THE LHCspin PROJECT*

P. Di Nezza[a,†], V. Carassiti[b], G. Ciullo[b,c], P. Lenisa[b,c]
L.L. Pappalardo[b,c], M. Santimaria[a], E. Steffens[d], G. Tagliente[e]

[a]INFN Laboratori Nazionali di Frascati, Frascati (Rome), Italy
[b]INFN Ferrara, Italy
[c]Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, Italy
[d]Department of Physics, FAU Erlangen-Nurnberg, Erlangen, Germany
[e]INFN Bari, Italy

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The goal of LHCspin is to develop innovative solutions and cutting-edge technologies to access the field of spin physics over the next few years by exploring a unique kinematic regime and exploiting new reaction processes. To this end, 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 per nucleon up to 115 GeV, using both proton and heavy-ion beams, 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 unpolarised gas target (SMOG2) in the LHCb spectrometer. This setup not only constitutes a unique project but also provides an invaluable playground for its polarized upgrade. This article provides an overview of the physics potential, a description of the LHCspin experimental setup, and the first output of the SMOG2 system.

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1. Introduction

The LHC delivers proton and lead beams with an energy of up to 7 TeV and 2.76 TeV per nucleon, respectively, with the world's highest intensity. However, the beams 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 per nucleon,

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† Corresponding author: `Pasquale.DiNezza@lnf.infn.it`

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 a pseudorapidity 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. This makes it an ideal tool to access, *e.g.*, the essentially unexplored spin-dependent gluon Transverse Momentum Distribution functions (TMDs) or to explore the nucleons internal dynamics in kinematic regions poorly probed before. Figure 1 shows a drawing of the upgraded LHCb detector [2], which has a clear fixed-target-like geometry.

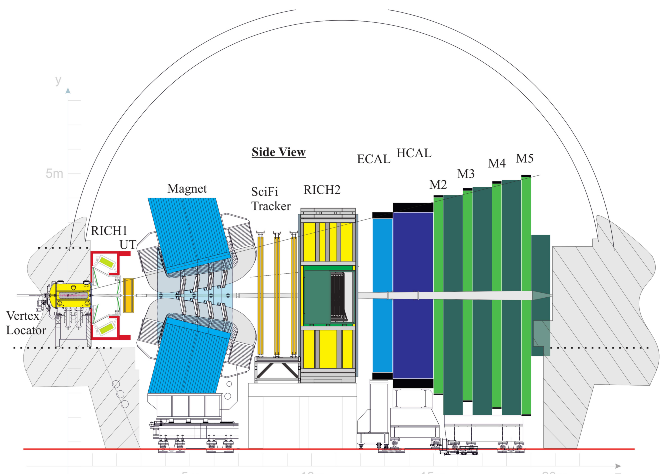


Fig. 1. The upgraded LHCb detector.

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

The SMOG2 data delivered by the first LHC beam in 2022, collected with a novel reconstruction algorithm, showed that the system is fully compatible with simultaneous beam–beam and beam–gas data-taking. Data also allowed to validate MC simulations predicting a very high tracking efficiency in the beam–gas interaction region, despite its upstream position relative to the LHCb silicon vertex detector (VELO), where the beam–gas

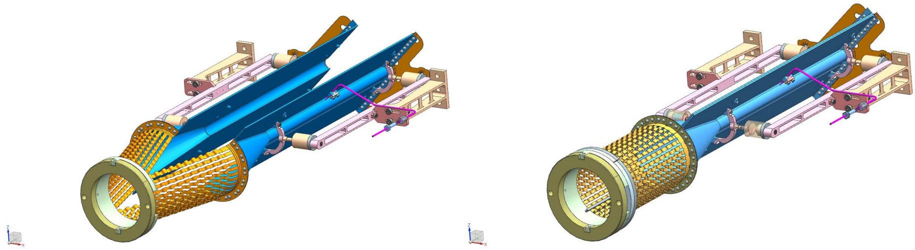


Fig. 2. The SMOG2 storage cell in the open (left) and closed (right) configuration.

and beam–beam vertices are well separated along the z coordinate. The SMOG2 system provides a rich physics program for Run 3 and, simultaneously, permits the investigation of the dynamics of the beam–target system, laying the basis for future developments.

