to two orders of magnitude with the same gas flow used for the original SMOG setup. The upgraded system, SMOG2 [4], in operation since the beginning of Run 3, also comprises a new and more sophisticated Gas Feed System (GFS) which allows to measure the injected gas density with a precision at the level of a few percents, and to inject several more gas species, including $H_2$ and $D_2$. The LHCspin project [5] aims at extending the LHCb fixed-target program in Run 4 (expected to start in 2029) with the installation of a new generation HERMES-like polarized gas target. The project, which also foresees the use of a storage cell for the target gas (polarized hydrogen or deuterium), poses its basis on the well consolidated polarized-target technology and expertise, successfully employed at the HERMES experiment at HERA [6] and at the ANKE experiment at COSY [7]. Furthermore, thanks to the well displaced interaction regions, it can be run in parallel (*i.e.*, simultaneously) with the collider mode, as already demonstrated with the SMOG2 setup. Finally, the system will also allow to inject unpolarized gases (*à la* SMOG2) and will benefit from both the LHC proton and heavy-ion beams and the state-of-the-art upgraded LHCb detector. All this will allow to cover a broad physics program that ranges from the study of the nucleon structure, to the measurement of cold nuclear-matter effects and heavy-ion phenomena, to astroparticle physics related to dark-matter searches. While several of these subjects are already at reach with SMOG2, the study of the spin structure of the nucleon is only possible at LHC with the use of a polarized target, and constitutes the main physics objective of the project.

## 2. – The LHCspin physics case

The physics case of LHCspin is mainly devoted to the investigation of the nucleon spin structure, with a special focus on the Transverse-Momentum–dependent parton Distribution functions (TMDs) and the Generalized Parton Distribution functions (GPDs) of quarks and gluons. Polarized quark and gluon distributions can be probed with LHCspin in collisions of high-energy protons on polarized hydrogen or deuterium targets.

Quark TMDs describe spin-orbit correlations inside the nucleon, making them indirectly sensitive to the unknown quark orbital angular momentum. Furthermore, they allow to construct 3D maps of the nucleon structure in the momentum space (*nucleon tomography*). The golden process to get access to the quark TMDs in hadronic collisions is Drell-Yan (DY), where a quark and an anti-quark annihilate yielding a charged lepton pair (*e.g.*, $\mu^+\mu^-$) in the final state. By injecting unpolarized hydrogen one can get sensitivity to the unpolarized quark TMD, $f_1^q$, and the Boer-Mulders (B-M) function, $h_1^{\perp,q}$, through the azimuthal dependence of the DY cross section: $d\sigma_{UU}^{DY} \propto f_1^{\bar{q}} \otimes f_1^q + \cos(2\phi)\, h_1^{\perp,\bar{q}} \otimes h_1^{\perp,q}$, where the symbol $\otimes$ denotes a convolution integral over the incoming quarks transverse momenta, and $\phi$ the azimuthal orientation of the lepton pair in the di-lepton centre-of-mass frame. On the other hand, by using transversely polarized hydrogen ($p^\uparrow$) or deuterium ($d^\uparrow$) targets, one can get sensitivity to the spin-dependent quark TMDs, such as the Sivers function, $f_{1T}^{\perp,q}$, and the transversity distribution, $h_1^q$, through a Fourier decomposition of the Transverse Single-Spin Asymmetry (TSSA),

$$A_N = \frac{1}{P}\frac{\sigma^\uparrow - \sigma^\downarrow}{\sigma^\uparrow + \sigma^\downarrow} \sim A_{UT}^{\sin(\phi_s)} \sin(\phi_s) + A_{UT}^{\sin(2\phi-\phi_s)} \sin(2\phi - \phi_s) + \cdots , \tag{1}$$

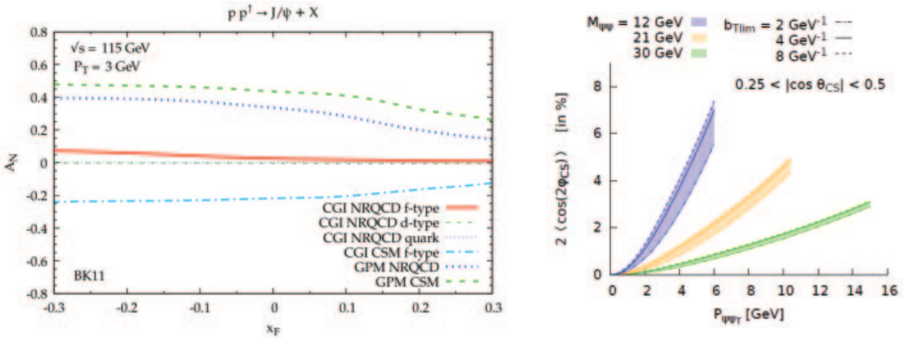

Fig. 1. – Theoretical predictions for: (left) $A_N$ in inclusive J/$\psi$ production as a function of $x_F$ [10]; (right) cos($2\phi$) asymmetry amplitudes for inclusive di-$J/\psi$ production as a function of the relative transverse momentum [11].

