PROCEEDINGS OF SCIENCE

Fixed Target Program at the LHC

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Collisions provided by a TeV-scale beam at the LHC on a fixed target will explore a unique kinematic region that has been poorly probed until now. Furthermore, advanced detectors make available probes that have never been accessed before. The LHCb spectrometer possesses the unique capability to function as a fixed-target experiment by injecting gas into the LHC beampipe while proton or ion beams are circulating. The resulting beam-gas collisions cover an unexplored energy range above that of previous fixed-target experiments but below the energies of the RHIC or LHC collider. In light of this, the LHCspin project aims to develop innovative solutions and cutting-edge technologies to access the field of spin physics over the next few years. This will be achieved by exploring a unique kinematic regime and exploiting new reaction processes. To accomplish this goal, a polarized gaseous target will be operated in combination with the high-energy, high-intensity LHC beams and the highly performing LHCb particle detector. This configuration has the potential to open new physics frontiers and deepen our understanding of the intricacies of strong interaction in the non-perturbative regime of QCD. With center-of-mass energies per nucleon up to 115 GeV and utilizing both proton and heavy-ion beams, this setup covers a wide backward rapidity region, including the poorly explored high Bjorken-x and high Feynman-x regimes. This ambitious task is based on the recent installation of an unpolarized gas target (SMOG2) in the LHCb spectrometer. This setup not only constitutes a unique project but also provides an invaluable platform for its polarized upgrade. This article offers an overview of the physics potential, a description of the LHCspin experimental setup, and details the initial findings from the SMOG2 system.

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1. Introduction

The LHC delivers proton and lead beams with energies up to 7 TeV and 2.76 TeV per nucleon, respectively, boasting the world's highest intensity. However, these beams cannot be polarized. The only possibility for performing polarized collisions is through the use of a polarized fixed-target system. These collisions will occur at energies in the center-of-mass of up to 115 GeV per nucleon, providing an unprecedented opportunity to investigate partons carrying a large fraction of the target nucleon momentum.

In the forward kinematics of such events, LHCb, with a pseudorapidity acceptance of $2 < \eta < 5$, stands out as a perfect spectrometer both in terms of geometry and performance. The LHCb detector [1] is a general-purpose forward spectrometer specializing in detecting hadrons containing c and b quarks. It is the only LHC detector capable of collecting data in both collider and fixed-target modes simultaneously. This makes it an ideal tool to access, for example, the essentially unexplored spin-dependent gluon Transverse Momentum Distribution functions (TMDs) or to explore the internal dynamics of nucleons in kinematic regions poorly probed before.

Figure 1 illustrates a drawing of the upgraded LHCb detector [2], which has a clear fixed-target-like geometry.

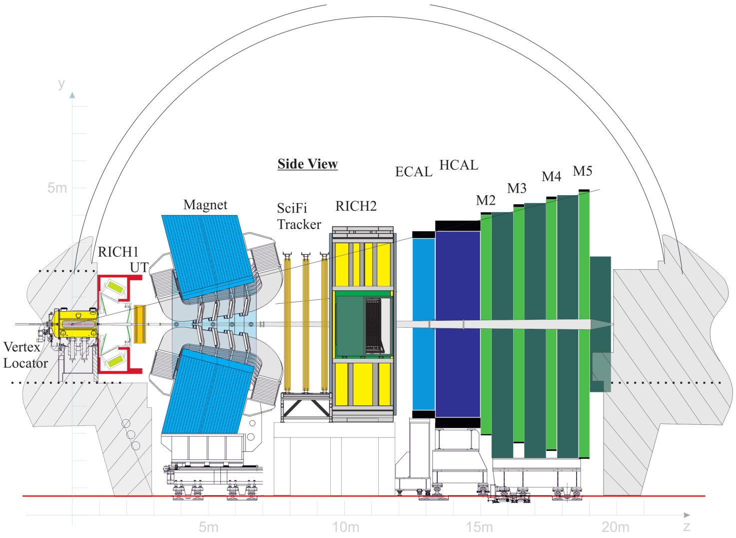

Figure 1: The upgraded LHCb detector.