The strengths of the project include: *(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 $-541 < \mathrm{IP}_z < -341$ mm from the beam–beam IP, is well separated from the latter and the two can be reconstructed without ambiguity; *(iii)* the reconstruction efficiency of the fixed-target events is essentially equal to the one of the beam–beam collisions. Figure 3 (left) shows a rather unique Primary Vertex distribution, where two clearly separated regions for pAr and pp collisions around the nominal interaction point can be seen. Figure 3 (right) shows a comparison of the normalised invariant mass distributions for K^0_S candidates reconstructed with a primary vertex in the SMOG2 (pAr) or in the pp region. Despite the different event topologies, the two mass resolutions are very similar [2].

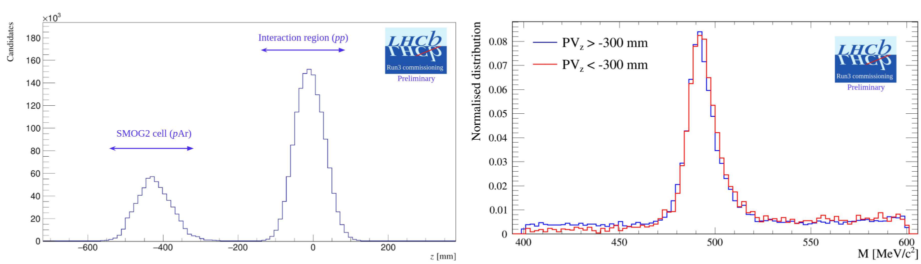


Fig. 3. Left: Distribution of the reconstructed primary vertex longitudinal coordinate for pp and pAr collisions. Right: Comparison of the normalised invariant mass distributions for K^0_S reconstructed with a primary vertex in the SMOG2 ($\mathrm{PV}_z <$ 300 mm) or in the pp ($\mathrm{PV}_z >$ 300 mm) region.

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 $\Delta y = y_{\rm Lab} - y_{\rm CM} \simeq 4.8$. At these conditions, the LHCb acceptance allows for coverage of backward and central rapidities in the center-of-mass frame ($-3 < y_{\rm CM} < 0$). Such a coverage offers 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. 4), corresponding to large and negative Feynman-x values ($x_{\rm F} \simeq x_{\rm b} - x_{\rm t}$ where $x_{\rm b}$ and $x_{\rm t}$ are the Bjorken-x values of the beam and target nucleon, respectively, with $x_{\rm b} \ll x_{\rm t}$).

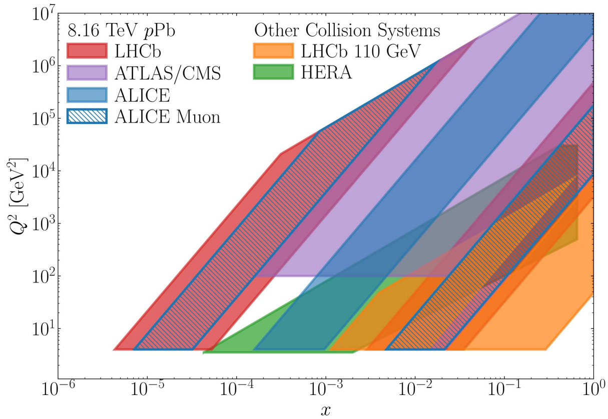


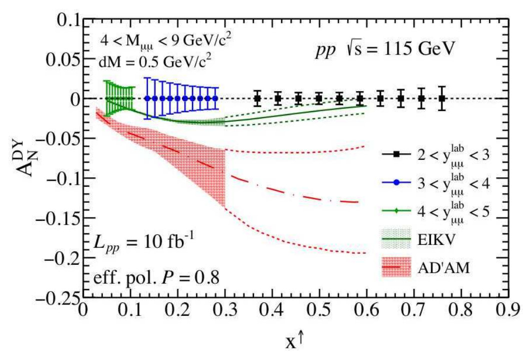
Fig. 4. Kinematic coverage of LHCb fixed-target collisions compared to other experiments.