where $P$ denotes the effective target polarization degree and $\phi_s$ the azimuthal angle of the target transverse polarization with respect to the reaction plane. The azimuthal amplitudes $A_{UT}^{\sin(\Omega)}$, with $\Omega$ representing all relevant combinations of the $\phi$ and $\phi_s$ azimuthal angles, constitute the relevant physical observables and provide direct access to combinations of quark TMDs, *e.g.*,

$$A_{UT}^{\sin(\phi_s)} \sim \frac{f_1^{\bar{q}} \otimes f_{1T}^{\perp,q}}{f_1^{\bar{q}} \otimes f_1^q}, \quad A_{UT}^{\sin(2\phi-\phi_s)} \sim \frac{h_1^{\perp,\bar{q}} \otimes h_1^q}{f_1^{\bar{q}} \otimes f_1^q}, \text{ etc.} \tag{2}$$

Being T-odd, it is predicted that the Sivers and the B-M functions measured in DY must have opposite sign compared to the corresponding functions measured in Semi-Inclusive Deep Inelastic Scattering (SIDIS) [8]. This fundamental QCD prediction can be tested experimentally with LHCspin thanks to the large DY data-set expected over a LHC Run. Furthermore, isospin effects can be studied by comparing p-p$^{(\uparrow)}$ and p-d$^{(\uparrow)}$ collisions.

While first phenomenological extractions of quark TMDs have been performed in recent years, based mainly on SIDIS data, gluon TMDs are presently essentially unknown. Measurements of observables sensitive to gluon TMDs, such as, *e.g.*, the gluon Sivers function [9], represent nowadays the new frontier of this research field. Since, at LHC, heavy quarks are mainly produced via gluon-gluon fusion, production of quarkonia and open heavy-flavour states represents the most efficient way to study the gluon dynamics inside nucleons and to probe the gluon TMDs. Specifically, by measuring inclusive production of J/$\psi$, $\psi'$, D$^0$, $\eta_c$, $\chi_c$, $\chi_b$, etc., for which LHCb is well suited and optimized, using the high-energy and high-intensity LHC proton beams in conjunction with a transversely polarized H or D target, LHCspin has the potential to become a unique facility for these studies. While the unpolarized $f_1^g$ and the Boer-Mulders $h_1^{\perp,g}$ gluon TMDs can be accessed through the azimuthal dependence of the unpolarized cross section, the gluon TMDs that require a transversely polarized nucleon, such as the gluon Sivers function $f_{1T}^{\perp,g}$, can be probed through a Fourier decomposition of the TSSA, similarly to the quark TMDs case. Asymmetries as large as 40% in inclusive J/$\psi$ production are predicted in the negative $x_F$ region [10] (fig. 1 left), where the LHCspin sensitivity is highest. Since transverse-momentum–dependent QCD factorization requires $p_T(Q) \ll M_Q$, where $Q$ denotes a heavy quark, the safest inclusive processes to be studied is associated quarkonium production, *e.g.*, pp$^\uparrow \to$ J/$\psi +$ J/$\psi +$ X, pp$^\uparrow \to$ J/$\psi + \psi' +$ X, etc., where only the

Table I. – *Event rates and total yields expected with LHCspin in Run 4 for various physics channels of interest based on preliminary SMOG2 pAr results and realistic Run 4 beam conditions.*

| Channel | Rate per week | Yield |
|---|---|---|
| $J/\psi \to \mu^+\mu^-$ | $3.6 \times 10^6$ | $4.3 \times 10^8$ |
| $D^0 \to K^-\pi^+$ | $1.8 \times 10^7$ | $2.2 \times 10^9$ |
| $\psi(2S) \to \mu^+\mu^-$ | $6.4 \times 10^4$ | $7.7 \times 10^6$ |
| $J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (DPS) | 2.4 | $2.8 \times 10^2$ |
| $J/\psi J/\psi \to \mu^+\mu^-\mu^+\mu^-$ (SPS) | 7.1 | $8.5 \times 10^2$ |
| Drell Yan ($5 < M_{\mu\mu} < 9$ GeV) | $2.0 \times 10^3$ | $2.5 \times 10^5$ |
| $\Upsilon \to \mu^+\mu^-$ | $1.5 \times 10^3$ | $1.9 \times 10^5$ |
| $\Lambda_c^+ \to pK^-\pi^+$ | $3.6 \times 10^5$ | $4.3 \times 10^7$ |

relative $p_T$ has to be small compared to $M_Q$. Asymmetries as large as 5% are predicted as a function of the relative $p_T$ for the $\cos(2\phi)$ and $\cos(4\phi)$ modulations of the unpolarized cross section for quarkonium-pair production [11] (fig. 1 right). Table I shows the estimated event rates and yields (per LHC Run) for several physics channels of interest.

