LHCspin

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The goal of LHCspin is to develop, in the next few years innovative solutions and cutting-edge technologies to perform high-energy polarized frontier physics at the LHC by exploring a unique kinematic regime and by exploiting new reaction processes. This ambitious task is based on the recent installation of an unpolarized gas target in front of the LHCb spectrometer. Specifically, the unpolarized target, already in itself a groundbreaking project, will allow us to carefully study the dynamics of the beam-target system, and to clarify the potential of the entire system, as a basis for an innovative physics program at the LHC. With the instrumentation of the proposed target system, LHCb will become the first experiment delivering simultaneously unpolarized beam-beam at $\sqrt{s}$=14 TeV and polarized and unpolarized beam-target collisions at $\sqrt{s_{NN}}$~100 GeV. LHCspin could open new physics frontiers by combining the potential of the existent most powerful collider with one of the most advanced detectors.

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The physics potential of this project is extremely wide and diverse. However, in order to study the non-collinear properties of the nucleon structure, one can start from the transversely single-polarized Drell-Yan (DY) reactions ($pp \rightarrow l^+l^- X$) where two TMD mechanisms are expected to contribute to the Single Spin Asymmetries (SSA): the Sivers effect (on the transversity), from the polarized target proton, and the Boer-Mulders effect, from the unpolarized beam proton [1]. The analysis of the dilepton angular distribution allows one to separate out the two effects. LHCspin, with an expected instantaneous luminosity of $5 \cdot 10^{32}$ cm^{-2} s^{-1} and a wide and unique kinematic coverage, is well placed to measure SSA in DY processes, especially at large x_F. It has been emphasized [2] that studying the unpolarized and single-polarized DY processes in the limiting case $xp \ll x_\uparrow p$, where p indicates the longitudinal momentum of the nucleon and x ($x_\uparrow$) the fraction carried by the quarks in the unpolarized (polarized) proton, one can directly extract the ratio of transversity and the first moment of the Boer-Mulders TMD. This is exactly the easiest limit to look at with a fixed target on the LHC proton beam, contrary to other fixed-target projects where DY studies are planned where this limit cannot be reached easily. It is also interesting to check the small size of sea-quark Boer-Mulders function expected from the negligible azimuthal dependence observed recently for DY dimuons in *pd* collisions [3], contrary to π-induced DY.

The Sivers function is also one of the most interesting TMDs. It describes the correlation between the transverse momentum of the parton and the transverse spin of the nucleon and it requires a non-vanishing parton Orbital Angular Momentum. The experimental proof of breaking the universality of QCD through final state effects intrinsic to TMDs requires a direct comparison between the Sivers functions extracted through SSA measurements in DY with those measured in Semi Inclusive DIS (SIDIS) processes. Unfortunately, presently available results are not conclusive. LHCspin can investigate this issue by measuring transverse SSA in single-polarized DY [5] over a wide range of x providing a solid experimental basis to confirm or falsify a sign-change prediction with respect to SIDIS results.

Another mechanism, known as the Collins effect [6], was initially expected to be the main source of SSA in single π hadroproduction. Recently, a careful treatment of the non-collinear partonic interactions showed it to be eventually suppressed [7]. Since it allows quark transversity, $h_1(x)$, to be probed in single polarized

collisions, it remains important to investigate on processes for which Collins-type asymmetries may contribute.
Spin asymmetries with a final state polarization can be probed at LHCspin through hyperon (Λ, Σ, ...) production in single polarized pp collisions to access transversity [8]. The measurement of the spin-transfer asymmetry between the initial polarized proton and the hyperon at large p_T will allow one to check whether it derives from a leading twist (driven by transversity) or a higher-twist effect.
Contrary to the quark sector, where first benchmark results (e.g. the so called "Sivers effect") were obtained more than a decade ago, very little is known about the **gluon** contributions to the orbital motion inside the nucleon and, more in general, about their transverse momentum distributions. Only recently, COMPASS observed a non-zero asymmetry of the order of 20% (with a 2σ away significance), which hints at a non-zero value of the gluon angular momentum [9].
DY lepton-pair production is the golden process to access the intrinsic transverse motion of quarks in a nucleon. There is, however, no analogous process, which is at the same time experimentally clean and theoretically well controlled, to probe the gluon dynamics inside nucleons, one of the main and most ambitious goals of the LHCspin project. Naturally, **quarkonium production** can serve as an ideal tool to access gluon-sensitive observables, being gluon fusion the dominant contribution to these processes in high-energy hadron collisions. Specific heavy-quarks observables can provide sensitivity to the unknown gluons TMDs [10], allowing access, e.g., to the unmeasured gluon Sivers function, which provides precious information on the spin-orbit correlations of gluons inside nucleons and is sensitive to the unknown gluon orbital angular momentum. Measuring quarkonia production via their leptonic decays is an affordable task with the right experimental setup. In the last years, only RHIC provided polarized pp collisions at large enough energies that hints at a dominance of a color-singlet mechanism at low k_T and at a non-zero gluon Sivers effect. With LHCspin, such measurements could be extended to larger x_F as well as to other quarkonia states, including bottomonia. Another interesting SSA concerns the open charm sector (polarized $pp \rightarrow D\,X$), also proposed [11] as a direct access to gluon Sivers effect. This measurement could be carried out with very high efficiency by LHCspin, *e.g.* by tagging μ from D and B's and non-prompt J/ψ from B. Doing so, one would have a set of observables sensitive to the gluon Sivers effect. In practice, **one of the most efficient tools to access the gluon dynamics inside nucleons is the measurement of SSA in inclusive production of quarkonium states and open heavy-flavour mesons in polarized fixed-target hadron collisions. This constitutes a major strength of LHCspin that benefits of the LHCb detector, a highly performing forward spectrometer conceived and optimized for heavy-flavor physics**. Measurements of other quarkonium states have fundamental importance, for instance, extremely important are the **C-even quarkonia** ($\chi_{c,b}$, η_c) that give access to the tri-gluon correlation functions and the transverse momentum dependence of the gluon Sivers function relevant for hadron-induced reactions. They can be produced and reconstructed very efficiently in the proposed experimental environment of LHCspin. The hadroproduction of η_c has already been measured by LHCb [12], as well as non-prompt $\eta_c(2S)$ [11]. Here transverse SSA for χ_c , χ_b and η_c are at reach, as demonstrated by studies of various χ_c states [13] down to p_T as low as 2 GeV.
Finally, exclusive lepton-pair production may also be detected at LHCspin to investigate the 3D structure of hadrons in terms of generalized parton distributions (GPDs) through the timelike Compton Scattering (TCS) process. The interference term between TCS and the Bethe-Heitler (BH) process, where the lepton pair is emitted from photons originating from each colliding proton, can be disentangled in the cross section by analyzing the angular distribution of the produced leptons. The interference term contribution to the cross section is expressed through a linear combinations of GPDs [14].

