Polarization puts a New Spin on Physics

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Abstract. Polarization and spin effects are useful for probing the Standard Model, in both the electroweak sector and the strong sector, where the spin decomposition of the nucleon is still a hot topic, with important new data on the net polarizations of the gluon and the strange quarks. Spin phenomena are also useful in searches for new physics, for example via measurements of the anomalous magnetic moment of the muon and searches for electric dipole moments. The cross sections for the direct detection of dark matter may also have an important spin-dependent component, related to the spin decomposition of the nucleon, that could be an important diagnostic tool. Polarization effects are also important diagnostic aids for high-energy experiments at electron-proton, proton-proton and electron-positron colliders.

Keywords: Precision electroweak tests, proton spin, dipole moments, high-energy colliders


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INTRODUCTION

Elementary particles have both external properties, namely the quantum numbers that determine their couplings, and internal degrees of freedom associated with spin. These are often linked: for example, the two helicity states of a fermion may have different electroweak interactions. Polarization experiments and spin observables may therefore provide key insights into the properties of particles and their interactions. There are many examples illustrating how such spin effects are helping to elucidate the Standard Model, and there are justified hopes that they may help identify new physics beyond the Standard Model. Indeed, the anomalous magnetic moment of the muon may already be providing the first hints for new physics.

In this talk, I preview some of the hot topics for discussion at this conference, including polarization phenomena in the electroweak interactions, the continuing puzzle of the nucleon spin, searches for new physics via spin effects in low-energy experiments, and the prospects for polarization experiments in high-energy collider experiments. Spin and polarization effects are integral parts of the experimental toolkit for disentangling new physics.
FIGURE 1. As seen in the left panel, measurements of $\sin^2 \theta_W$ using leptonic asymmetries prefer a low value of $m_H$, whereas hadronic measurements prefer a higher value \cite{2}. The right panel shows present and prospective probes of the energy dependence of $\sin^2 \theta_W$, including Moeller scattering, parity violation in atomic physics, and asymmetry measurements at high energy \cite{1}.

PROBING THE STANDARD MODEL

Electroweak Physics

Many of the most sensitive tests of the electroweak sector of the Standard Model are being made with polarized beams, or using final-state spin effects \cite{1}. For example, one of the most accurate individual measurements at the $Z$ pole has been the $A_{LR}$ asymmetry measured at SLAC using polarized beams, and one of the most precise LEP determinations of $\sin^2 \theta_W$ was made using final-state $\tau$ polarization.

The name of the electroweak game now is to use the precision measurements to estimate the mass of the Higgs boson. As seen in Fig. 1 the leptonic asymmetries tend to prefer a relatively low value of the Higgs mass, but the agreement between these and the hadronic determinations of $\sin^2 \theta_W$ is not perfect, and the latter prefer a heavier Higgs mass \cite{2}. The conventional attitude towards this discrepancy is to regard it as a statistical fluctuation, and to ignore it in performing a global fit to the precision electroweak data, which leads to a relatively low Higgs mass: $m_H = 85^{+39}_{-28}$ GeV \cite{3}. However, it is also possible that the discrepancy is real, and betokens new physics, in which case this Standard Model estimate would be invalid \cite{2}. A direct resolution of this issue is unlikely in the near future, since a high-precision return to the $Z$ peak is not foreseen unless and until the Giga-$Z$ option (with polarized electrons and positrons) is exercised at the ILC \cite{4}. Perhaps the issue will be resolved by the detection of the Higgs boson at the LHC, and the comparison of its mass with the prediction of the global electroweak fit and/or subsets of the electroweak data?

For the time being, the action in precision electroweak tests is in measurements at both low and high energies, aiming to check the specific energy dependence predicted by radiative corrections in the Standard Model \cite{1}. As also seen in Fig. 1 there are puzzles below the $Z$ pole, such as the anomalous value of $\sin^2 \theta_W$ extracted from deep-inelastic $\nu$-N scattering \cite{5}. This might also indicate some problem with the Standard
Model, although the interpretation of this experiment is vulnerable to hadronic uncertainties. However, this discrepancy certainly increases the interest in other low-energy experiments with different systematic uncertainties.