During the LHC Long Shutdown 2, the SMOG2 system, the first storage cell located along the LHC (Fig. 2, 3), was successfully installed in the primary vacuum of the machine and connected to a sophisticated Gas Feed System (GFS). This new GFS enables the measurement of injected gas density (and, thereby, instantaneous luminosity) with a precision of a few percent and facilitates the injection of various gas species such as H_2, D_2, ^{3}He, ^{4}He, Ne, N_2, O_2, Ar, Kr, and Xe.

Data from the SMOG2 system, collected by the first LHC beam in 2022 and processed using a novel reconstruction algorithm, demonstrated full compatibility with simultaneous beam-beam and beam-gas data-taking. The data also allowed the validation of Monte Carlo (MC) simulations predicting very high tracking efficiency in the beam-gas interaction region, despite its upstream

PoS(SPIN2023)036

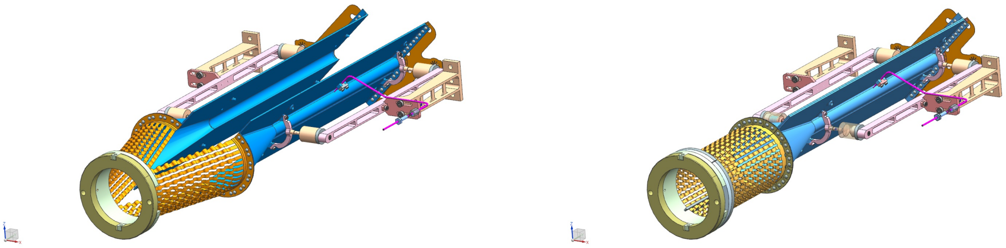

Figure 2: The SMOG2 storage cell in the open (left) and closed (right) configuration.

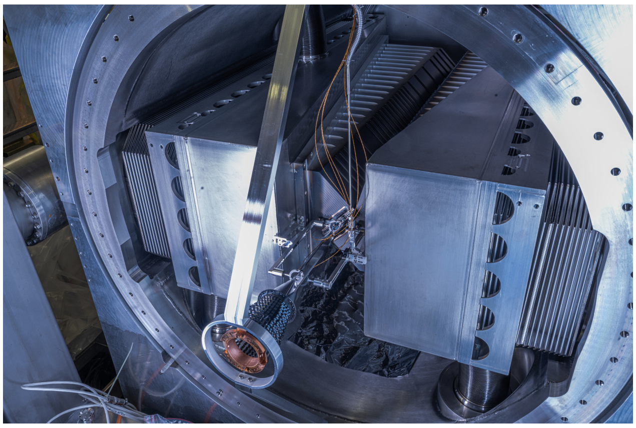

Figure 3: Picture of the SMOG2 storage cell installed in the VELO vessel, in front of the VELO rf-foil.

PoS(SPIN2023)036

position relative to the LHCb silicon vertex detector (VELO), where the beam-gas and beam-beam vertices are well separated along the z coordinate. The SMOG2 system offers a rich physics program for Run 3 and, simultaneously, enables the investigation of the dynamics of the beam-target system, laying the groundwork for future developments.

The project's strengths include: i) the negligible reduction of beam lifetime due to the presence of gas in the cell; ii) the well-separated beam-target interaction region, located at $-541 < IP_z < -341$ mm from the beam-beam IP, allowing unambiguous reconstruction of the two; iii) the reconstruction efficiency of fixed-target events being essentially equal to that of beam-beam collisions. Figure 4 (left) illustrates a rather unique Primary Vertex distribution, featuring two clearly separated regions for pAr and pp collisions around the nominal interaction point. Figure 4 (right) presents a comparison of normalized invariant mass distributions for K^0_S candidates reconstructed with a primary vertex in the SMOG2 (pAr) or in the pp region. Despite different event topologies, the two mass resolutions are very similar [2].

Additional decay channels were subsequently examined, and two examples of the obtained results are detailed in [3]. The provided illustrations showcase the invariant mass distributions for reconstructed $D^0 \rightarrow K^-\pi^+$ and $\Lambda \rightarrow p\pi^-$ candidates, obtained from data collected during simultaneous $pp + pAr$ and $pp + pH_2$ collisions, respectively.

