Supersymmetric Effects in Parity-Violating Deep Inelastic Electron-Nucleus Scattering

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We compute the supersymmetric (SUSY) corrections to the parity-violating, deep inelastic electron-deuteron asymmetry. Working with the Minimal Supersymmetric Standard Model (MSSM) we consider two cases: R parity conserving and R parity-violating. Under these scenarios, we compare the SUSY effects with those entering other parity-violating observables. For both cases of the MSSM, we find that the magnitude of the SUSY corrections can be as large as ~ 1% and that they are strongly correlated with the effects on other parity-violating observables. A comparison of various low-energy parity-violating observables thus provides a potentially interesting probe of SUSY.

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I. INTRODUCTION

The study of parity-violation (PV) in nuclei and atoms is playing an important role in the search for physics beyond the Standard Model (SM) [1]. Historically, the first such study in the neutral current sector involved a measurement of the PV “left-right” asymmetry, $A_{LR}$, for deep inelastic electron-deuteron scattering [2]. That experiment, which established the validity of the SM for weak neutral currents, was followed by several studies of parity-violation in atoms [3] as well as in both quasi-elastic [4] and elastic electron-nucleus scattering [5]. Recently, the first results have been reported for a measurement of $A_{LR}$ for $e^-e^-$ scattering at the Stanford Linear Accelerator Center (SLAC) [6, 7], and a proposal to measure $A_{LR}$ in elastic $ep$ scattering has been approved at the Jefferson Laboratory (JLab) [8]. The precision expected for the latter two measurements allows one both to test the $q^2$-evolution of the
weak mixing angle as well as to probe for new physics. In light of these developments, ideas have been generated for a new generation of PV DIS measurements with deuterium targets at both SLAC\[9\] and JLab\[10\].

In this note, we analyze the prospective implications of new PV DIS measurements for supersymmetric extensions of the Standard Model. Supersymmetry (SUSY) remains one of the most strongly-motivated new physics scenarios, and one hopes that future collider measurements will provide the first direct evidence for its existence. At present, the phenomenological evidence for SUSY, derived from precision electroweak measurements, is sparse. Although the new measurements of the muon anomalous magnetic moment\[11\] generated considerable excitement in the SUSY community, the initial indications of a deviation from the SM have been superseded by subsequent developments in SM theory. In the charged current sector, the long-standing deviation from unitarity of the CKM matrix – taken in conjunction with measurements of the $W$-mass and muon anomaly – could signal the insufficiency of standard SUSY-breaking models\[12\], though recent experimental and theoretical developments\[13, 14\] involving kaon leptonic decays have clouded the situation somewhat. The implications of precision neutral current experiments are mixed as well. Fits to $Z$-pole observables, performed using different assumptions about the mechanism of SUSY-breaking mediation, have lead to varying conclusions about whether or not the data favor the presence of SUSY\[15, 16\]. At much lower energy scales, the results of cesium atomic PV are consistent with both the SM\[17\] as well as its minimal SUSY extensions\[18\]. In contrast, the substantial deviation from the SM in deep-inelastic neutrino-nucleus scattering reported by the NuTeV collaboration\[19\] cannot be explained using any of the most common SUSY scenarios\[20\]. In principle, the new PV $ee$ and $ep$ measurements will help clarify the low-energy neutral current situation.

In this context, one would like to know what new insight – if any – a precise measurement of the PV DIS $eD$ asymmetry might provide. To that end, we compute the SUSY electroweak radiative corrections to this asymmetry using the Minimal Supersymmetric Standard Model (MSSM). We also analyze the possible effects of SUSY interactions that violate R parity. In doing so, we compare the effects of either scenario on the DIS asymmetry with the corresponding effects in other low-energy neutral current experiments. As we noted in our previous studies of PV $ee$ and $ep$ scattering\[18\], we find that there exist notable correlations involving the SUSY effects on different observables. We also work out the level of precision
needed for a PV DIS measurement in order for it to be a significant probe of SUSY.

