The LHCspin project

S. Okamura^{1, 2*}, V. Carassiti¹, G. Ciullo^{1,2}, P. Di Nezza³, P. Lenisa^{1,2}, S. Mariani^{4,5}, L. L. Pappalardo^{1,2}, M. Santimaria³, and E. Steffens⁶

1 INFN Ferrara, Italy
2 Department of Physics, University of Ferrara, Italy
3 INFN Laboratori Nazionali di Frascati, Frascati, Italy
4 INFN Firenze, Italy
5 Department of Physics, University of Firenze, Italy
6 Physics Dept., FAU Erlangen-Nurnberg, Erlangen, Germany
* shinichi.okamura@unife.it

Presented at DIS2022: XXIX International Workshop on Deep-Inelastic Scattering and Related Subjects, Santiago de Compostela, Spain, May 2-6 2022

Abstract

The goal of LHCspin is to develop, in the next few years, innovative solutions and cuttingedge technologies to access spin physics in polarized fixed-target collisions at high energy, exploring the unique kinematic regime offered by LHC and exploiting new final states by means of the LHCb detector. The forward geometry of the LHCb spectrometer is perfectly suited for the reconstruction of particles produced in fixed-target collisions. This configuration, with centre of mass energies per nucleon ranging from 115 GeV in pp interactions to 72 GeV in heavy ion collisions, allows to cover a wide backward rapidity region, including the poorly explored high-x regime. With the instrumentation of the proposed target system, LHCb will become the first experiment simultaneously collecting unpolarised beam-beam collisions at 14 TeV and both unpolarised and polarized beam-target collisions. The status of the project is presented along with a selection of physics opportunities.

1 Introduction

LHCb is presently the only experiment at the CERN Large Hadron Collider (LHC) that can collect data in both collider and fixed-target mode. The detector [1] is a general-purpose forward spectrometer 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 thanks to the SMOG (System for Measuring the Overlap with Gas) device, which enables the injection of noble gases at a pressure of $O(10^{-7})$ mbar in the beam pipe section crossing VELO. Several dedicated short SMOG runs have been performed since 2015, exploiting only the LHC non-colliding bunches to avoid overlap with the beam-beam collisions.

During the LHC Long Shutdown 2, the SMOG system has been upgraded. The new setup, named SMOG2, consists of a storage cell, shown in Fig. 1, installed coaxially with the LHC beam at the upstream edge of the VELO, and an advanced Gas Feed System (GFS). The main advantage of SMOG2 is the possibility to increase the target gas density by up to two orders of

magnitude at the same gas injection flow rate of SMOG. This will boost the target areal density by a factor of 8 to 35 depending on the injected gas species.



Figure 1: SMOG2 storage cell in open (left) and closed (right) configuration.

One of the key features of SMOG2 is that it allows to measure the injected gas density (and so, in turn, the instantaneous luminosity) with precision at the level of a few percent, and to inject several more gas species, including H_2 , D_2 , N_2 , O_2 , Kr and Xe in addition to the He, Ne, Ar, already used with SMOG. In particular, the use of H_2 and D_2 targets, available for the first time at the LHC, would open new physics frontiers that include the study of the proton structure in terms of quark and gluon distributions in a unique kinematic region (see Fig. 2 right).

The SMOG2 data will be collected with a novel reconstruction algorithm that provides very high tracking efficiency in the beam-gas interaction region (-500 mm < z < -300 mm)¹, despite its upstream position with respect to VELO. Moreover, as shown Fig.2 left, beam-gas vertices (in red) and beam-beam vertices (in yellow) are well detached along the beam axis. In this way, thanks to SMOG2, LHCb can become the first experiment able to run collider and fixed-target mode simultaneously.



Figure 2: Left: primary vertex distributions for beam-gas (red) and beam-beam (yellow) [2]. Right: kinematic coverage of LHCspin (orange) and other existing experiments.

2 The LHCspin project

The LHCspin project [3] aims at extending the LHCb fixed-target program in Run 4, with the installation of a new-generation HERMES-like polarized gas target in front of the LHCb spectrometer. The project will benefit from both the LHC proton and heavy-ion beams and the

¹Here z=0 indicated the nominal interaction point for the collider mode.

state-of-the-art upgraded LHCb detector as well as from the well-consolidated polarized-target technology and expertise, successfully employed at the HERMES experiment at HERA [4] and at the ANKE experiment at COSY [5].