It is noteworthy that these two data acquisition sessions, lasting 18 and 20 minutes respectively, yielded impressive results. Despite their relatively short durations, they encompassed over four thousand D^0 and eight thousand Λ candidates. This underscores the potential for achieving very high statistics in the production of charm states during routine LHCb simultaneous beam-beam and beam-gas operations in Run 3.

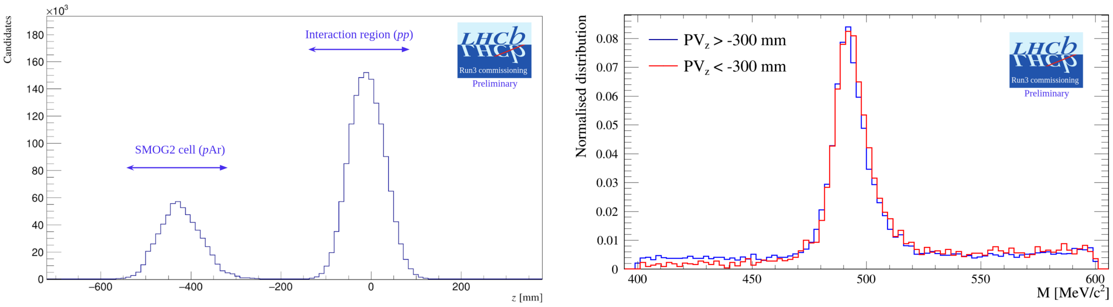

Figure 4: Left: Distribution of the reconstructed primary vertex longitudinal coordinate for pp and pAr collisions. Right: Comparison of the normalised invariant mass distributions for K^0_S reconstructed with a primary vertex in the SMOG2 ($PV_z < 300$ mm) or in the pp ($PV_z > 300$ mm) region.

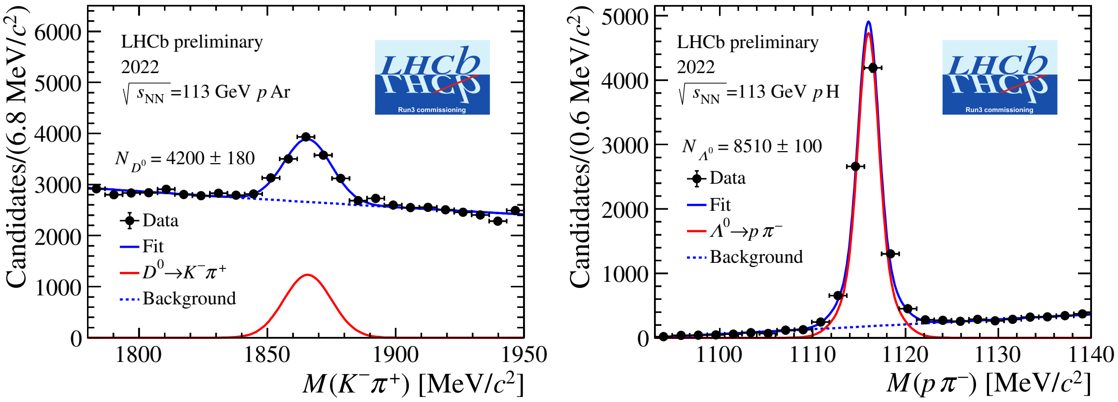

Figure 5: Invariant mass distributions for $D^0 \to K^-\pi^+$ (left) and $\Lambda \to p\pi^-$ (right) decay candidates in 2022 data-takings with simultaneous $pp + pAr$ and $pp + pH_2$ collisions, respectively.

With a 7 TeV proton beam, fixed-target beam-gas collisions occur at a center-of-mass energy per nucleon of $\sqrt{s_{NN}} = 115$ GeV. This corresponds to a large Lorentz boost ($\gamma \simeq 60$) of the center-of-mass in the laboratory system, resulting in a rapidity shift of $\Delta y = y_{Lab} - y_{CM} \simeq 4.8$. Under these conditions, the LHCb acceptance covers both backward and central rapidities in the center-of-mass frame ($-3 < y_{CM} < 0$). This coverage presents an unprecedented opportunity to investigate partons carrying a large fraction of the target nucleon momentum, i.e., large Bjorken-x values, at intermediate Q^2 (Fig. 6), corresponding to large and negative Feynman-x values ($x_F \simeq x_b - x_t$ where x_b and x_t are the Bjorken-x values of the beam and target nucleon, respectively, with $x_b \ll x_t$).

