The LHCspin project

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The goal of LHCspin is to develop, in the next few years, innovative solutions and cutting-edge technologies to access the field of spin physics by exploring a unique kinematic regime and by exploiting new reaction processes. In fact, a polarized gaseous target, operated in combination with the high-energy, high-intensity LHC beams and the highly performing LHCb particle detector, has the potential to open new physics frontiers and deepen our understanding of the intricacies of the strong interaction in the non-perturbative regime of QCD. This configuration, with center of mass energies up to 115 GeV, using both proton and heavy-ion beams covers a wide backward rapidity region, including the poorly explored high x-Bjorken and high x-Feynman regimes. This ambitious task poses its basis in the recent installation of an unpolarized gas target (SMOG2) in the LHCb spectrometer resulting not only in a unique project itself, but also in an invaluable playground for its polarized upgrade. An overview of the physics potential, a description of the LHCspin experimental setup, and the first output the of SMOG2 system are presented.

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1. Introduction

LHC delivers proton and lead beams with an energy of 7 TeV and 2.76 TeV per nucleon, respectively, with the world's highest intensity. The beams, however, cannot be polarized. The only possibility to perform polarized collisions is by using a polarized fixed-target system. These will occur at energies in the center of mass of up to 115 GeV, thus offering an unprecedented opportunity to investigate partons carrying a large fraction of the target nucleon momentum. The forward kinematics of such events finds in LHCb, with an acceptance of $2 < \eta < 5$, a perfect spectrometer in terms of geometry and performance. The LHCb detector [1] is a general-purpose forward spectrometer specialized in detecting hadrons containing c and b quarks, and the only LHC detector able to collect data in both collider and fixed-target mode, simultaneously. All this results in an ideal tool to access, e.g., the essentially unexplored spin-dependent gluon TMDs or to explore the nucleons internal dynamics in kinematic regions poorly probed before.

During the LHC Long Shutdown 2, the SMOG2 system, the first storage cell present along LHC, has been successfully installed in the machine primary vacuum, including a sophisticated Gas Feed System (GFS). This new GFS will allow to measure the injected gas density (and so, in turn, the instantaneous luminosity) with a precision at the level of a few percent, and to inject several gas species like H_2, D_2, ^3He, ^4He, Ne, N_2, O_2, Ar, Kr, and Xe. With the first beams delivered in 2022 by LHC, the system showed to be completely compatible with a parallel data-taking beam-beam and beam-gas. This is possible based: i) the reduction of the beam lifetime due to the presence of the gas in the cell is negligible, ii) the beam-target interaction region, placed at -541 mm $<IP_z<$-341 mm from the beam-beam IP is well separated from the latter, and the two can be reconstructed without ambiguity. In Fig.1 up two clearly separated regions for pAr and pp collisions around the nominal interaction point can be seen, iii) the reconstruction efficiency of the fixed-target event is equal to the one of the beam-beam collisions. Fig.1 down shows a comparison of the normalised invariant mass distributions for K_S^0 candidates reconstructed with a primary vertex in the SMOG2 (pAr) or in the pp region. Despite the different event topologies, the mass resolution is found to be comparable [2].

2. The LHCspin project

LHCspin [3] aims at extending the LHCb fixed-target program in Run 4 (expected to start in 2029) with the installation of a polarized gas target for H or D. The project poses its basis on the well-consolidated polarized-target technology and expertise, successfully employed at the HERMES experiment at HERA and at the ANKE experiment at COSY [4] necessary for the development of a new generation target implemented in a complex system like the LHC+LHCb one.

The physics case of LHCspin encompasses the wide physics potential offered by unpolarized gas targets, including QGP formation and cold nuclear-matter studies in heavy-ion collisions, but is primarily devoted to the investigation of the nucleon spin structure. While the first two areas are common to SMOG2 and are presented in [5] and not discussed here, the latter requires a polarized target and, as such, is unique to LHCspin.

