

How to determine nucleon polarization at existing collider experiments?

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We propose a novel approach to measure the spin polarization of protons produced in electron-positron collisions. Using existing tracking devices and supporting structure material, general-purpose spectrometers can be utilized as a large-acceptance polarimeter without a hardware upgrade. With the proposed approach, the spin polarization of protons can be revealed, providing a complementary and accurate description of the final-state particles. This could have far-reaching implications, such as enabling the complete determination of the nucleon timelike electromagnetic form factors.

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Spin is a fundamental property of atoms and subatomic particles. It affects their interactions and is essential for explaining the structure of nuclei and atoms, and the properties of materials. The study of spin has led to many important discoveries and continues to be a very important area of research—e.g., precision determination of muon anomalous magnetic moment as a test of the Standard Model of elementary particles [1,2].

In nuclear and particle physics, many experiments are performed using spin-polarized beams and targets, where the polarization can be controlled [3] and determined using dedicated devices [4–9]. This ensures a complete and accurate description of the initial state of the reactions. To measure the polarization of the final-state particles, a variety of dedicated detectors are built that act as secondary polarimeters. In the case of decaying particles, the polarization can be determined from distributions of the daughter particles. In particular, complete determination of the polarization is possible when parity-violating weak decays are involved. Due to this property, the polarization of hyperons is investigated in various reactions, such as at electron-positron [10,11], proton-proton or proton-nucleus [12,13], and heavy

ion collisions [14,15]. For the final states involving protons, the spin information is normally not measured, since it would require an external polarimeter based on secondary interactions. Many such devices have restricted angular acceptance or cannot be accommodated by modern detectors. This has made the information on the final state incomplete, limiting the experimental studies in the field.

In this paper, we propose a novel approach that uses information collected by the standard detectors to measure the spin polarization of the protons. Using the tracking detector and certain supporting material, most general-purpose spectrometers have a potential to serve as large-acceptance polarimeters without hardware modification. Here, we evaluate the feasibility of such polarization measurements, using as an example the currently operating electron-positron collider experiment BESIII [16]. A similar method can be easily adopted in various experiments at electron-positron colliders, and in pp/pA and lepton-proton scattering machines with low track multiplicity and outgoing protons with laboratory momenta up to a few GeV. For planned or to-be-upgraded detectors, we propose minor hardware modifications to increase efficiency of the polarization measurement without a significant impact on the detector performance.

The BESIII detector records symmetric e^+e^- collisions provided by the BEPCII storage ring operating in the center-of-mass (c.m.) energy range $\sqrt{s} = 1.8\text{--}5.0$ GeV. BESIII has collected $10^{10} J/\psi$ events [17], including processes such as $J/\psi \rightarrow p\bar{p}$ and $J/\psi \rightarrow \Lambda\bar{\Lambda}$ with branching fractions $2.12(3) \times 10^{-3}$ and $1.88(8) \times 10^{-3}$, respectively [18]. The BESIII detector is described in detail in Ref. [16]. The cylindrical core of the BESIII detector

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covers a polar angle range of 35° – 145° and consists of a helium-based multilayer drift chamber (MDC), a plastic scintillator time-of-flight system (TOF), and a CsI(Tl) electromagnetic calorimeter (EMC), which are all enclosed in a superconducting solenoidal magnet providing a 1.0 T magnetic field. The charged-particle momentum resolution at 1 GeV/c is 0.5%.