2. The LHCspin project

LHCspin [4] aims to expand the LHCb fixed-target program by installing a new generation of polarized gas targets for either hydrogen or deuterium. The project builds upon well-consolidated

PoS(SPIN2023)036

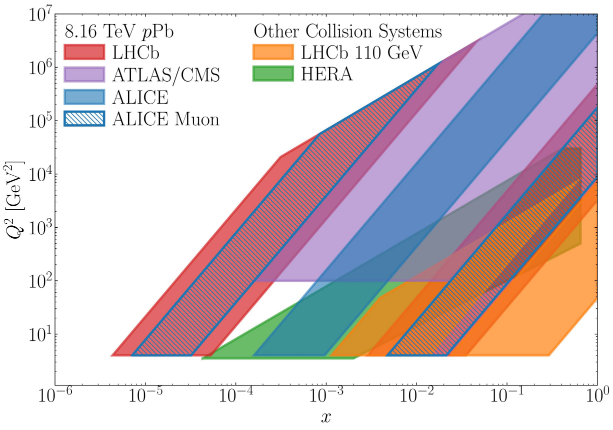

Figure 6: Kinematic coverage of LHCb fixed-target collisions compared to other experiments.

polarized-target technology and expertise, successfully employed at the HERMES experiment at HERA and the ANKE experiment at COSY [5]. This highly specialized expertise is crucial for developing a new generation of targets to be integrated into the complex system of LHC+LHCb.

The physics case of LHCspin encompasses a broad range of physics potential offered by unpolarized gas targets, including studies on Quark-Gluon Plasma (QGP) formation and investigations into cold nuclear matter in heavy-ion collisions. However, its primary focus is on probing the nucleon spin structure. While the first two areas are common with SMOG2 and are presented in [6] (not discussed here), the latter necessitates a polarized target, making it a unique aspect of LHCspin.

LHCspin aims to probe polarized quark and gluon distributions through proton collisions on polarized hydrogen and deuterium targets. Various leading-twist distributions, accessible with either unpolarized or transversely polarized targets, provide independent information about the spin structure of the nucleon.

The exploration of quark TMDs stands out as a key physics goal for LHCspin. Quark TMDs describe spin-orbit correlations within the nucleon, indirectly providing sensitivity to the unknown quark orbital angular momentum. Moreover, they facilitate the construction of 3D maps of the nucleon structure in momentum space, a concept known as nucleon tomography. The preferred process for accessing quark TMDs in hadronic collisions at the LHC fixed-target kinematic conditions is Drell-Yan (DY).

Under these conditions, the dominant contribution to the process occurs when the anti-quark from the proton beam is probed at small-x, and the quark from the target proton is probed at large-x. Furthermore, LHCb boasts excellent Particle Identification and high reconstruction efficiency for muons.

By utilizing a transversely polarized hydrogen (or deuterium) target, sensitivity to spin-dependent quark TMDs, such as the Sivers function, $f_{1T}^{\perp,q}(x, p_T^2)$, and the transversity distribution, $h_1^q(x, p_T^2)$, can be obtained through a Fourier decomposition of the Transverse Single-Spin Asymmetry (TSSA). Projections for DY measurements, evaluated at LHCb fixed-target kinematics and based on an integrated luminosity of 10 fb^{-1}, are depicted in Fig. 7 [7].

The transversity distribution, currently constrained to valence quarks and a relatively limited x region, holds great interest. Its precise determination, particularly the first moment known as

PoS(SPIN2023)036

the tensor charge, could impose stringent constraints on new physics Beyond the Standard Model (BSM). As a T-odd quantity, it is theoretically established that the Sivers and Boer-Mulders functions extracted in DY must exhibit an opposite sign compared to the same quantities extracted in semi-inclusive deep inelastic scattering (SIDIS). This fundamental QCD prediction can be tested by leveraging the large sample of DY data expected at LHCspin. Additionally, isospin effects can be explored through a comparison of p-H and p-D collisions.