One particularly clean measurement is that of parity violation in Moeller scattering [6], which is theoretically very clean. The new SLAC measurement agrees with the Standard Model to within about one standard deviation, and a new measurement with greater accuracy would be particularly interesting. Also interesting are measurements of atomic parity violation, which are currently also within about one standard deviation of the Standard Model prediction, and show potential for improved accuracy in the future. Above the $Z$ pole, we can also expect future measurements to improve on the current determination of $\sin^2 \theta_W$ using the forward-backward asymmetry at $Q > 1000$ GeV.

The few examples given above illustrate the importance of spin and polarization experiments in the analysis of electroweak physics.

### The Nucleon Spin Puzzle

There are several approaches to this problem, in particular via measurements of scaling violations, via jet and charm production asymmetries in polarized deep-inelastic scattering, and via asymmetries in polarized proton-proton scattering. The COMPASS collaboration has recently presented new data on the deuteron polarized structure function $g_1^d(x)$ [7]. These provide significant improvements at small $x$, in particular, and have interesting sensitivity to the net polarizations of the strange quarks, $\Delta s$, and the gluons, $\Delta G$. The HERMES collaboration has also presented new data on $g_1^n(x)$ and $g_1^d(x)$ [8], which provide significant improvements at large $x$. These two data sets tell strikingly similar stories about the singlet axial-current matrix element $a_0$, which is related to the total net quark contribution $\Delta \Sigma$ to the nucleon spin:

$$a_0(Q^2 = 3\text{GeV}^2) = 0.35 \pm 0.03 \text{(stat.)} \pm 0.05 \text{(syst.)}[\text{COMPASS}],$$

$$a_0(Q^2 = 5\text{GeV}^2) = 0.330 \pm 0.011\text{(th.)} \pm 0.025\text{(exp.)} \pm 0.028\text{(ev.)}[\text{HERMES}].$$

The value of $a_0$ has remained quite stable and consistent over the past decade, ever since SLAC and CERN data on deep-inelastic electron and muon scattering on proton and deuteron targets were first compared including perturbative $\mathcal{O}(\alpha_3^3)$ contributions to the integrals over $g_1^n(x)$ and $g_1^d(x)$ [9], as seen in Fig. 2.

Correspondingly, the two experiments also tell very similar stories for the net contribution to the nucleon spin of the strange quarks and antiquarks:

$$\Delta s = -0.08 \pm -0.01\text{(stat.)} \pm 0.02\text{(syst.)}[\text{COMPASS}],$$

$$\Delta s = -0.085 \pm 0.013\text{(th.)} \pm 0.008\text{(exp.)} \pm 0.009\text{(ev.)}[\text{HERMES}].$$

According to these experiments, $\Delta s$ is significantly negative. The measurements of scaling violations in structure functions also indicate that $\Delta G$ is probably not large, as seen in Fig. 3 and may favour small positive values [11].
FIGURE 2. As seen in the left panel, measurements of the total quark contribution to the nucleon are remarkably consistent and stable, once higher-order perturbative corrections are taken into account [9]. The right panel shows current measurements of $\Delta G$ by the SMC, HERMES and COMPASS Collaborations. The latter, in particular, indicate that $\Delta G$ is unlikely to be very large [10].

FIGURE 3. Left panel: Contributions to the $\chi^2$ function for $\Delta G$ due to positivity, deep-inelastic inclusive data (blue dashed line), earlier RHIC data (red dash-dotted line) and total (black solid line) [11]. Right panel: Indications on $\Delta G$ from more recent PHENIX data from RHIC [12].

More direct information on the possible magnitude of $\Delta G$ has been emerging from a series of measurements by the SMC, HERMES, COMPASS and RHIC Collaborations. As seen in Fig. 2 the early SMC and COMPASS measurements of jet asymmetries and open charm production had quite large errors, and indicated only that $\Delta G$ was unlikely to be very large and positive: $\Delta G \ll G$ [10]. The most accurate information on $\Delta G$ is now that provided by the new COMPASS measurement of the jet asymmetry at low $Q^2$, based on data taken between 2002 and 2004. It indicates that $\Delta G(x)$ must be close to zero in a range of $x \sim 0.085$ for $\mu^2 \sim 3$ GeV$^2$ [13]. A recent update of the earlier HERMES measurement also indicates a small value of $\Delta G(x)$ in a range of $x \sim 0.22$ for
\[ \mu^2 \sim 1.35 \text{ GeV}^2 \] \[ \Delta G = 0.016 \pm 0.058 \text{ (stat.)} \pm 0.055 \text{ (syst.)} \text{[COMPASS]}, \] \[ \Delta G = 0.071 \pm 0.034 \text{ (stat.)}^{+0.105}_{-0.127} \text{ (syst.)} \text{[HERMES]}. \]