2. The LHCspin project

The LHCspin [3] aims at extending the LHCb fixed-target program with the installation of a new generation polarized gas target for H or D. The project is based on the well-consolidated polarized-target technology and expertise, which was successfully employed in the HERMES experiment at HERA and the ANKE experiment at COSY [4]. This highly specialized expertise is essential for the development of a new generation of targets to be implemented in a complex system such as 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 can be probed using either unpolarized or transversely polarized targets, provide independent information on the spin structure of the nucleon. The study of quark 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 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. Moreover, LHCb has excellent Particle IDentification and high reconstruction efficiency for muons. By using a transversely polarized hydrogen (or deuterium) target, one can obtain 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 Transverse Single-Spin Asymmetry (TSSA). 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. 5 [6].



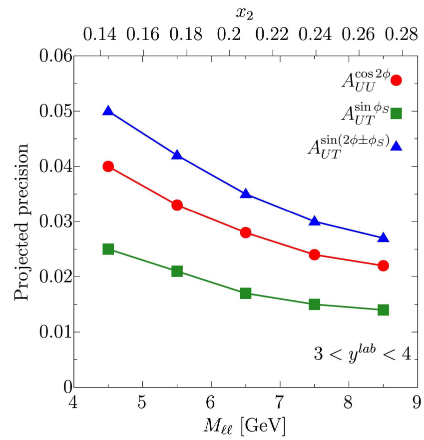


Fig. 5. Left: Projections of A_N as a function of x for DY events at the LHCb fixed-target kinematics compared to theoretical predictions. Right: Projected precision for selected azimuthal asymmetry amplitudes with DY data in a specific rapidity interval, as a function of the di-lepton invariant mass.

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 compared to the same quantities extracted in semi-inclusive deep inelastic scattering (SIDIS). 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.

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 the new frontier of this research field. Since, at the LHC, heavy quarks are mainly produced via gluon–gluon fusion, the production of quarkonia and open heavy-flavour states is 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.

While the unpolarized f_1^g and the Boer–Mulders $h_1^{\perp,g}$ gluon TMDs can be accessed through the study of the azimuthal dependence of the cross section, the gluon TMDs that require a transversely polarized nucleon, such as the gluon Sivers function $f_{1\mathrm{T}}^{\perp,g}$, can be probed through a Fourier decomposition of the TSSA. Figure 6 shows the x_F dependence of two model predictions for A_N for inclusive J/Ψ events [7]. Asymmetries as large as 5–10% could be expected in the negative x_F region, where the LHCspin sensitivity is highest.

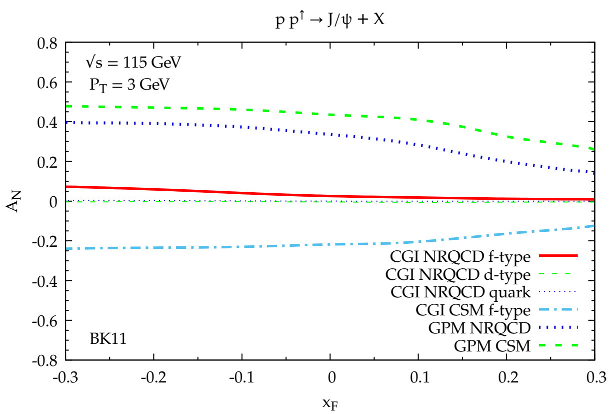


Fig. 6. Theoretical predictions for A_N for inclusive J/Ψ production [7].

Since transverse-momentum-dependent QCD factorization requires a transverse momentum $p_\mathrm{T}(Q) \ll M_Q$, where Q denotes a heavy quark, the safest inclusive processes to be studied with a polarized hydrogen target is the associated quarkonium production, where only the relative p_T has to be small compared to M_Q.

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 the 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.