A measurement of a proton polarization usually utilizes the spin-dependent cross section for the proton-proton (pp) or proton-carbon (pC) elastic scattering given their large analyzing powers. In the case of an unpolarized target, the differential cross section for a given c.m. polar angle θ is expressed as [19,20]

$$\frac{d\sigma}{d\phi d\cos\theta} = \frac{1}{2\pi} \frac{d\sigma_0}{d\cos\theta} [1 + P_y A_N(\theta) \cos\phi]. \quad (1)$$

Here, σ_0 indicates the unpolarized cross section, ϕ is the azimuthal angle, and P_y is the transverse polarization of the proton to be determined. $A_N(\theta)$ is the scattering-angle-dependent analyzing power. In the following, we use effective A_N , defined as

$$A_N^2 = \frac{1}{D} \int_{-1}^1 d\cos\theta \frac{d\sigma}{d\cos\theta} \int_0^{2\pi} d\phi A_N^2(\theta) \varepsilon(\theta, \phi), \quad (2)$$

with $\varepsilon(\theta, \phi)$ being the reconstruction efficiency for the secondary scattering events, and the denominator D being

$$D = \int_{-1}^1 d\cos\theta \frac{d\sigma}{d\cos\theta} \int_0^{2\pi} d\phi \varepsilon(\theta, \phi).$$

The quantity $A_N^2 \cdot D$ represents the figure of merit for such studies, since the statistical uncertainty of the polarization determination is given as $\sigma(P_y) = \sqrt{2}/(A_N \sqrt{N})$.

In collider experiments, such as BESIII, the produced protons usually have momenta ranging from a few hundred MeV/c to a few GeV/c. The analyzing powers for the reactions pp and pC have been determined with high precision in this energy region [21–31], and the values are large—up to 60% [27].

Hydrogen and carbon can be found in many construction elements in the detectors. For example, in the BESIII detector, a layer of cooling fluid of high-purity mineral oil with the thickness of 0.8 mm circulates between the inner and outer beryllium shells of the beam pipe. The inner radius of the oil layer is 32.3 mm [16,32]. The mineral oil is mainly composed of carbon and hydrogen, which are the perfect target material. The tracking detector has an inner tube wall made of carbon fiber with a thickness of 1.2 mm, which is also a good target candidate. These supporting components of the detector were originally undesired and were optimized to be as thin as possible to improve detector performance. Here, we utilize these supporting layers to

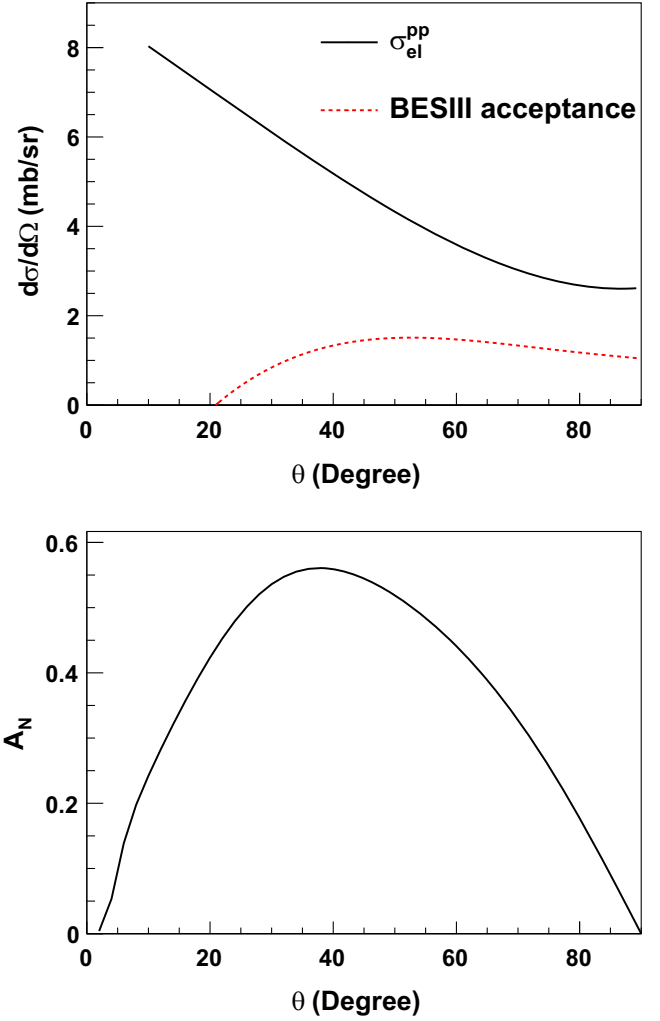


FIG. 1. Top: the pp elastic differential cross section at a proton momentum of 1.23 GeV/c with a fast simulation including the BESIII detector acceptance. Bottom: the analyzing power of this process [34].

prove the feasibility of measuring the polarization of final-state protons at the high-luminosity colliders.

