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The LHCspin project: A polarized fixed target for LHC

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Summary. — A polarized fixed-target experiment at LHC will open the way for a broad and unique physics program. The kinematic coverage will allow studying the negative-rapidity region in the CM, corresponding to the poorly explored high x-Bjorken domain for the target proton. Furthermore, the use of a transversely polarized H or D gas will allow precision measurements of spin-asymmetries in Drell-Yan processes and in inclusive production of quarkonia, opening the way for the measurement of the unknown gluon PDFs, such as the gluon Sivers function. The status of the project, the R&D for the implementation of the setup at the LHCb experiment, as well as the physics case, are discussed.

1. – Introduction

The Large Hadron Collider (LHC) provides proton and lead beams with energies of 7 TeV and 2.76 TeV per nucleon, respectively, and world highest intensities. LHCb is currently the only detector capable of collecting data in both collider and fixed-target mode. Fixed-target collisions can occur at energies up to 115 GeV in the center of mass, giving researchers an unprecedented opportunity to study partons that carry a large fraction of the target nucleon momentum, *i.e.*, large Bjorken-x values (corresponding to large and negative Feynman-x values), at intermediate Q^2.

The LHCb detector [1] is a general-purpose forward spectrometer specialised in detecting hadrons containing c and b quarks. The spectrometer is completely 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. Since the installation of the SMOG (System for Measuring Overlap with Gas) device [2] in 2011, fixed-target measurements at LHCb have been possible, allowing the injection of noble gases at a pressure of $\mathcal{O}(10^{-7})$ mbar in the

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beam pipe portion traversing the VELO. In 2020, as part of the SMOG2 upgrade [3], an openable storage cell has been installed in front of the VELO. Depending on the injected gas species, this increases the target areal density by a factor of 8 to 35 compared to the original SMOG setup.

The LHCspin project [4] plans to extend the SMOG2 physics program in Run 4 and to bring spin physics to the LHC by utilizing the well suited upgraded LHCb detector and a new generation polarised gas target. Section **2** presents a selection of physics opportunities achievable with LHCspin, whereas sect. **3** discusses the experimental setup.

2. – Physics case

LHCspin's physics case focuses on three main areas: exploring the broad physics potential provided by the use of unpolarized gas targets, studying QGP and cold nuclear matter effects in fixed-target heavy-ion collisions, and studying the nucleon spin structure at unique kinematic conditions. The first two areas are common to SMOG2 and are presented in [5]. Below, only the spin-physics part of the program, which is unique of LHCspin, is discussed.

Proton collisions on polarized hydrogen and deuterium targets can be studied to investigate polarized quark and gluon distributions with LHCspin. One of the key physics tasks is to investigate the quark Transverse-Momentum Dependent parton distribution functions (TMDs). Describing spin-orbit correlations inside the nucleon, quark TMDs are sensitive to the unknown quark orbital angular momentum. They also enable for a 3D mapping of the nucleon structure in momentum space (*nucleon tomography*), as shown in fig. 1 (left). Light quark TMDs can be accessed by measuring Transverse Single Spin Asymmetries (TSSAs) in Drell-Yan, where a quark and an anti-quark annihilate yielding a charged lepton pair (*e.g.*, $\mu^+\mu^-$) in the final state.

By using a transversely polarized hydrogen (or deuterium) target, one can get sensitivity to the spin-dependent quark TMDs, such as the Sivers function, $f_{1T}^{\perp,q}(x, p_T^2)$, and the transversity distribution, $h_1^q(x, p_T^2)$, through a Fourier decomposition of the TSSA,

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

Here P denotes the effective target polarization degree (*e.g.*, 80%), ϕ_s the azimuthal angle of the target transverse polarization with respect to the reaction plane and ϕ the azimuthal orientation of the lepton pair in the di-lepton centre-of-mass frame. The azimuthal amplitudes $A_{UT}^{\sin(\Omega)}$, with Ω representing all relevant combinations of the ϕ and ϕ_s azimuthal angles, constitute the relevant physical observables and provide direct access to combinations of quark TMDs, *e.g.*,

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

Figure 1 (right) shows the projected precision for some relevant azimuthal amplitudes measured in Drell-Yan processes at LHCspin kinematics assuming $10\,\text{fb}^{-1}$ of data.