While TMDs provide a "tomography" of the nucleon in momentum space, complementary 3D maps of the nucleon can be obtained in the spatial coordinate space by measuring GPDs. Correlating transverse position and longitudinal momentum, GPDs provide an access to the parton orbital angular momentum, whose contribution to the total nucleon spin can be inferred, *e.g.*, via the Ji sum rule [12]. The essentially unknown gluon GPDs can be experimentally probed at LHC in exclusive quarkonia production in Ultra-Peripheral Collisions (UPCs), which are dominated by the electromagnetic interaction, in events where a pomeron exchange with the target nucleon occurs [13]. First measurements of J/$\psi$ production in UPC in PbPb collisions have recently been reported by the LHCb Collaboration [14]. With the LHCspin polarized target, TSSAs in UPCs can be exploited to access, *e.g.*, the $E_g$ GPD, which has never been measured so far and represents a key element of the proton spin puzzle.

## 3. – Experimental setup and R&D

The R&D of the LHCspin setup points at the development of a new-generation polarized gas target, based on the same concept of that employed at the HERMES experiment [6], which comprises three main components: an Atomic Beam Source (ABS), a Storage Cell (SC), and a diagnostic system. The ABS injects a beam of polarized hydrogen or deuterium atoms into the SC, which is located in the LHC primary vacuum along the beam pipe section upstream of the VELO. The SC, similar to SMOG2 one, is located inside a vacuum chamber and surrounded by a compact superconductive dipole magnet, as shown in fig. 2 (left). The magnet generates a 300 mT static transverse field with a homogeneity of 10% over the full volume of the cell, which is necessary to maintain the transverse polarization of the gas inside the cell [15]. Studies for the inner coating of the SC are currently ongoing, with the aim of producing a surface that minimizes the molecular recombination rate as well as the secondary electron yield. The diagnostic system continuously analyses gas samples drawn from the SC and comprises a target gas analyzer to detect the molecular fraction, and thus the degree of dissociation, and a Breit-Rabi polarimeter to measure the relative population of the injected hyperfine states. The entire setup installed in the VELO alcove is sketched in fig. 2 (right).

The alternative solution of a jet target, *i.e.*, without storage cell, is also under investigation and could be adopted in case no suitable coatings are found for the target

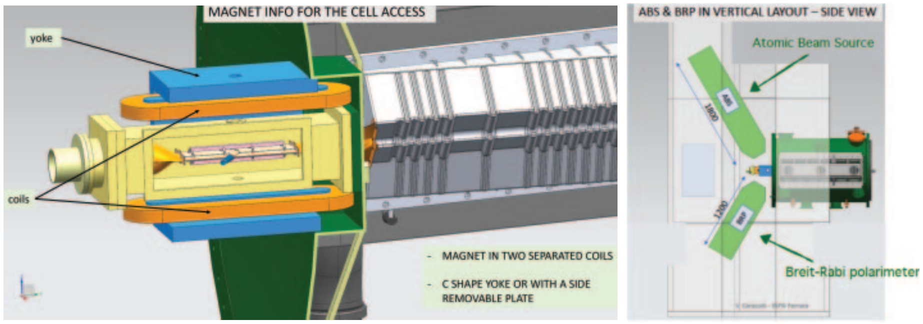

Fig. 2. – Left: a drawing of the LHCspin vacuum chamber (yellow) hosting the storage cell. The chamber is inserted between the coils of the magnet (orange) and the iron return yoke (blue). The VELO vessel and RF box are shown in green and grey, respectively. Right: sketch of the full setup installed in the VELO alcove.

cell. Furthermore, the idea of a dedicated in-beam R&D program at the LHC Interaction Region 3 (IR3), with the possibility to realize a proof-of-principle prototype experiment during Run 4, is being explored.

## 4. – Conclusions

The fixed-target physics program at LHC has been greatly enhanced with the recent installation of the SMOG2 setup at LHCb. LHCspin is the natural evolution of SMOG2 and aims at installing a polarized gas target to bring spin physics at LHC for the first time, opening a whole new range of exploration. With strong interest and support from the international theoretical community, LHCspin is a unique opportunity to advance our knowledge on several unexplored QCD areas, complementing both existing facilities and the future Electron-Ion Collider [16].

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