We take as an example (anti)protons from the $e^+e^- \rightarrow J/\psi \rightarrow p\bar{p}$ process, where a significant transverse proton spin polarization is possible, such as that observed in the J/ψ decays into hyperon-antihyperon pairs [10,33]. In this process, the (anti)proton momenta are 1.23 GeV/c, implying that the c.m. energy of the elastic pp scattering with the detector material is 2.16 GeV. The differential cross section of elastic scattering [34] is given by the black solid curve in the upper plot of Fig. 1, while the cross section after taking into account BESIII acceptance is given by the red dashed curve. The angular dependence of the analyzing power at this energy is shown in the bottom plot of Fig. 1. The average analyzing power is 0.4.

An elastic scattering event pp is illustrated in Fig. 2. In the right plot, the original proton and the final-state

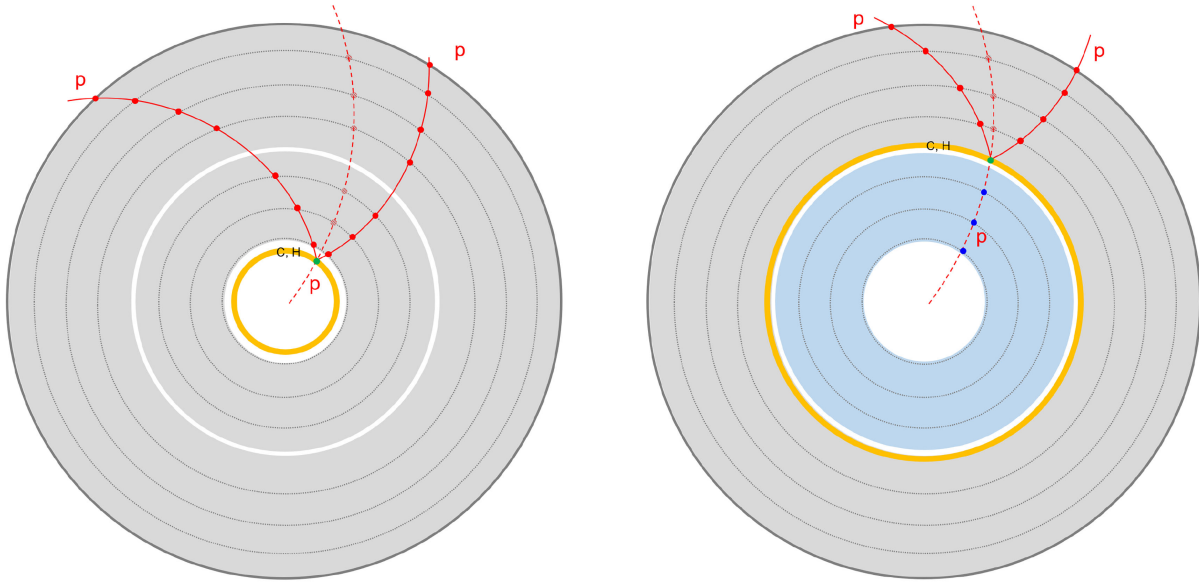


FIG. 2. Illustration of a pp elastic scattering event at the BESIII detector. Left: in a case where the scattering layer is downstream of the tracking detector, a full event could be reconstructed to deduce the original proton (dashed line). Right: in a case where the scattering layer is between the tracking detector layers, both the initial proton and two final-state protons are measured. Noncylindrical detectors are also applicable.

protons (recoil and scattered proton) are all detected. Complete information of $pp \rightarrow pp$ is available, from which polarization can be extracted. The plot on the left shows a setup with the secondary scattering layer upstream of the tracking detector. The two final-state protons are detected, while the original proton is not. This is the case with the BESIII experiment, where the scattering layers are the beam pipe or the inner MDC wall. Here, the complete reconstruction of an event can be performed due to the low multiplicity of the final states. In particular, the projectile proton momentum can be deduced from the kinematical constraints.

