THE LHCspin PROJECT: A POLARISED GAS TARGET AT THE LHC*

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LHCb is the only experiment at the LHC able to reconstruct simultaneously events from beam–beam and beam–gas collisions taking place in a gas storage cell. The aim of the LHCspin project is to bring spin physics at the LHC for the first time by injecting polarised hydrogen and deuterium. This would enable the high-energy LHC beam and the peculiar forward geometry of LHCb to explore the 3D structure of matter in a unique kinematic regime and by means of probes that are not accessible in other facilities.

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1. Fixed-target physics at the LHCb

The LHCb detector [1] is a general-purpose forward spectrometer specialised in reconstructing hadrons containing c and b quarks. The detector is fully instrumented in the $2 < \eta < 5$ region with a vertex locator (VELO), a tracking system with silicon and scintillating fiber stations, two Cherenkov detectors, electromagnetic and hadronic calorimeters, and a muon detector.

The fixed-target physics program at the LHCb has been active since Run 2 thanks to the SMOG system [2], which allowed for the injection of noble gases at pressures of $\mathcal{O}(10^{-7})$ mbar into the beam pipe section crossing the VELO. In Run 3, the SMOG2 gas storage cell [3] has been installed in front of the VELO, as shown in Fig. 1 (left). With respect to SMOG, the cell boosts the target areal density by a factor of 8 to 35 depending on the injected gas species, and creates a localised beam–gas collision region which

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is well detached from the beam–beam vertices along the beam axis (z). Updated reconstruction algorithms and dedicated trigger lines have been developed to achieve full tracking capabilities in the upstream region, as shown in Fig. 1 (right), with negligible impact on the trigger load.

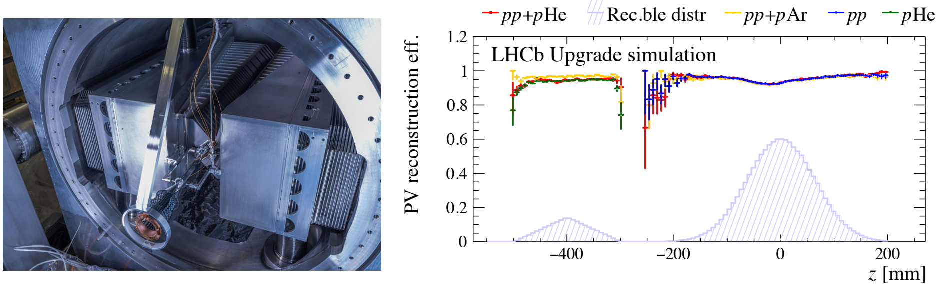

Fig. 1. Left: the SMOG2 gas storage cell during its installation in the vacuum vessel of the VELO. Right: vertex reconstruction efficiency for simultaneous proton–proton ($z \sim 0$ mm) and proton–gas ($z \sim -400$ mm) collisions [4].

The simultaneous reconstruction of $K^0_{\rm s} \to \pi^+\pi^-$ events in proton–proton and proton–argon collisions in early 2022 data is shown in Fig. 2 (left). With SMOG2, large samples of fixed-target collisions can be collected in a short amount of time, as shown in Fig. 2 (right).

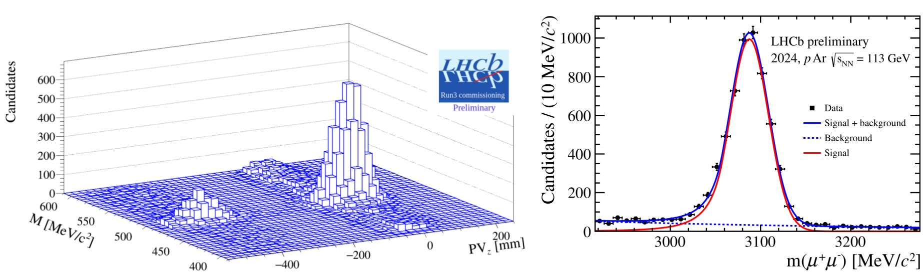

Fig. 2. Left: $K^0_{\rm s} \to \pi^+\pi^-$ invariant mass reconstructed in both proton–proton and proton–argon collision in 2022 data [5]. Right: $J/\psi \to \mu^+\mu^-$ events reconstructed with only 1 hour and 40 minutes of proton–argon data in 2024 [6].

The success of SMOG2 sets the basis for its future development: the LHCspin project aims at bringing spin physics at the LHC for the first time with the installation of a polarised-gas target.