The experimental setup is based on a storage cell for the target gas (polarized H or D) and poses its basis on the recent installation of the SMOG2 storage cell. Recent dedicated studies have shown that the system will have negligible interference with the LHC beam lifetime and the LHCb mainstream physics program and performance, and could run in parallel with the collider mode, thanks to the well-displaced interaction regions. Finally, LHCspin will also allow to inject unpolarized gases, similarly to SMOG2.

All these factors combined will contribute to defining a broad and ambitious physics program in a poorly explored kinematic region (large x at intermediate Q^2).

2.1 Physics opportunities

The physics case of LHCspin covers three main areas: the exploration of the physics potential offered by unpolarized gas targets, heavy ions collisions, and investigation of the nucleon spin. While the first two areas are common to SMOG2 study of spin-dependent functions is unique to LHCspin. In the following, the physics cases that require a polarized target are presented.

2.1.1 Quark TMDs

The study of quark Tranverse Momentum Depedent PDFs (TMDs), such as the Sivers function $f_{1T}^{\perp,q}(x, p_T^2)$ and the transversity distribution $h_1^q(x, p_T^2)$, is among the main physics goals of LHCspin. Quark TMDs describe spin-orbit correlations inside the nucleon, making them indirectly sensitive to the unknown quark orbital angular momentum. The golden channel to access quark TMDs in hadronic collisions is Drell-Yan (DY), where a quark and an antiquark annihilate, yielding to a charged lepton pair (e.g. $\mu^+\mu^-$) in the final state. The main observable is the Transverse Single Spin Asymmetry (TSSA), defined as:

$$A_N^{DY} = \frac{1}{P} \frac{\sigma_{DY}^{\uparrow} - \sigma_{DY}^{\downarrow}}{\sigma_{DY}^{\uparrow} + \sigma_{DY}^{\downarrow}} \sim A_{UU}^{\cos(2\phi)} \cos(2\phi) + A_{UT}^{\sin(\phi_s)} \sin(\phi_s) + A_{UT}^{\sin(2\phi - \phi_s)} \sin(2\phi - \phi_s) + \dots, \quad (1)$$

where *P* denotes the effective polarization degree (e.g. 80%) and ϕ_s the azimuthal angle of the target transverse polarization with respect to the reaction plane. In particular, by performing a Fourier analysis on the TSSA, it is possible to extract the azimutal amplitudes, which are directly sensitive to combinations of quark TMDs, e.g.:

$$A_{UU}^{\cos 2\phi} \sim \frac{h_1^{\perp,\bar{q}} \otimes h_1^{\perp,q}}{f_1^{\bar{q}} \otimes f_1^{q}}, \quad A_{UT}^{\sin\phi_S} \sim \frac{f_1^{\bar{q}} \otimes f_{1T}^{\perp,q}}{f_1^{\bar{q}} \otimes f_1^{q}}, \quad A_{UT}^{\sin(2\phi+\phi_S)} \sim \frac{h_1^{\perp,\bar{q}} \otimes h_{1,T}^{\perp,q}}{f_1^{\bar{q}} \otimes f_1^{q}}, \quad \dots$$
(2)

Projections for DY measurements evaluated at the LHCb fixed-target kinematics and based on an integrated luminosity of 10 fb^{-1} are shown in Fig. 3.

2.1.2 gluon TMDs

Compared to quark TMDs, the present knowledge of gluon TMDs is at a lower stage since the experimental access to these functions is still extremely limited. In this sense, LHCspin can become a unique facility to study gluon TMDs, such as the gluon Sivers function $f_{1T}^{\perp,g}$. The most efficient way to study the gluon dynamics at the LHC is by looking at quarkonia production and open heavy-flavor states, since they are mainly produced via gluon fusion in ppcollisions. Considering that the transverse-momentum-dependent QCD factorization requires



Figure 3: Left: projections of A_N^{DY} as a function of x for DY events at the LHCb fixedtarget kinematics compared to theoretical predictions. Right: projected precision for some asymmetry amplitudes with Drell-Yan data with x_2 being the longitudinal momentum fraction of the target nucleon and $M_{\ell\ell}$ the dilepton invariant mass [6].