Noteworthy, the present extractions of the Sivers and transversity functions are restricted to the $x < 0.3$ region. Thanks to its unique kinematic coverage, LHCspin could help to extend the present knowledge of TMDs in the poorly explored high-x (valence)

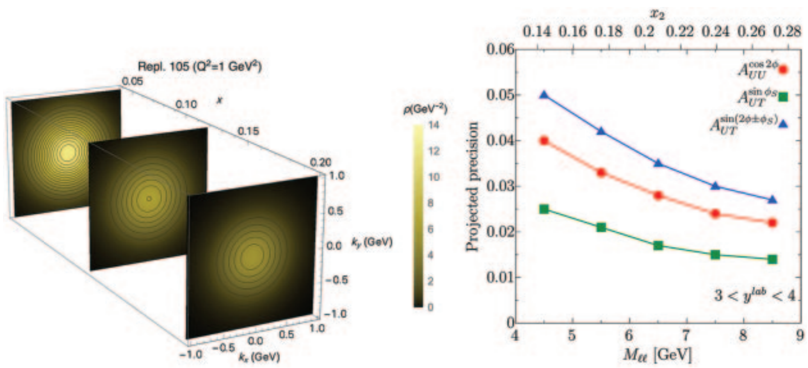

Fig. 1. – Left: up quark densities in momentum space [6]. Right: projected precision for some relevant azimuthal amplitudes with Drell-Yan data with x_2 being the longitudinal momentum fraction of the target nucleon and $M_{\ell\ell}$ dilepton invariant mass [7].

region. In addition to providing a clean access to quark TMDs in hadronic collisions, the study of Drell-Yan events gives also the possibility to test the expected sign-change of the T-odd TMDs, such as the Sivers function, with respect to the corresponding ones measured in Semi-Inclusive DIS (SIDIS), a fundamental prediction of QCD that still needs to be conclusively tested. LHCspin could play a crucial role in this context. While several quark TMDs have been phenomenologically extracted from experimental data in recent years (mainly from SIDIS measurements), gluon TMDs are still mostly unknown. Gluon TMDs could also help to study the intricate role of initial- and final-state interactions and, eventually, improving our knowledge on QCD. Measurements of observables sensitive to gluon TMDs, such as the gluon Sivers function [8], represent the new frontier of this research field. Because at the LHC heavy quarks are mostly created through gluon-gluon fusion, production of quarkonia and open heavy-flavour states is the most efficient way to examine the gluon dynamics inside nucleons and to explore the gluon TMDs. Specifically, inclusive production of J/ψ, ψ', D^0, η_c, χ_c, χ_b, etc. with a transversely polarized H or D target can be pursued at LHCspin.

3. – Experimental setup

The LHCspin R&D points at the development of a new generation of Polarized Gas Targets (PGT). The polarized target system used in the HERMES experiment at HERA [9] constitutes the starting point of the project. It consists of three basic components: an Atomic Beam Source (ABS), an openable Storage Cell (SC), and a diagnostic system. The ABS consists of a cooled nozzle dissociator, a Stern-Gerlach apparatus for focusing the desired hyperfine states, and adiabatic RF-transitions for setting and switching the target polarization between opposite spin states. The ABS injects a polarized atomic hydrogen or deuterium beam into the SC, which is positioned in the LHC primary vacuum along the beam pipe section upstream of the VELO. The SC is housed in a vacuum chamber and surrounded by a compact superconductive dipole magnet. The magnet generates a 300 mT static transverse field with a homogeneity of 10% over the entire volume of the cell, which is necessary to set the transverse polarization of the gas inside the cell, and to avoid beam-induced depolarization [10]. The diagnostic system is based on a Target Gas Analyzer to identify the molecular fraction, and hence the degree

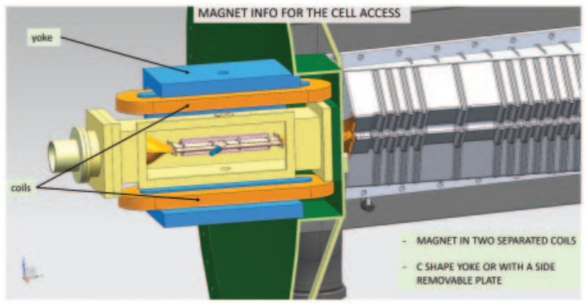

Fig. 2. – Drawing of the LHCspin target chamber (yellow) with the magnet coils (orange) and the iron return yoke (blue) enclosing the storage cell. The VELO vessel and detector box are shown in green and grey, respectively.

of dissociation, and a Breit-Rabi polarimeter to determine the relative population of the injected hyperfine states. Figure 2 depicts the system installed in front of the VELO.

An instantaneous luminosity of $\mathcal{O}(10^{32})\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ is foreseen for fixed-target p-H collisions in Run 4, with a further factor of 3-5 increase for the high-luminosity LHC phase from Run 5 (2032).

4. – Conclusion

With the recent installation of the SMOG2 setup, the LHCb fixed-target physics program will be substantially boosted. LHCspin is the natural extension of SMOG2, and it intends to deploy a polarized gas target at the LHC for the first time, allowing for a whole new range of exploration. The LHCspin project, which benefits from the strong support of the international hadron-physics theoretical community, provides a great opportunity to expand our understanding on various QCD domains, complementing both existing facilities and the upcoming Electron-Ion Colliders [11].

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