The long list of potential discoveries and relevant measurements based on the use of the LHC proton beam will be further enriched by the unique possibility to merge the LHC heavy-ion program with the polarization physics, allowing, for the first time, to measure polarized Pb-p$^{\downarrow\uparrow}$ and Pb-d$^{\downarrow\uparrow}$ collisions at $\sqrt{s_{NN}} \sim 72$ GeV [15].

LHCspin aims to yield much greater insight into the nucleon structure primarily by extending our knowledge to the poorly constrained gluon sector and, more in general, by providing high-quality results at unique kinematic conditions that will facilitate the construction of multidimensional maps of the distributions of partons in space, momentum, spin, and flavor.

The LHCspin project consists in the development and implementation of the first polarized fixed-target system though as a complement of the existing and upgraded LHCb spectrometer at the LHC.
The collisions of the 7 TeV LHC proton beam on a fixed target correspond to a center-of-mass energy close to $\sqrt{s}$=115 GeV, half way between those of SPS and RHIC. The center-of-mass rapidity covers a wide

negative region -3<y<0, corresponding to the region of large Bjorken-x (x_{Bj}), i.e. to the poorly explored "valence region". In nuclear targets, due to the Fermi motion, x_{Bj} can be even >1, giving the possibility to access a totally unexplored bridge between QCD and nuclear physics, where the parton dynamics is influenced by the interaction between the nucleons within the nucleus.
The proposed fixed-target system is conceived in such a way to be safely operated simultaneously with the standard beam-beam data taking at the LHC collider experiments, including LHCb. Note that the LHC beams cannot be polarized. **This is therefore the only way to perform spin-physics measurements at the LHC**.
The study of fixed-target collisions with a polarized gaseous target [16,17] offers several unique advantages:

- very high polarization degrees (up to 85%);
- absence of dilution effects due to the presence of unpolarized materials in the target;
- possibility to invert very quickly the polarization direction (to reduce systematics);
- possibility to achieve relatively high luminosities with sufficiently dense targets;
- beams at the TeV scale in conjunction with a forward spectrometer allow **to access a unique and mainly unexplored kinematic regime**, characterized by the coverage of the large negative Feynman x_F and the large Bjorken-x regions at intermediate Q^2 with beam-gas collisions at $\sqrt{s_{NN}} \sim 100$ GeV;
- precise determination of the beam-gas luminosity;
- negligible effects on the beam lifetime;
- possibility to also inject unpolarized gases, such as: H_2, D_2, $^{3,4}He$, N, O_2, Ne, Ar, Kr, Xe, etc.;
- negligible impact on the LHCb collider physics program and performances.

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A pre-requisite of outmost importance for the success of LHCspin is the **SMOG2 project** [17]. It regards the recently installed unpolarized gas target system in the primary vacuum of LHC, upstream of the LHCb detector, that constitutes a fundamental playground for the R&D of LHCspin.

The LHCspin experimental set-up is based on the combination of know-how and technologies successfully developed and applied on previous generation accelerators. At the same time, it calls for a jump forward towards a new generation system able to run, without compromises, at the most advanced hadron collider and in conjunction with the most sophisticated particle detectors.

An instantaneous luminosity of $L_{pp} = 5 \cdot 10^{32}$ cm^{-2}s^{-1} can be reached keeping the pressure inside the vacuum chamber around ~10^{-7} mbar, i.e. two orders of magnitude below the LHC tolerable limit.

The statistical precision reachable is very high, also for channels never measured before, indicating the realistic possibility to provide a strong boost to the research field in a relatively short time.

In the last 10–15 years the first measurements of azimuthal asymmetries in Semi Inclusive Deep Inelastic, together with the advances from the theory side (establishment of the theory framework and formalism, development of models, phenomenological fits and lattice QCD calculations), have both revealed the fundamental role of the nucleon non-collinear degrees of freedom in establishing its 3-D dynamical structure. Important data in different kinematic domains have been published and others are expected soon in the hadron physics community from the Drell-Yan processes at COMPASS2 and RHIC, and from JLab-12 GeV. Great expectations are linked to the future EIC in US, which has been recently approved for its early phase. In this context, the potential offered by the use of the LHC beams – proton and heavy-ion – to perform, in relatively short time, polarized fixed target measurements at an extremely reduced cost. **This is particularly relevant if a comparison in terms of costs and timing (including possible delays) is done with the new big sciences initiatives foreseen in the current, particular, global economic scenario**. Moreover, **LHCspin findings can, not only anticipate part of the upcoming American EIC program on the polarized physics, but perform complementary analyses.**

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