In view of the results in Fig. 2 and the positivity constraints shown in Fig. 3, it seems inescapable that \( \Delta G \) cannot be large enough for gluon renormalization effects \[ \text{[15]} \] to be able to make any significant contribution to \( a_0 \) \[ \text{[10]} \], even forgetting about the renormalization-scheme ambiguity \[ \text{[16]} \]. COMPASS obtained significantly more data in 2006, in particular on open charm production, and one may hope that these will cast more light on the size of \( \Delta G \). The next step will be to establish whether \( \Delta G \) makes any significant contribution to the nucleon spin, or whether its contribution is negligible, i.e., whether \( \Delta G \) is closer to 1/2 or to zero.

In this respect, the main future competition for COMPASS will come from the RHIC experiments \[ \text{[17, 12]} \]. Currently, these also indicate that \( \Delta G \ll G \), but do not yet provide qualitative additional information, in particular because their measurements of \( A_{LL} \) depend quadratically on \( \Delta G \). However, the RHIC data taken in 2006 should provide significant extra information.

My list of the main issues for the future includes the following.

• Obtain direct information on the magnitude and sign of \( \Delta s \), e.g., from asymmetries in strange particle production. The pioneering data from HERMES \[ \text{[18]} \] are not at large enough \( Q^2 \) and \( W^2 \) to be sure that asymptotic factorizing models for fragmentation can be applied easily \[ \text{[19]} \].

• Determine whether \( \Delta G \) provides a large fraction of the nucleon spin, e.g., via production asymmetries in deep-inelastic scattering or at RHIC.

• Determine the magnitude of the orbital angular momentum component, e.g., by measurements of deeply-virtual Compton scattering.

• Forge better theoretical connections with other spin-dependent observables, such as particle production in low-energy proton-antiproton annihilation and \( \Lambda \) production in deep-inelastic scattering. Data on the polarization of \( \Lambda \) baryons produced in deep-inelastic scattering are suggestive, but subject to significant theoretical uncertainties.

LOOKING FOR NEW PHYSICS BEYOND THE STANDARD MODEL

The standard list of questions in particle physics beyond the Standard Model includes the following.

• What is the origin of particle masses? Are they due to a Higgs boson, and is this accompanied by other new physics such as supersymmetry? These questions are likely to be answered at energies below \( \sim 1 \text{ TeV} \).

• Why are there so many different types of matter particles? How is this issue related to the small CP-violating matter-antimatter difference that has been seen in the laboratory, and can the answer to this question be related to the cosmological dominance of matter over antimatter?
• Are the fundamental forces unified? If so, unification may occur only at some very high energy $\sim 10^{16}$ GeV. Direct probes of unification include neutrino physics and the search for baryon decay, but indirect probes are also possible at colliders via measurements of particle masses and couplings.

• How can one formulate a quantum theory of gravity? Is it based on (super)string theory, in which case are there large extra space-time dimensions?

As discussed below, spin and polarization phenomena may play important roles in many of the searches for new physics. For example, spin correlations may be crucial for distinguishing between supersymmetry and some scenarios with large extra dimensions. The anomalous magnetic dipole moment of the muon may already be providing us with a hint of new physics, that could be compatible with supersymmetry. Electric dipole moments are key probes of CP violation. Spin-dependent interactions may also be provide valuable tools in the search for astrophysical dark matter.

An example of possible new physics

Supersymmetry is the last undiscovered particle symmetry. The first reason why it appeared interesting was because it could link particles with spins differing by half a unit, namely fermions and bosons, and hence unify matter and force particles. With sufficiently many supersymmetries, one could relate particles of all different spins, including Higgs-like particles with spin 0, matter particles with spin 1/2, gauge particles with spin 1, the gravitino with spin 3/2, and the graviton with spin 2. This very elegant motivation gave, however, no indication of the possible mass scale of the supersymmetric partners of the particles of the Standard Model. The first indication that their masses might be around a TeV was provided by the observation that in this case they could help fix the electroweak masses, by controlling the loop corrections that would otherwise destroy the hierarchy of fundamental mass scales [20]. Later motivations that supersymmetry might appear at the TeV scale were provided by its potential help in achieving grand unification [21], and the possibility that the lightest supersymmetric particle (LSP) might provide the astrophysical dark matter [22]. Since supersymmetry involves spin in an essential way, it should come as no surprise that many promising ways to probe the theory involve observables based on spin and/or polarization.