The method utilizes a tiny layer of hydrogen- or carbon-rich material in the existing detector, so the probability of pp scattering is small. However, it could be compensated at high-luminosity machines, such as the BESIII and the future STCF [35]. Taking BESIII as an example, several millions of (anti)protons from J/ψ have been collected. Secondary interactions in the beam pipe were utilized in many BESIII analyses to study hyperon-nucleon scattering [36,37]. The probability of the proton elastically scattering off a proton in the oil layer of 0.8 mm is roughly 1.2×10^{-4} , assuming a 20 mb pp elastic scattering cross section in acceptance of the BESIII [18]. Using GEANT4 simulation with a realistic detector geometry, we expect to have on the order of $N = 10^3$ pp elastic scattering events to measure spin polarization. The tracks of the scattered protons, the projectile, and the interaction vertex are reconstructed to provide the scattering angle θ as well as the azimuthal angle ϕ to determine the analyzing power $A_N(\theta)$ from the database [34] and to measure the asymmetry $A := P_y A_N(\theta)$. Figure 3

shows the reconstructed ϕ MC distribution for an input transverse polarization of 0.59 and a pp analyzing power of $A_N = 0.4$. The extracted asymmetry is consistent with the input value.

The statistical uncertainty of the product $A = P_y A_N$ determination is

$$\sigma(A) \approx \sqrt{\frac{2}{N}}.$$

Therefore, for 10^3 pp elastic secondary scattering events, as expected from the $J/\psi \rightarrow p\bar{p}$ process at BESIII, $\sigma(A) = 0.04$. The transverse polarization $P_y = A/A_N$, so the uncertainty $\sigma(P_y) = \sigma(A)/A_N = 0.1$, if we ignore the uncertainty on A_N and take the average A_N of 0.4 at a proton momentum of 1.23 GeV/c.

Therefore, we have found promising results while considering only the pp elastic scattering signal. The pC scattering events have the potential to further improve the precision of the polarization measurement. In the pC case, the identification of the carbon using energy deposition or time of flight is nontrivial and has to be investigated; alternatively, if the original proton is measured, the carbon could be left undetected. This method can be used to measure antiprotons, neutrons, and antineutrons, as long as the analyzing powers of the corresponding processes are determined [38].

For the existing detectors, a single element target dedicated as a polarimeter is hard to find. At BESIII, the target is mineral oil, a mixture of hydrogen and carbon. The selected $pp \rightarrow pp$ signal might be from a collision with a quasifree

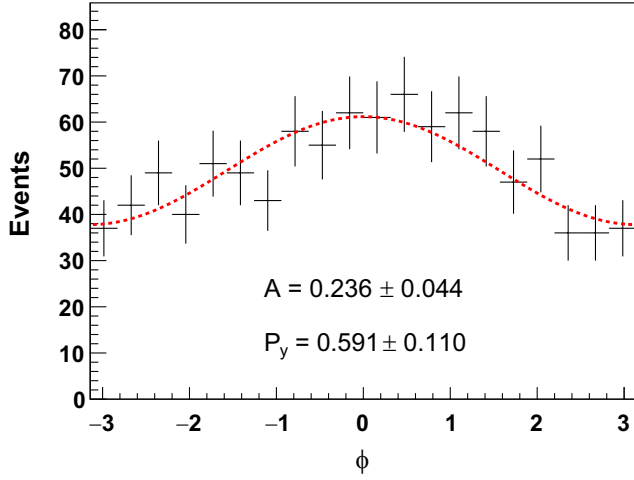


FIG. 3. Single-spin asymmetry (A) and transverse polarization extracted from the ϕ distribution. In the MC, an input transverse polarization of 0.59 and a single-spin asymmetry of 0.236 is assumed.