2. LHCspin experimental setup

The experimental setup of LHCspin comprises three main components: an Atomic Beam Source (ABS), a Target Chamber (TC), and a diagnostic system. The ABS consists 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 polarisation between states of the opposite sign. The ABS injects a beam of polarised hydrogen or deuterium into the TC, which is located in the LHC primary vacuum. The TC hosts a T-shaped openable storage cell, sharing the SMOG2 design, and a dipole holding magnet ($B = 300$ mT), as shown in Fig. 3.

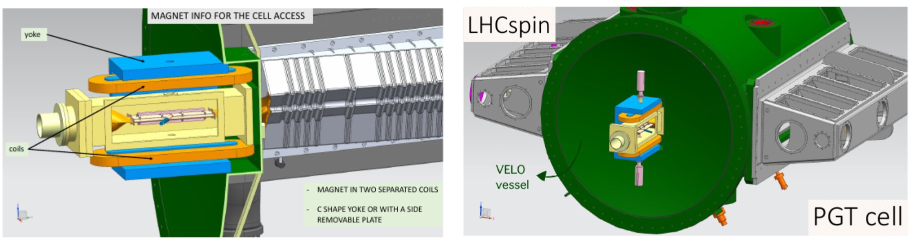

Fig. 3. Two views of the TC with the magnet coils (orange) and the iron return yoke (blue) enclosing the storage cell. The VELO vessel and detector box are shown in green and grey, respectively.

The diagnostic system continuously analyses gas samples drawn from the TC and comprises a target gas analyser 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.

This setup does not require any additional detector and only foresees a modification of the flange of the vacuum vessel to allow the cell to be installed as close as possible to the VELO sensors in order to provide broader kinematic acceptance, as shown in Fig. 4.

If the present beam parameters of the LHC are considered, *i.e.* 1.4×10^{14} protons per bunch and up to 2808 colliding bunches at the LHCb, an instantaneous luminosity of $\mathcal{O}(10^{32})$ cm^{-2}s^{-1} can be achieved for p–H collisions with the hydrogen flux provided by the existing ABS developed for the HERMES experiment [7], which is shown in Fig. 5 (left).

Prior to the implementation in the LHCb, the R&D foresees a first phase at Interaction Region 4 of the LHC (Fig. 5, right), where the target implementation in the LHC vacuum and polarimeter studies can be carried out. A minimal experimental setup would also allow to perform a first set of unique measurements already at this early stage.

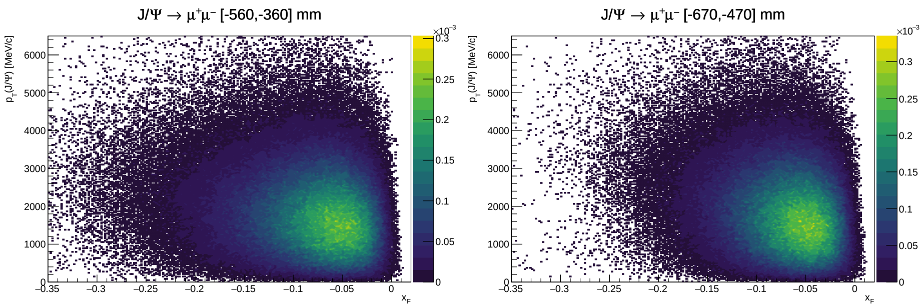

Fig. 4. Transverse momentum (p_{T}) *versus* Feynman-x (x_{F}) coverage for simulated $J/\psi \to \mu^+\mu^-$ events reconstructed in p–H collisions at LHCspin with two different cell positions (square brackets).

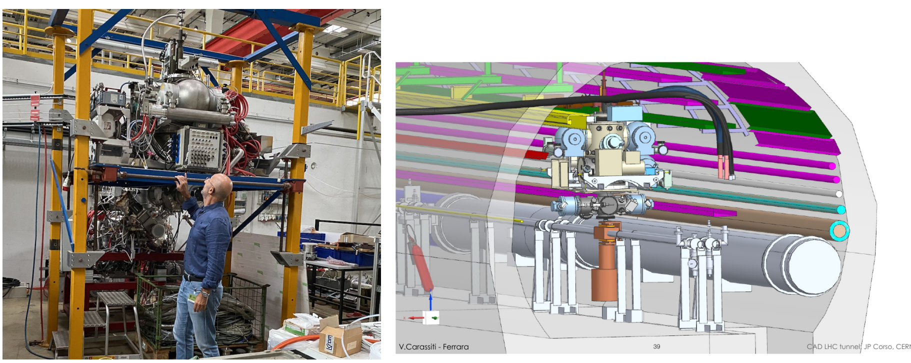

Fig. 5. Left: the HERMES ABS at Jülich. Right: drawing of the ABS at the IR4.