 $p_T(Q) \ll M_Q$, where M_Q denotes the mass of a heavy quark, the safest inclusive processes to be studied with a polarized target are back-to-back production of quarkonia and isolated photons, e.g.:

$$pp^{\uparrow} \rightarrow J/\psi + \gamma + X, \quad pp^{\uparrow} \rightarrow J/\psi + \gamma + X, \quad pp^{\uparrow} \rightarrow \Upsilon + \gamma + X, \quad etc.,$$
 (3)

or associated quarkonium production, e.g.:

$$pp^{\uparrow} \rightarrow J/\psi + J/\psi + X, \quad pp^{\uparrow} \rightarrow J/\psi + \psi' + X, \quad pp^{\uparrow} \rightarrow \Upsilon + \Upsilon + X, \quad etc.,$$
 (4)

where only the relative p_T has to be small compared to M_Q . Figure 4 left shows several the-



Figure 4: Left: theoretical prediction for A_N in inclusive J/ψ production for polarized fixed-target measurements at LHCb [7]. Right: projections of the kinematic coverage for the single J/ψ production at LHCspin for three different positions of the target cell.

oretical predictions for A_N for single J/ψ production. Asymmetries up to 40-50% could be expected in the negative x_F region, where the LHCspin sensitivity is highest (see Fig. 4 right).

2.2 The experimental setup

The LHCspin experimental setup requires the development of a new generation polarized target. The starting point is based on the HERMES (DESY) polarized target system and comprises three main components: an Atomic Beam Source (ABS), a Target Cell (TC) with a dipole holding magnet, and a diagnostic system.

Atomic Beam Source The ABS converts unpolarized molecules into a collimated polarized atomic beam with high intensity. It is made of a dissociator with a cooled nozzle, a Stern-Gerlach apparatus to focus the wanted hyperfine states, and adiabatic RF transitions for setting and switching the target polarization between states of opposite sign. The goal is to reach at least the same injection rate in the storage cell achieved at HERMES, at around 6.5×10^{16} atoms/s.

Target Cell and magnet The Target Cell hosts a T-shaped openable storage cell and a dipole holding magnet, which provides the transverse polarization. The cell will be installed upstream of the LHCb VELO detector (see Fig. 5), almost in the same position as the SMOG2 cell and same dimensions (20 cm length, 1 cm diameter). The TC will support the injection of both unpolarized and transversely polarized gaseous targets. The dipole magnet is made of superconductive coils supported by an iron yoke. By inverting the current in the coils, it will be possible to rapidly invert the polarity of the transverse magnetic field. A static transverse field of 300 mT is necessary to maintain the transverse polarization. Furthermore, an homogeneity of 10% over the full volume of the cell is required to suppress as much as possible beam-induced depolarization effects.



Figure 5: The TC drawing 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.

Diagnostic system The diagnostic system continuously analyses gas samples drawn from the TC 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.

3 Conclusion

The LHCspin project aims to bring, for the first time, spin physics at the LHC, offering a broad and ambitious physics program in a poorly explored kinematic region. The SMOG2 system, recently installed in front of the LHCb spectrometer, will greatly enhance the fixed-target program at LHC and represents an ideal starting point to develop a new generation of polarized gas targets. With strong interest and support from the international theoretical community, LHCspin is a unique opportunity to advance our knowledge in several unexplored QCD areas, complementing both existing facilities and the future Eletron-Ion Collider [8].

References

- [1] LHCb Collaboration, The LHCb Detector at the LHC, JINST **3**, S08005 (2008), doi:10.1088/1748-0221/3/08/S08005.
- [2] LHCb Collaboration, LHCB-FIGURE-2022-002 (2022).
- [3] C. A. Aidala et al., The LHCSpin Project (2019), 1901.08002.
- [4] Hermes Collaboration *et al.*, *The HERMES polarized hydrogen and deuterium gas target in the HERA electron storage ring*, arXiv preprint physics/0408137 (2004).
- [5] M. Mikirtychyants et al., The polarized H and D atomic beam source for ANKE at COSY-Jülich, Nuclear Instruments and Methods **721**, 83 (2013).
- [6] C. Hadjidakis et al., A fixed-target programme at the LHC: Physics case and projected performances for heavy-ion, hadron, spin and astroparticle studies, Physics Reports 911, 1 (2021), doi:https://doi.org/10.1016/j.physrep.2021.01.002.
- [7] U. D'Alesio et al., Process dependence of the gluon sivers function in $p^{\uparrow}p \rightarrow J/\psi + x$ within a TMD scheme in NRQCD, Physical Review D **102**(9), 094011 (2020).
- [8] Accardi *et al.*, *Electron-ion collider: The nextQCD frontier*, The European Physical Journal A **52**(9), 1 (2016).