The muon anomalous magnetic moment

The anomalous magnetic moment of the muon, $a_\mu = (g_\mu - 2)/2$ may already be providing the first accelerator evidence for new physics. The measurement by the BNL g-2 Collaboration [23] disagrees significantly with the Standard Model if $e^+e^-$ annihilation data are used to calculate the Standard Model contribution, although there is no significant discrepancy if this is calculated using $\tau$-decay data [24]. The jury has yet to deliver its verdict, but the weight of evidence is accumulating on the side of the $e^+e^-$ data and hence in favour of a hint for new physics. There are several new sets of low-energy $e^+e^-$ data, which have a good level of consistency. In contrast, new $\tau$-decay data from...
the BELLE Collaboration seem significantly different from the previous ALEPH and
CLEO data, and agree better with the $e^+e^-$ data. If the $e^+e^-$ estimate of the hadronic
contribution to the Standard Model calculation is accepted, the theoretical error is just a
few per cent, and is comparable to the experimental error [25]:

\[
a_\mu^{(\text{theory})} = (11659180.5 \pm 5.6) \times 10^{-10},
\]

(7)

\[
a_\mu^{(\text{experiment})} = (11659208.0 \pm 6.3) \times 10^{-10},
\]

(8)

\[
\Delta a_\mu = (27.5 \pm 8.4) \times 10^{-10},
\]

(9)
yielding a discrepancy at the 3.3-$\sigma$ level, that could be due to supersymmetry [26], for
example.

### Electric dipole moments

Aspects of supersymmetry can also be probed by searches for electric dipole
moments, whose existence would be direct evidence for CP and T violation. They are ex-
pected to be unobservably small in the Standard Model, which makes them ideal for
searches for new physics. In particular, they are sensitive to the many CP-violating
phases in supersymmetric models, some of which could be responsible for the domi-
nance of matter over antimatter in the Universe. Interesting upper limits on these CP-
violating phases are already provided by the present upper limits on electric dipole
moments:

\[
|d_{Tl}| < 9 \times 10^{-25} \text{ em},
\]

(10)

\[
|d_{Hg}| < 2 \times 10^{-28} \text{ em},
\]

(11)

\[
|d_n| < 6 \times 10^{-26} \text{ em},
\]

(12)

and even more interesting would be the prospective sensitivities:

\[
|d_e| < 3 \times 10^{-29} \text{ em},
\]

(13)

\[
|d_D| < 2 \times 10^{-27} \text{ em},
\]

(14)

\[
|d_n| < 1 \times 10^{-27} \text{ em},
\]

(15)

obtainable in upcoming experiments.

The relevant CP-violating parameters in an effective low-energy Lagrangian include
the CP-violating strong-interaction phase $\theta$:

\[
\mathcal{L}_{\text{eff}} \cong \frac{g_s^2}{32\pi^2} \theta G_{\mu\nu}^a \tilde{G}^{\mu\nu,a},
\]

(16)

conventional and colour electric dipole moments of elementary fermions:

\[
\mathcal{L}_{\text{eff}} \cong -\frac{1}{2} \sum_{i=e,u,d,s} d_i \bar{\psi}_i(F\sigma) \gamma_5 \psi_i - \frac{1}{2} \sum_{i=u,d,s} \bar{d}_i \bar{\psi}_i(F\sigma) \gamma_5 \psi_i,
\]

(17)
a three-gluon operator:

$$L_{\text{eff}} \ni \frac{1}{3} f^{abc} w G_{\mu \nu}^a \tilde{G}^{\nu \beta \beta} G_{\beta}^{\mu \nu} ,$$

and four-fermion operators:

$$L_{\text{eff}} \ni \Sigma_{i,j} C_{i j} (\bar{\psi}_i \psi_i) (\bar{\psi}_j i \gamma_5 \psi_j) + \ldots$$