proton in a carbon nucleus. In order to suppress this background, both final-state protons shall be reconstructed. Combined with the original proton, a four-momentum constraint can be applied to suppress the quasifree collisions. An MC study indicates that the background level can be reduced to below 3%. In the case of a pure hydrogen target, the signal reconstruction will be simpler. For example, the detection of only one final-state proton would improve the overall efficiency. The detection efficiency can also be improved if the thickness of the scattering layer is increased. An optimization was performed to study the influence of the increased material budget on the resolution. In a case where the thickness is increased by an order of magnitude (from 0.2% to 2% X_0) [16], the detector efficiency and the momentum resolutions of the final-state proton decrease by less than 1%. This exercise indicates a minor impact on the normal detector performance, whereas the efficiency of the polarization measurement is increased by 1 order of magnitude.

To validate the polarization measurements, protons with known polarizations are needed. For this purpose, protons from hyperon decays can be used. For example, the proton polarization from unpolarized Λ decay into $p\pi^-$ is $\alpha_\Lambda = 0.75$ [18,39] and is directed along the proton momentum in the Λ rest frame. In the $J/\psi \rightarrow \Lambda\bar{\Lambda}$ reaction at BESIII, the protons acquire transverse polarization with respect to the direction of the proton in the detector reference frame.

The protons emitted from the decay of Λ with 1 GeV/ c lab momentum have transverse polarization distribution shown in Fig. 4 with an average value of 0.59. In the upper plot, θ^* is the angle between the proton momentum in the Λ rest frame and the Λ momentum in the laboratory frame. This is a well-known way to produce polarized (anti)proton beams that was used at Fermilab in the 1990s [40]. The

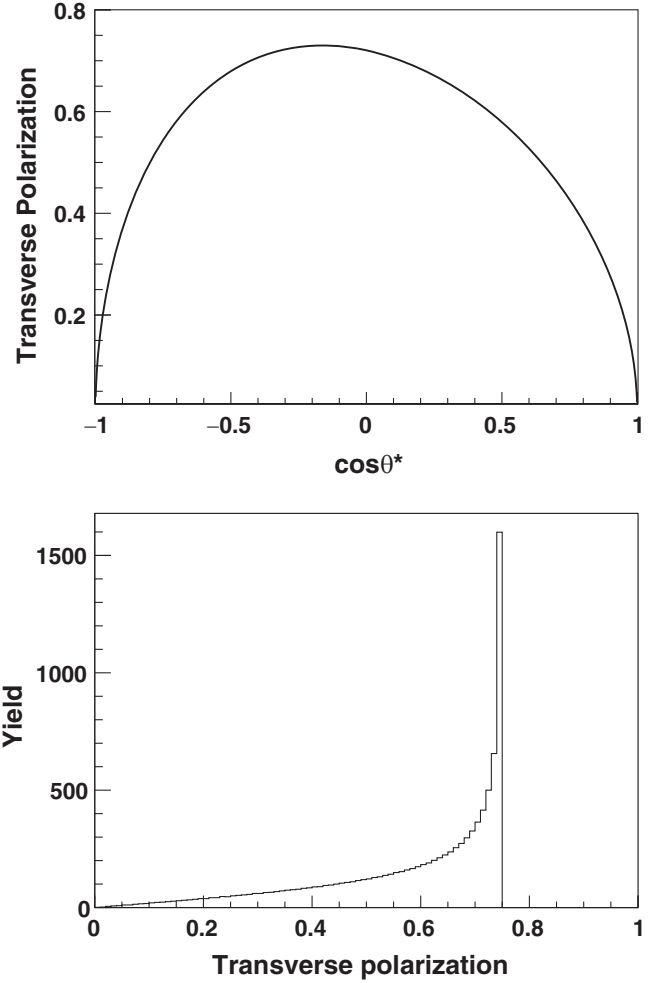


FIG. 4. Top: transverse polarization of the proton from unpolarized Λ decay as a function of $\cos \theta^*$ of proton momentum in the Λ rest frame. Bottom: distribution of transverse polarization of the proton from unpolarized Λ decay.