The PV asymmetry for deep inelastic eD scattering, \( A_{LR}^{\text{DIS}} \), has the simple form

\[
A_{LR}^{\text{DIS}} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = \frac{G_\mu Q^2}{4\sqrt{2}\pi\alpha} \left( \tilde{a}_1 + \tilde{a}_2 \left[ \frac{1 - (1 - y)^2}{1 + (1 - y)^2} \right] \right),
\]

where

\[
\tilde{a}_1 = \frac{2}{3} (2C_{1u} - C_{1d})
\]

\[
\tilde{a}_2 = \frac{2}{3} (2C_{2u} - C_{2d})
\]

and \( y \in [0, 1] \) is the fractional energy transfer to the target (in the lab frame)\(^1\). The quantities \( C_{iq} \) parameterize the low-energy, PV electron-quark interaction

\[
\mathcal{L}_{\text{PV}}^{eq} = \frac{G_\mu}{\sqrt{2}} \sum_q \left[ C_{1q} \bar{e} \gamma^\mu \gamma_5 e \bar{q} \gamma_\mu q + C_{2q} \bar{e} \gamma^\mu e \bar{q} \gamma_\mu \gamma_5 q \right].
\]

Note that in writing down Eqs. (1,2), we have neglected target mass and higher-twist corrections as well as contributions from sea quarks\(^2\).

The presence of SUSY interactions will modify the \( C_{iq} \) from their SM values. The \( C_{iq} \) are conveniently computed using the expressions

\[
C_{1q} = 2\rho_{PV} I_3^f (I_3^q - 2Q_{KPV} \hat{s}^2) - \frac{1}{2} \hat{\lambda}_{1q}
\]

\[
C_{2q} = 2\rho_{PV} I_3^f (I_3^q - 2Q_{KPV} \hat{s}^2) - \frac{1}{2} \hat{\lambda}_{2q},
\]

where \( I_3^f \) and \( Q_f \) are, respectively, the third component of weak isospin and electric charge of fermion \( f \), \( \hat{s} = \sin \hat{\theta}_w \) is the sine of the mixing angle in the \( \overline{\text{MS}} \) scheme, and \( \rho_{PV} = 1 = \kappa_{PV} \) and \( \hat{\lambda}_{iq} = 0 \) at tree-level in the SM. Electroweak radiative corrections modify the latter quantities from their tree-level values: \( \rho_{PV} = 1 + \delta \rho_{PV}, \kappa_{PV} = 1 + \delta \kappa_{PV} \), with \( \delta \rho_{PV}, \delta \kappa_{PV} \), and \( \hat{\lambda}_{iq} \) being of order \( \alpha \).

The SM values for \( \delta \rho_{PV}, \delta \kappa_{PV} \), and \( \hat{\lambda}_{iq} \) are well-known\(^{[22]}\). When R parity is an exact symmetry of the MSSM, the presence of virtual SUSY particles will modify these quantities solely via the loop amplitudes of Fig. 1. The SUSY contributions to \( \rho_{PV} \) and \( \kappa_{PV} \) have been

\(^1\) For simplicity, we have neglected a correction to the denominator of the \( y \)-dependent term in Eq. 1 arising from longitudinal gauge boson contributions\(^{[21]}\).

\(^2\) While the magnitude and theoretical reliability for these corrections are important for the interpretation of \( A_{LR}^{\text{DIS}} \), we do not consider them in detail here.
FIG. 1: Various types of radiative corrections to parity-violating electron scattering: $Z^0$ boson self-energy and $Z - \gamma$ mixing (a), anapole moment contributions (b), vertex corrections (c), and box graphs (d). External leg corrections are not explicitly shown.