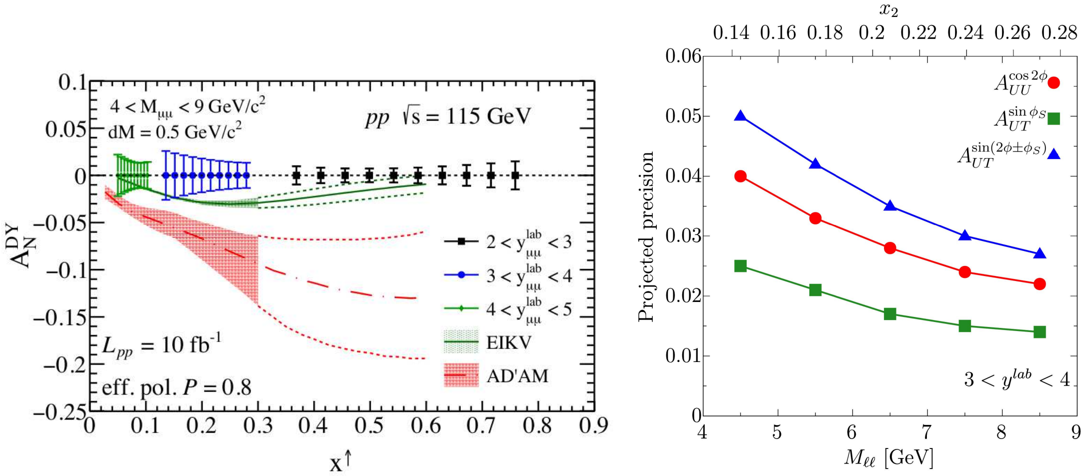

Figure 7: Left: projections of A_N as a function of x for DY events at the LHCb fixed-target kinematics compared to theoretical predictions. Right: projected precision for selected azimuthal asymmetry amplitudes with DY data in a specific rapidity interval, as a function of the di-lepton invariant mass.

While the first phenomenological extractions of quark TMDs have been conducted in recent years, primarily based on SIDIS data, our understanding of gluon TMDs remains limited. Exploring observables sensitive to gluon TMDs, such as the gluon Sivers function, marks the new frontier in this research field. Given that, at the LHC, heavy quarks are predominantly produced through gluon-gluon fusion, the production of quarkonia and open heavy-flavor states emerges as the most effective approach to study the gluon dynamics within nucleons and probe gluon TMDs. Specifically, through the measurement of inclusive production of J/Ψ, Ψ′, D^0, η_c, χ_c, χ_b, and so on—suitable and optimized for LHCb—LHCspin holds the potential to become a unique facility for these investigations.

While the unpolarized gluon TMD f_1^g and the Boer-Mulders gluon TMD $h_1^{\perp,g}$ can be explored by studying the azimuthal dependence of the cross-section, gluon TMDs requiring a transversely polarized nucleon, such as the gluon Sivers function $f_{1T}^{\perp,g}$, can be investigated through a Fourier decomposition of the TSSA. Figure 8 illustrates the x_F dependence of two model predictions for the inclusive J/Ψ events [8]. Asymmetries as significant as 5-10% could be anticipated, particularly in the negative x_F region where LHCspin exhibits its highest sensitivity.

Since transverse momentum-dependent QCD factorization necessitates a transverse momentum $p_T(Q) \ll M_Q$, where Q denotes a heavy quark, the most secure inclusive processes to be examined with a polarized hydrogen target involve associated quarkonium production. In this scenario, only the relative p_T needs to be small compared to M_Q.

While TMDs offer a tomographic view of the nucleon in momentum space, complementary

PoS(SPIN2023)036

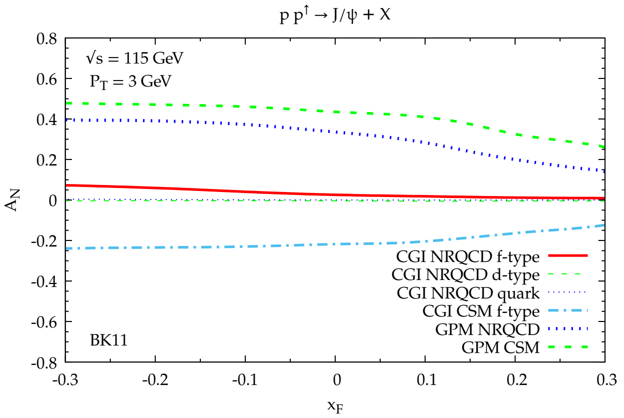

Figure 8: Theoretical predictions for A_N for inclusive J/Ψ production [7].