polarization is nearly independent of the Λ momentum, ensuring high and controlled proton polarization. Most existing or future facilities can use this method to prepare polarized protons, as long as there is enough energy to produce hyperons. Figure 5 shows the transverse polarization axis of the proton from the decay of Λ . This source of polarized (anti)nucleons could be also used to determine the analyzing powers for processes where they are not precisely known, such as $\bar{p}p$, np , or $\bar{n}p$.

This method can be adopted for various reactions. For an experiment with low multiplicity similar to the BESIII, which is normally the case in $e^+e^-/ep/pp$ collisions, it is not required that the projectile proton be detected. For experiments with high multiplicity, such as in heavy ion collisions [41], the projectile proton should be detected to extract the full information on the pp scattering. This indicates that the polarimeter target should be placed in between the tracking detector layers, allowing the detection of both the projectile and the two outgoing protons.

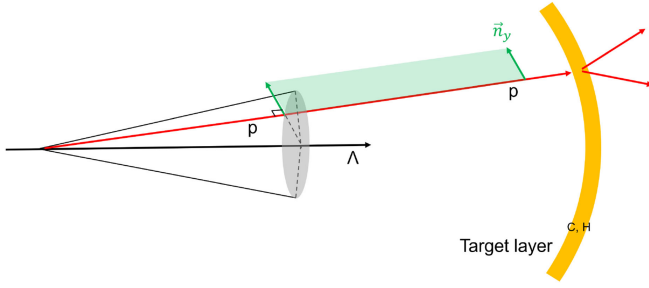


FIG. 5. Transverse polarization axis of the proton from Λ decay. Red lines with arrows indicate the momentum of the daughter proton. The daughter pion is not shown. Green lines with arrows indicate the transverse polarization axis of the proton.

Many applications of the proton polarimeter can be foreseen in nuclear and particle experiments. The polarization of the final-state proton (or antiproton) in $e^+e^- \rightarrow p\bar{p}$ is directly related to the relative phase between the electric and magnetic form factors of the proton. Therefore, using our method, the timelike form factors could be completely determined for the first time. This approach is also applicable to neutron form factors, but the detection of neutrons is more challenging.

Future electron ion colliders (EIC and EicC) [42,43] aim to perform multidimensional imaging of the internal structure of the proton. With the proton polarization determined, more spin-related observables can be extracted to benefit both the experimental and theoretical frameworks.

In the pp/pA collision, many measurements of hyperon polarization have been performed to study the production mechanism. When the polarization of the proton is determined, it is possible to analyze how it arises from various sources. In heavy ion collisions, the global polarization could be studied in a similar way as for Λ to bring new

insights into properties of the extreme media created in such conditions [14,15].

In this paper, we propose a novel approach to measure the final-state proton polarization in large-acceptance collider experiments. This approach can be used to measure the polarization of the antiproton. For the neutron or antineutron polarization, the difficulty lies in the detection of the scattered neutron or antineutron, which may require a high-performance calorimeter. This approach is tested at BESIII, and it can be applied at nearly all major facilities, such as Belle-II [44], CMS [45], ATLAS [46], LHCb [47], CBM [48], EIC [42], etc., enabling a general-purpose spectrometer to extract final-state proton polarization in addition to the traditional four-momentum measurements. This capability would vastly expand the physics reach of these experiments, and it has potential for substantial impact across nuclear and particle physics.

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Data availability. The data are not publicly available. The data are available from the authors upon reasonable request.

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