The study of collective phenomena in heavy–light systems through ultra-relativistic collisions of heavy nuclei with transversely polarized deuterons represents a unique and interesting point of contact between heavy ion and spin physics. A transversely polarized deuteron target offers the opportunity to control the orientation of the formed fireball by measuring the elliptic flow relative to the polarization axis (ellipticity). The spin-1 deuteron nucleus is prolate (oblate) in the $j_3 = \pm 1$ ($j_3 = 0$) configuration, where j_3 is the projection of the spin along the polarization axis. The deformation of the target deuteron can influence the orientation of the fireball in the transverse plane, as shown in Fig. 7. The measurement proposed in [8] can be performed at the LHCspin using high-intensity LHC heavy-ion beams.

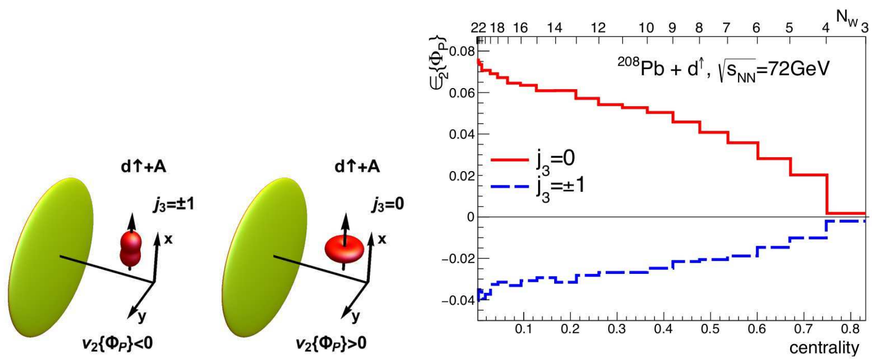
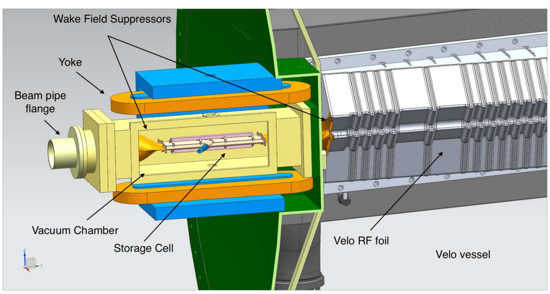


Fig. 7. Left: Sketch of an ultra-relativistic collision of a lead nucleus against a transversely polarized deuteron in two different angular momentum projections. Right: Ellipticity with respect to the polarization axis as a function of the collision centrality with LHCspin kinematics [8].

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 as the SMOG2 one, is located inside a vacuum chamber (primary vacuum) and surrounded by a compact superconductive dipole magnet generating a 300 mT static transverse field with homogeneity of 10% over the full volume of the cell. This is necessary to set 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 hosting the storage cell, installed in front of the LHCb VELO detector, is shown in Fig. 8. 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.



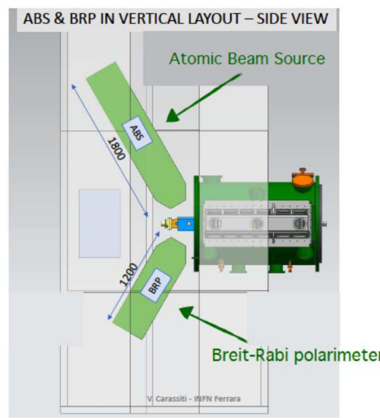


Fig. 8. Left: A drawing of the LHCspin vacuum chamber (yellow) hosting the storage cell. The chamber is inserted between the coils of the magnet (orange) and the iron return yoke (blue). The VELO vessel and RF box are shown in green and grey, respectively. Right: Sketch of the full setup installed in the VELO alcove.

Parallel studies are being conducted to find a backup solution in case the atomic recombination on the cell wall surface is not satisfactory. In this case, a jet target, meaning an ABS without a storage cell, can be considered. The advantage lies in the high polarisation of the atomic ultrasonic beam with a very small systematic contribution to the polarisation determination. On the contrary, the density reachable is lower by more than one order of magnitude compared to the solution with the SC. The R&D will determine the figure of merit of the two solutions.