Each of the CP-violating parameters $\theta, d_i, \tilde{d}_i, w, C_{ij}$ may receive contributions from the underlying CP-violating parameters of some extension of the Standard Model, such as supersymmetry. For example, the electron electric dipole moment $d_e$ is given at the one-loop level by [27]:

$$d_e = \frac{e m_e}{16 \pi^2 M_{\text{SUSY}}^2} \left[ \left( \frac{5 g_2^2}{24} + \frac{g_1^2}{24} \right) \tan \beta \sin \theta \mu + \frac{g_1^2}{12} \sin \theta_A \right] ,$$

where $\theta \mu \equiv \text{Arg}(\mu M_2 m_1^2)$ and $\theta_A \equiv \text{Arg}(M_1^2 A_e)$ are two CP-violating relative phases between supersymmetric model parameters.

In the case of Thallium, the contributions from the electric dipole moment of the electron and from four-fermion interactions are [27]

$$d_{Tl} \ni -585 d_e - 0.43 \text{GeV} \cdot C_S ,$$

where $C_S$ contains a contribution from possible four-fermion interactions connecting the electron to $d$ and heavier quarks: $C_S \ni C_{de} (29 \text{MeV} / m_d) + \ldots$. In the case of the neutron, the contributions of the electric dipole moments of the quarks are

$$d_n \ni (1.4 \pm 0.6) (d_d - 0.25 d_u) + (1.1 \pm 0.5) (\tilde{d}_d + 0.5 \tilde{d}_u) e.$$
Searching for supersymmetric dark matter

As already mentioned, in many supersymmetric models, the LSP $\chi$ is stable, and a suitable candidate for astrophysical dark matter [22]. Several strategies to search for LSP dark matter have been proposed, including looking for the products of $\chi\chi$ annihilations in the galactic halo, such as antiprotons and positrons, or for energetic photons due to annihilations in the galactic centre. Other strategies include looking for energetic neutrinos produced by annihilations inside the core of the Sun or Earth. The rate for solar annihilations is generally controlled by the capture rate, which is largely due to $\chi$ energy loss during scattering on protons inside the Sun: $\chi + p \rightarrow \chi + p$. This scattering is in turn dominated by spin-dependent interactions that are sensitive to axial-current matrix elements related to the magnitude of $\Delta s$ [30]. This quantity may also be important for the direct search for dark matter scattering on nuclei in the laboratory: $\chi + A \rightarrow \chi + A$.

The experimental upper limits on spin-independent scattering of dark matter particles are beginning to eat into the parameter spaces of some supersymmetric models, as seen in the left panel of Fig. 5 [31]. The limits on spin-dependent dark matter scattering currently lie far above the predictions in favoured supersymmetric models, as seen in the right panel of Fig. 5 [31], but there are proposals to improve the experimental sensitivity significantly. If ever a dark matter candidate is found, a measurement of spin-dependent could be a key tool for diagnosing the underlying supersymmetric model.
FIGURE 5. Upper limits on spin-independent LSP scattering (left) and spin-dependent LSP-proton scattering (right), compared with theoretical estimates \[31\]. The plots are from \[32\].

HIGH-ENERGY COLLIDERS

Electron-proton collisions

HERA has recently started providing the first measurements of polarization asymmetries in deep-inelastic high-energy $e^\pm$-proton collisions \[25\], and will continue to take these data until mid-2007. These data remove overall sign ambiguities in the vector and axial couplings of the $u$ and $d$ quarks to the $Z$ boson, confirming that they have the signs predicted in the Standard Model. This ambiguity has also been lifted by previous unpolarized HERA data, but the determinations using polarized data are already much more precise, particularly in pinning down the $u$ couplings to the $Z$ boson.