Polarized quark and gluon distributions can be probed with LHCspin by means of proton collisions on polarized hydrogen and deuterium targets. Several leading-twist distributions, that
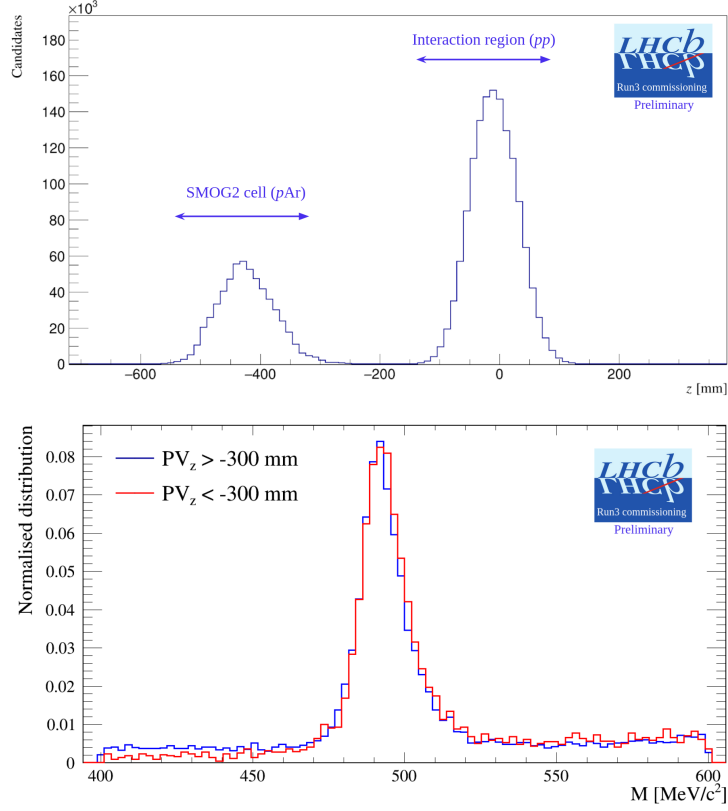
Figure 1: Up: Distribution of the reconstructed primary vertex longitudinal coordinate for pp and pAr collisions. Down: Comparison of the normalised invariant mass distributions for K_S^0 reconstructed with a primary vertex in the SMOG2 (pAr) or in the pp region.

can be probed using either unpolarized or transversely polarized targets, provide independent information on the spin structure of the nucleon. The study of quark Transverse Momentum Distribution functions (TMDs) 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. Furthermore, they allow to construct 3D maps of the nucleon structure in the momentum space (nucleon tomography). The golden process to access the quark TMDs in hadronic collisions is Drell-Yan (DY). At the LHC fixed-target kinematic conditions the dominant contribution to the process is the one where the anti-quark from the proton beam is probed at small-x, and the quark from the target proton is probed at large-x. Moreover, LHCb has an excellent ID and high reconstruction efficiency for muons. By using a transversely polarized hydrogen (or deuterium) target, one can get sensitivity to the spin-dependent quark TMDs, such as the Sivers function, $f_1^q(x, p_T^2)$, and the transversity distribution, $h_1^q(x, p_T^2)$, through a Fourier decomposition of the Transverse Single-Spin Asymmetry (TSSA).

The transversity distribution, whose knowledge is currently restricted to the valence quarks and to a relatively limited x region, is extremely interesting also because a precise determination of its first moment, the tensor charge, could allow setting stringent constraints to new physics BSM. Being T-odd, it is theoretically established that the Sivers and the Boer-Mulders functions extracted in

DY must have an opposite sign with respect to the same quantities extracted in semi-inclusive deep inelastic scattering. This fundamental QCD prediction can be verified by exploiting the large sample of DY data expected at LHCspin. In addition, isospin effects can be investigated by comparing p-H and p-D collisions. Projections for DY measurements evaluated at the LHCb fixed-target kinematics are discussed in [6].

While the 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, 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/Ψ, Ψ', D^0, η_c, χ_c, χ_b, etc., for which LHCb is well suited and optimized, LHCspin has the potential to become a unique facility for these studies.