The LHCspin is also developing an R&D program to be performed directly on the LHC beam before its installation at the LHCb. Along the LHC tunnel, the Interaction Region 3 (IR3), in the middle between the ALICE and CMS experiments, has a long, straight section with very limited instrumentation and a low radiation profile. Here a *proof of principle* of the setup could be installed and studied in the next years before the final installation into the LHCb cavern. In particular, studies on a new compact target polarimeter, on Beam Induced Depolarisation, or on atomic recombination and depolarisation, are among the possible developments to be conducted in this area.

The complete reconstruction chain of LHCb has been run on events simulated considering the typical LHC parameters of Run 4. Figure 9 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 for reaching an absolute uncertainty of the order of $A_N = 0.6\%$ on $J/\Psi \to \mu^+\mu^-$ events in the case of 100% polarisation degree. The three curves represent the uncertainty on A_N resulting 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.

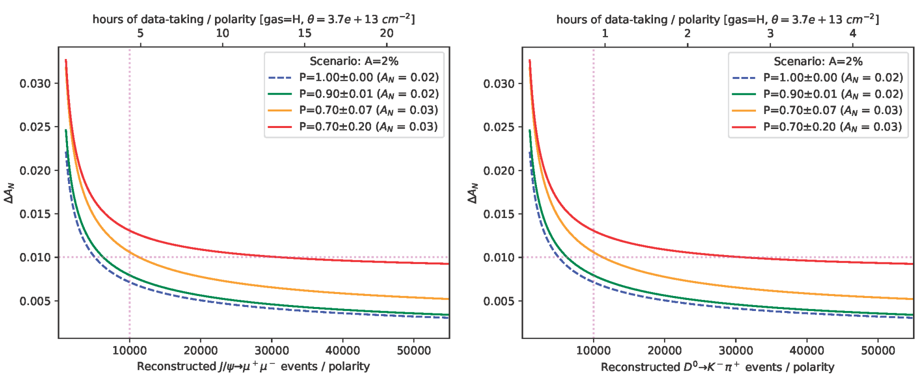


Fig. 9. Number of fully-reconstructed events and data-taking time to reach a given precision on a spin asymmetry at the LHCspin assuming three different polarisation degrees for $J/\Psi \to \mu^+\mu^-$ (left) and $D^0 \to \pi K$ (right) inclusive production.

In addition, also the TSSA asymmetry for the $J/\Psi \to \mu^+\mu^-$ channel can be large and well in reach with just 1 month of LHCspin data, as shown in simulated events (Fig. 10).

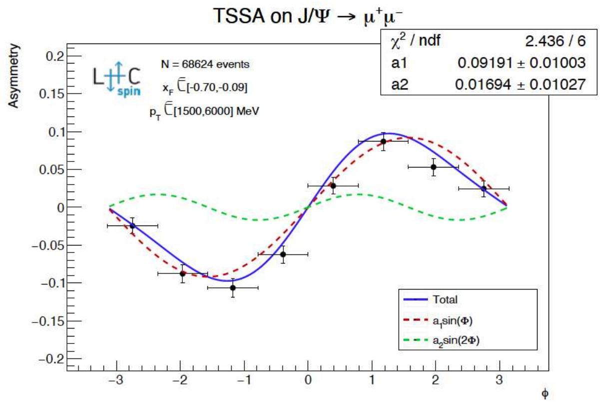


Fig. 10. Simulated $J/\Psi \to \mu^+\mu^-$ azimuthal asymmetries with a fit curve superimposed accounting for two azimuthal modulations.

4. Conclusions

The fixed-target physics program at the LHC has been greatly enhanced with the recent installation of the SMOG2 setup at the LHCb. The LHCspin is the natural evolution of SMOG2 and aims to install a polarized gas target to bring spin physics at the LHC for the first time, opening a whole new range of explorations. With strong interest and support from the international theoretical community, the 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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