3D maps can be derived in spatial coordinate space by measuring Generalized Parton Distribution functions (GPDs). The largely unexplored gluon GPDs can be experimentally investigated at the LHC through exclusive quarkonia production in Ultra-Peripheral Collisions (UPCs). Specifically, leveraging the LHCspin polarized target, TSSAs in UPCs can be utilized to probe, for example, the E^g GPD. This GPD has not been measured to date and stands as a crucial element in unraveling the proton spin puzzle.

The exploration of collective phenomena in heavy-light systems through ultra-relativistic collisions of heavy nuclei with transversely polarized deuterons presents a distinctive and captivating intersection of heavy-ion and spin physics.

Making use of a transversely polarized deuteron target provides the means to manage the orientation of the resulting fireball by gauging the elliptic flow concerning the polarization axis (ellipticity). The spin-1 deuteron nucleus exhibits prolate (oblate) characteristics in the $j_3 = \pm 1$ ($j_3 = 0$) configuration, where j_3 denotes the spin's projection along the polarization axis. The deformation of the target deuteron can impact the fireball's orientation in the transverse plane, as illustrated in Fig. 9. The proposed measurement outlined in [9] can be executed at LHCspin using the high-intensity LHC heavy-ion beams. Another interesting measurement using the Pb beam is detailed in [10].

3. Experimental setup and simulations

The R&D efforts for the LHCspin setup aim at advancing a new-generation Polarized Gas Target (PGT). Drawing from the polarized target system utilized in the HERMES experiment [5], the PGT comprises three key components: an Atomic Beam Source (ABS), a Storage Cell (SC), and a diagnostic system. The SC, modeled on the SMOG2 concept, resides within a vacuum chamber (primary vacuum) and is encompassed by a compact superconductive dipole magnet generating a 300 mT static transverse field with a homogeneity of 10% across the entire cell volume.

This configuration is crucial for establishing the transverse polarization of the gas within the cell and preventing beam-induced depolarization. Ongoing studies are addressing the inner coating of the SC with the objective of creating a surface that minimizes both the molecular recombination

PoS(SPIN2023)036

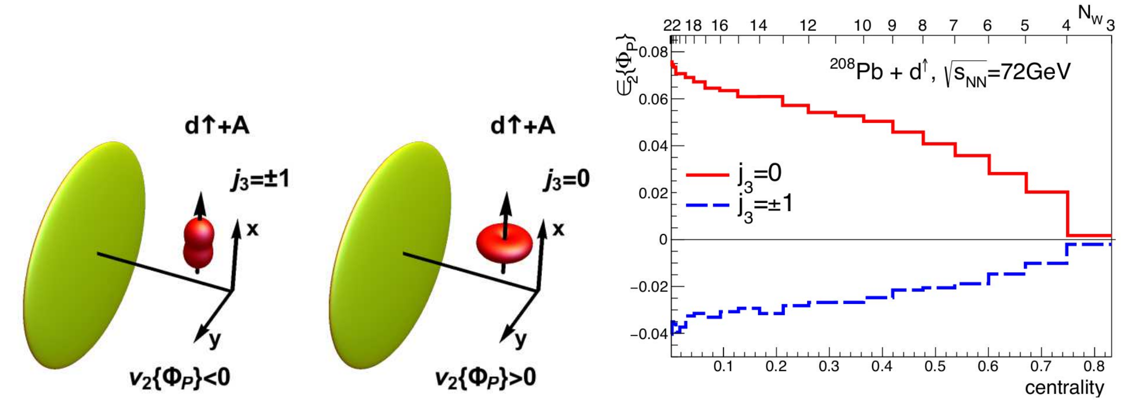

Figure 9: Left: Sketch of an ultra-relativistic collision of a lead nucleus against a transversely polarized deuteron in two different angular momentum projections. Right: Ellipticity with respect to the polarization axis as a function of the collision centrality with LHCspin kinematics [8].

rate and the secondary electron yield. The vacuum chamber housing the storage cell, positioned in front of the LHCb VELO detector, is depicted in Fig. 10.