Hadron-hadron collisions

Although present and planned hadron colliders will not have polarized beams, there is interesting information to be obtained from measurements of final-state spins and their correlations. One example is provided by measurement of the $W$ polarization in top quark decay. There are two observables, $f_0$, and the Standard Model predicts that only $f_0$ should be non-zero. Data from the CDF and D0 Collaborations are indeed compatible with the Standard Model value for $f_0$ and $f_+ = 0$, providing a valuable check on the weak interactions of the $t$ quark \[33\].
The LHC, now nearing completion at CERN, will collide proton beams of 7 TeV each with a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. All of the magnets have now been delivered to CERN, and most of them have been installed in the LHC tunnel. The interconnection of these and other machine components is proceeding apace, and the machine is expected to be closed by the end of August 2007, with first collisions planned for November 2007. It will not be possible before then to commission the entire machine for operation at the design energy, so the 2007 running will be at the injection energy of 900 GeV in the centre of mass. The commissioning will be completed in the first part of 2008, so that full-energy running can start by the middle of that year.

Spin effects in the decays of new particles produced at the LHC can be used to analyze the underlying theory. For example, as already mentioned, spin plays a central role in supersymmetry, which makes characteristic predictions for spin effects in sparticle decay chains. A generic decay chain may include as many as four sparticles: $D \rightarrow C \rightarrow B \rightarrow A$, each of which could in principle be vector (V), fermionic (F) or scalar (S). In the case of squark decay, for example, the decay sequence could be $\tilde{q} \rightarrow \chi_2^{\pm} + q \rightarrow \ell^\pm + \ell \rightarrow \chi \pm \ell$, with the spin signature SFSF. However, other sequences and spin signatures could hold, e.g., in models with large extra dimensions. There are many observables capable of distinguishing these spin signatures, such as the shape of the $\ell \ell$ spectrum shown in the left panel of Fig. 6, the shape of the $q\ell$ spectrum and its angular asymmetry as a function of its invariant mass [34].

Such spin effects can also be used to look for CP-violating effects in sparticle decay. Consider, for example, the case $gg \rightarrow \tilde{t}_1 \tilde{t}_1$ followed by $\tilde{t}_1 \rightarrow \chi_2^{\pm} + t$, followed by $\chi_2^{\pm} \rightarrow \chi \pm e^-$. The lepton decay asymmetry is sensitive to the CP-violating phase of the U(1) gaugino mass, as shown in the right panel of Fig. 6 [35].

**FIGURE 6.** Shapes of dilepton spectra in the cascade decays of new heavy particles at the LHC, for different sequences of spins (left) [34], and the sensitivity of a lepton asymmetry to a CP-violating phase in a supersymmetric model (right) [35].
Electron-positron collisions

Polarized positrons (as well as electrons) would add significant value to the physics programme of the ILC [36]. For example, in the direct channel, $RL$ and $LR$ collisions select vector-boson exchanges, whereas $LL$ and $RR$ collisions select scalar exchanges. Moreover, in many theories such as supersymmetry, the couplings of particles that might be exchanged in the cross channel depend on the helicities of the two colliding beams. the following are just a few examples of the gains for studies of new physics that would be provided by having polarized positrons as well as electrons at the ILC.

- They would provide improved measurements of sparticle couplings, both by providing new ways to suppress Standard Model backgrounds, e.g., from $W^+W^-$, by choosing suitable combinations of $e^\pm$ polarizations, and also by improving the discriminating power for the quantum numbers of sparticles exchanged in the cross channel.
- They would provide improved sensitivities to new four-fermion contact interactions, that could involve different combinations of $e^\pm$ helicities.
- They would add value to the GigaZ programme of high statistics at the $Z$ peak [4].

The measurements made possible by $e^\pm$ polarization would make possible improved constraints on Standard Model parameters as well as enable quantum tests of possible extensions of the Standard Model, such as supersymmetry, as seen in Fig. 7 [37].

THE POWER OF POLARIZATION

The examples given in the previous sections illustrate some of the physics interest in spin and polarization physics. It provides a unique tool for dissecting physics that we...
think we know, and often finds surprises, a prime example being the long-running puzzle of the nucleon spin. Polarization can also be a delicate probe for new physics, by providing new observables, suppressing backgrounds and enhancing signals. The probes of known physics are complementary to the searches for new physics. Indeed, the muon anomalous magnetic moment may already be providing a hint for new physics, and electric dipole moments are excellent probes of CP violation. In another example building on the previous probes of the Standard Model at the Z peak, future tests of its extensions using $e^\pm$ polarization at the ILC will be very interesting. As another example, our developing understanding of nucleon spin may eventually help us disentangle the nature of dark matter. We must understand the Standard Model in order to probe beyond it, and polarization is invaluable for both tasks.

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