An alternative setup exploiting a jet target is also considered. This would simplify the setup and improve the polarisation degree of the target but reduce the areal density by a factor of about 40.

3. Physics case

The LHC delivers proton and lead beams with an energy of 7 TeV and 2.76 TeV per nucleon, respectively, with world's highest intensity. This enables fixed-target collisions with centre-of-mass energies per nucleon of up to 115 GeV, while the large centre-of-mass boost allows to investigate partons carrying a large fraction of the target nucleon momentum, *i.e.* large Bjorken-x.

By means of the existing SMOG2 gas feed system, LHCspin will retain the ability to inject several species of unpolarised gases with negligible impact on the LHC beam lifetime[1]. This gives an excellent opportunity to

[1] About 2% beam loss over 10 hours for collisions of lead ions against argon [8].

investigate parton distribution functions (PDFs) in both nucleons and nuclei in the large-x and intermediate-Q^2 regime, which is especially affected by lack of experimental data and impacts several fields from basic QCD tests to astrophysics. For example, the large acceptance and high-reconstruction efficiency of the LHCb on heavy-flavour states enables the study of gluon PDFs, which are a fundamental input for theoretical predictions [9]. Nuclear PDFs can also be investigated in greater detail, helping to shed light on the anti-shadowing effect [10].

Besides standard collinear PDFs, LHCspin will offer the opportunity to probe transverse-momentum-dependent PDFs (TMDs) by means of proton collisions on polarised hydrogen and deuterium. Light quark TMDs, especially in the high-x regime, can be accessed by measuring transverse single-spin asymmetries (TSSAs) in Drell–Yan processes, as shown in Fig. 6 (left), for which the dimuon mass resolution is about 0.5%. An interesting topic joining heavy-ion collisions and spin physics is the dynamics of small systems which can be probed via ellipticity measurements in lead–ion collisions on polarised deuterons [11], shown in Fig. 6 (right).

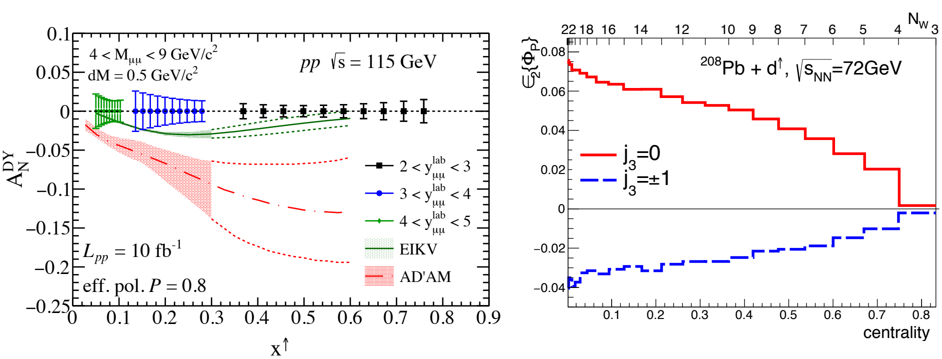

Fig. 6. Left: projected measurements of TSSAs with 10 fb^{-1} of Drell–Yan data [9]. Right: ellipticities of the fireball created in lead–ion collision on polarised deuteron [11].

Gluon densities, such as the gluon Sivers function, can be probed via heavy-flavour production, for which the LHCb reconstruction capabilities are optimal. In this case, the asymmetry can be large (Fig. 7, left) and well in reach with just one month of LHCspin data, as shown in simulated $J/\psi \to \mu^+\mu^-$ events (Fig. 7, right).

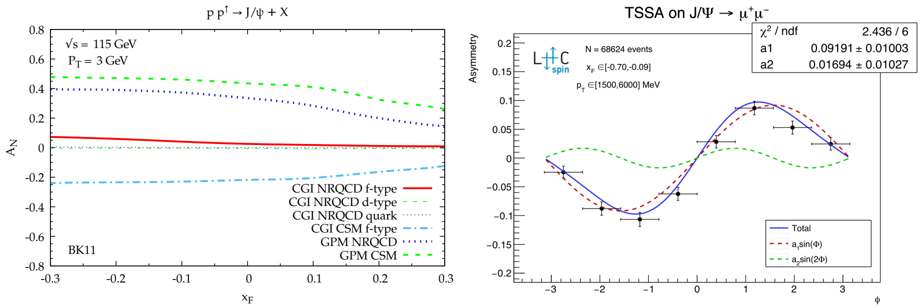

Fig. 7. Left: theoretical predictions for A_N in inclusive J/ψ production [12]. Right: simulated $J/\psi \to \mu^+\mu^-$ azimuthal asymmetries with a fit curve superimposed made of two Fourier terms.

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