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

Concurrently, investigations are underway to identify a contingency plan in the event that atomic recombination on the cell wall surface proves unsatisfactory. Should this be the case, a jet target—essentially an Atomic Beam Source (ABS) without a storage cell—could be considered. The notable advantage lies in the high polarization of the atomic ultrasonic beam, accompanied by a minimal systematic contribution to the polarization determination. However, it is essential to note that the achievable density in this scenario is substantially lower, exceeding one order of magnitude less compared to the solution incorporating the SC. The R&D efforts will ultimately determine the figure of merit for both solutions.

LHCspin is actively working on an R&D program to be conducted directly on the LHC beam before its integration into LHCb. Within the LHC tunnel, specifically in Interaction Region 3 or 4 (IR3 or IR4), positioned between the ALICE and CMS experiments, there exists a lengthy, unobstructed section characterized by limited instrumentation and a low radiation profile. This area presents an opportunity to install and examine a proof of principle for the setup in the coming years before its final implementation in the LHCb cavern. In particular, potential research in this space includes investigations into a novel compact target polarimeter, studies on Beam-Induced Depolarization, and examinations of atomic recombination and depolarization.

The entire reconstruction process of LHCb has been applied to events simulated based on the typical LHC parameters for Run 4. In Figure 11, the data-taking time required for each polarity state to achieve a specific precision on a Transverse Single Spin Asymmetry (TSSA) is illustrated. For instance, by collecting data for 10 hours on each polarity state (totaling 20 hours of data-taking time), an absolute uncertainty of approximately $A_N = 0.6\%$ can be obtained for $J/\Psi \to \mu^+\mu^-$ events

PoS(SPIN2023)036

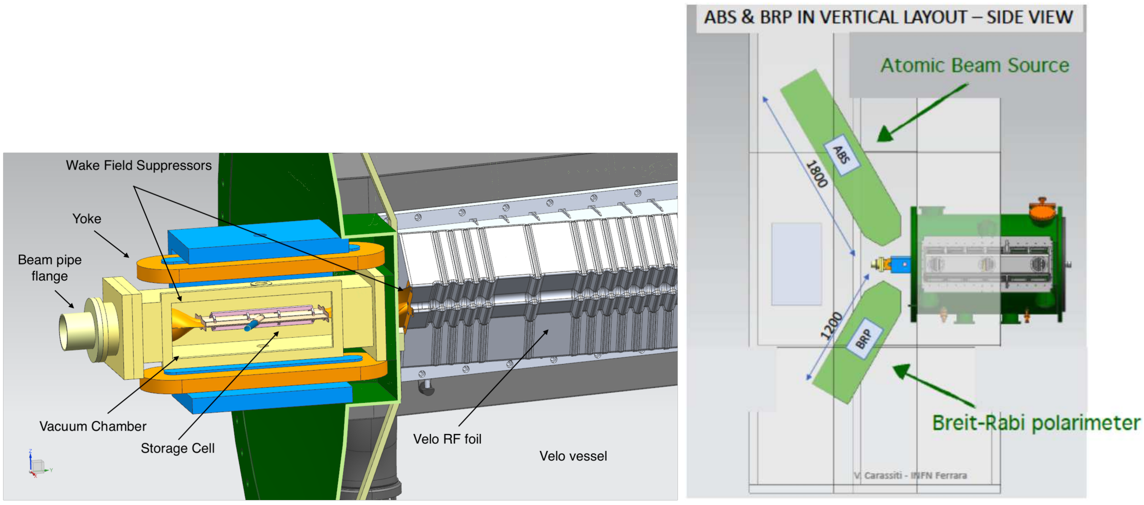

Figure 10: Left: A drawing of the LHCspin vacuum chamber (yellow) hosting the storage cell. The chamber is inserted between the coils of the magnet (orange) and the iron return yoke (blue). The VELO vessel and RF box are shown in green and grey, respectively. Right: Sketch of the full setup installed in the VELO alcove.

at a 100% polarization degree. The three curves depict the uncertainty on A_N, which results from both statistical uncertainty and knowledge of the polarization degree. Notably, a precision better than 1% can be achieved in just a few hours of data collection for the considered channels.