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 with a polarized hydrogen target is associated quarkonium production, where only the relative p_T has to be small compared to M_Q. The x_F dependence of two model predictions for the single spin asymmetry A_N in inclusive J/Ψ events described in [7] shows asymmetries as large as 5-10 % in the negative x_F region, where the LHCspin sensitivity is highest.

While TMDs provide a tomography of the nucleon in momentum space, complementary 3D maps can be obtained in the spatial coordinate space by measuring Generalised Parton Distribution functions (GPDs). The essentially unknown gluon GPDs can be experimentally probed at LHC in exclusive quarkonia production in Ultra-Peripheral Collisions (UPCs). In particular, 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.

An interesting topic merging heavy-ion and spin physics is the study of collective phenomena in heavy-light systems through ultrarelativistic collisions of heavy nuclei with transversely polarized deuterons. The measurement proposed in [8] can be performed at LHCspin exploiting the high-intensity LHC heavy-ion beams.

3. Experimental setup and simulations

The R&D of the LHCspin setup points to the development of a new-generation Polarized Gas Target (PGT). The base is the polarized target system employed at the HERMES experiment [4], and comprises three main components: an Atomic Beam Source (ABS), a Storage Cell (SC), and a diagnostic system. The SC, based on the same concept of the SMOG2 one, is located inside a vacuum chamber and surrounded by a compact superconductive dipole magnet generating 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, and to avoid beam-induced depolarization. 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 vacuum chamber containing the storage cell, installed in front of the LHCb VELO detector, is shown in Fig.2. New algorithms are currently being developed for

the Run 3 fixed-target reconstruction and are expected to sensibly improve the currently expected performance, as well as to enable the recording LHCspin data in parallel with beam-beam collisions. An instantaneous luminosity of $O(10^{32})$ cm^{-2} 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, starting from Run 5.
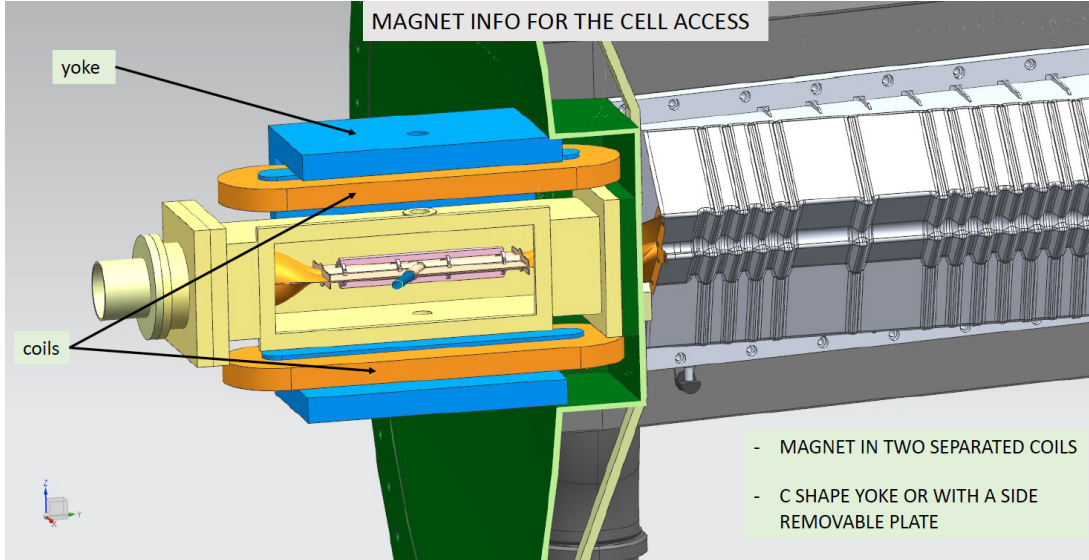
Figure 2: A drawing of the LHCspin vacuum chamber (yellow) hosting the storage cell. The chamber is inserted between the coils of the magnet (orange) and the iron return yoke (blue). The VELO vessel and RF box are shown in green and grey, respectively.