Furthermore, the TSSA asymmetry for the J/Ψ $\rightarrow \mu^+\mu^-$ channel can be substantial and easily achievable with only 1 month of LHCspin data, as shown in simulated events (see Fig. 12).

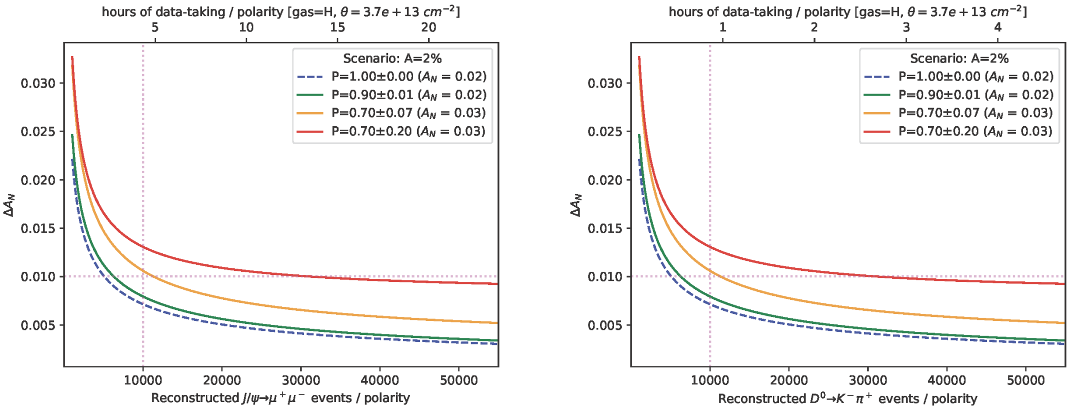

Figure 11: Number of fully-reconstructed events and data-taking time to reach a given precision on a spin asymmetry at LHCspin assuming three different polarisation degrees for J/Ψ $\rightarrow \mu^+\mu^-$ (left) and $D^0 \rightarrow \pi K$ (right) inclusive production.

4. Conclusions

The fixed-target physics program at LHC has received a significant boost following the recent implementation of the SMOG2 setup at LHCb. LHCspin, evolving from SMOG2, seeks to introduce

PoS(SPIN2023)036

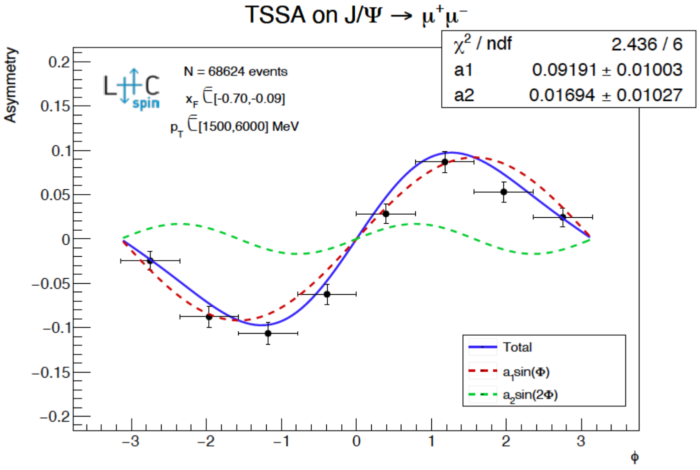

Figure 12: Simulated J/Ψ $\rightarrow \mu^+\mu^-$ azimuthal asymmetries with a fit curve superimposed accounting for two azimuthal modulations.

a polarized gas target, marking the inaugural incorporation of spin physics at LHC and paving the way for a host of new explorations. With enthusiastic interest and backing from the global theoretical community, LHCspin stands as a distinctive opportunity to deepen our understanding of various uncharted realms in Quantum Chromodynamics (QCD). This initiative complements both current facilities and the prospective Electron-Ion Collider (EIC), contributing to the advancement of our knowledge in the field.

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PoS(SPIN2023)036