The complete reconstruction chain of LHCb has been run on events simulated considering the typical LHC parameters of Run 4. Figure 3 shows the data-taking time needed for each polarity state to reach a given precision on a TSSA. For example, collecting data for 10 hours on each polarity state (i.e. 20 hours of total data-taking time) allows reaching an absolute uncertainty of the order of $A_N = 0.6$ % on $J/\Psi \rightarrow \mu^+\mu^-$ events in case of 100 % polarisation degree. The three curves represent the uncertainty on A_N coming from both the statistical uncertainty and the knowledge of the polarisation degree. It is remarkable that a precision better than 1 % can be reached in just a few hours of data-taking for the two channels considered.

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 areas of QCD, complementing both existing facilities and the future Electron-Ion Collider.

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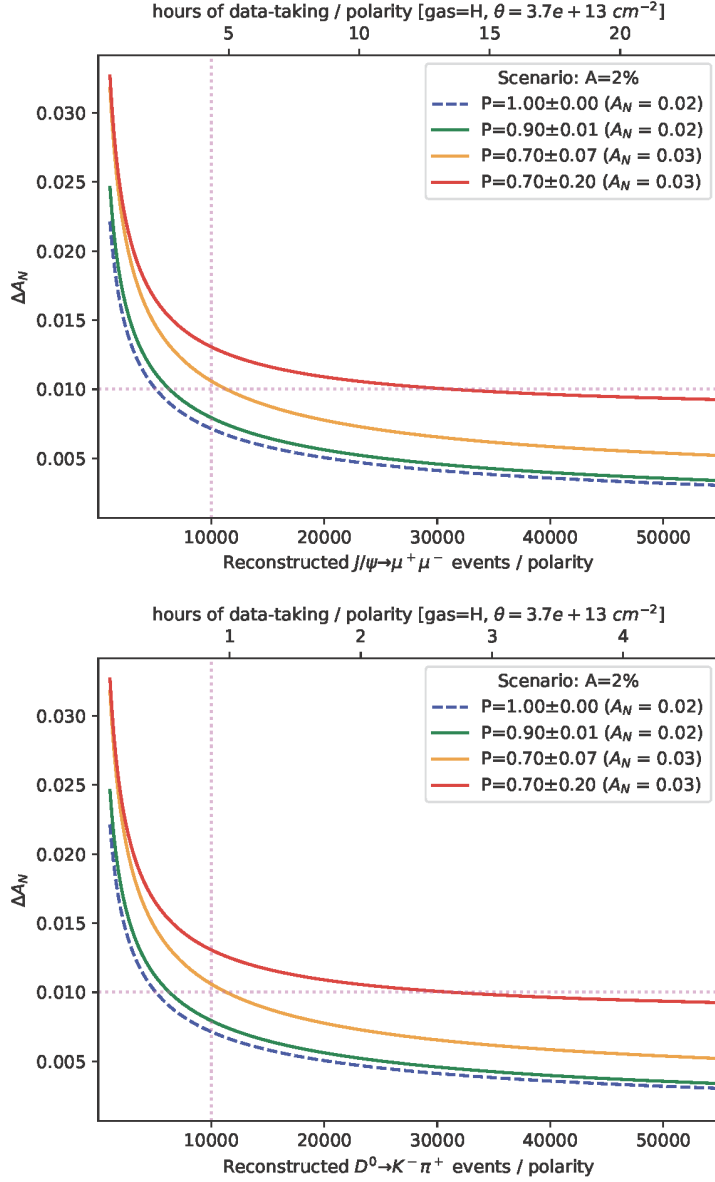
Figure 3: Number of fully-reconstructed events and data-taking time to reach a given precision on a spin asymmetry at LHCspin with three different polarisation degrees for $J/\Psi \rightarrow \mu^+\mu^-$ (up) and $D^0 \rightarrow \pi K$ (down) inclusive production.

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