worked out in Ref. [18]. These contributions, which are universal and can be applied to all low-energy PV processes, can be expressed in terms of the oblique parameters [18]:

$$\delta \rho_{PV}^{SUSY} = \hat{\alpha} T - \hat{\delta}_{VB}^{\mu},$$

$$\delta \kappa_{PV}^{SUSY} = \left( \frac{c^2}{c^2 - s^2} \right) \left( \frac{\hat{\alpha}}{4 s^2 c^2} S - \hat{\alpha} T + \hat{\delta}_{VB}^{\mu} \right)$$

$$+ \frac{\hat{c}}{s} \left[ \hat{\Pi}_{ZZ}(q^2) - \frac{\hat{\Pi}_{Z}(M_Z^2)}{M_Z^2} \right]_{SUSY} + \left( \frac{c^2}{c^2 - s^2} \right) \left[ - \frac{\hat{\Pi}_{\gamma\gamma}(M_Z^2)}{M_Z^2} + \frac{\Delta \hat{\alpha}}{\alpha} \right]_{SUSY}. \quad (6)$$

Note that we have modified the definition of $\delta \kappa_{PV}^{SUSY}$ compared to that given in Ref. [18], moving the anapole contribution into the non-universal correction terms $\hat{\lambda}_{iq}$. The quantities $\hat{\Pi}_{VV'}(q^2)$ are the gauge boson propagator functions, renormalized in the DR scheme\(^3\), and the oblique parameters $S$, and $T$ are defined in terms of various combinations of these quantities as given in Ref. [23]. The contribution $\hat{\delta}_{VB}^{\mu}$ denotes SUSY vertex, external leg, and box graph corrections to the amplitude for muon decay. These corrections must be subtracted from the semileptonic, neutral current amplitude since the latter is normalized in terms of the Fermi constant obtained from the muon lifetime. The quantity $\Delta \hat{\alpha}$ is the SUSY

\(^3\) Quantities renormalized in the DR scheme are indicated by a hat.
contribution to the difference between the fine structure constant and the electromagnetic coupling renormalized at $\mu = M_Z$: $\Delta \hat{\alpha} = [\hat{\alpha}(M_Z) - \alpha]^\text{SUSY}$. Note that gauge invariance implies that $\hat{\Pi}_{Z\gamma}(q^2)/q^2$ is finite as $q^2 \to 0$.

For the $\hat{\lambda}_{1,2q}$ one has

$$
\hat{\lambda}_1^\text{SUSY} = g^e_A (g^q_V \delta Z^e_q - g^q_A \delta Z^q_A + G^q_V) + g^q_V (g^e_A \delta Z^e_q - g^e_V \delta Z^e_A + G^e_A) \\
+ \delta^e_A q^V - 16 Q e^2 s^2 F_{A,e}
$$

(7)

$$
\hat{\lambda}_2^\text{SUSY} = g^e_A (g^q_V \delta Z^e_q - g^q_A \delta Z^q_A + G^q_V) + g^q_V (g^e_A \delta Z^e_q - g^e_V \delta Z^e_A + G^e_A) \\
+ \delta^e_V q^A - 16 Q e^2 s^2 F_{A,q}
$$

(8)

where the various couplings, counterterms as well as the vertex corrections are defined in Appendix A of Ref. [18]. In particular, the $g^f_V$ ($g^f_A$) is the vector (axial vector) coupling of fermion $f$ to the $Z^0$; $\delta Z^q_V$ ($\delta Z^q_A$) is $1/2 \times$ the sum (difference) of right- and left-handed fermion wave function renormalization constants; $G^f_V$ ($G^f_A$) give the loop contributions to the vector (axial vector) $Zff$ vertex; and in the notation introduced in Eq. (C14) of Ref. [18]

$$
\hat{\delta}^e_A q^V = -2 \left(-A^e + B^e - C^e + D^e\right)
$$

$$
\hat{\delta}^e_V q^A = -2 \left(-A^e + B^e + C^e - D^e\right)
$$

(9)

are the box diagram contributions to the $A(e) \times V(q)$ and $V(e) \times A(q)$ amplitudes, respectively.

![Diagram](image-url)

FIG. 2: Tree-level RPV contributions to (a) muon decay, (b) electron- u-quark scattering, and (c) electron- d-quark scattering. The quantities $\Delta_{ij}^{(l)}$ are defined in Eq. (10).

New tree-level SUSY contributions to the $C_{iq}$ can be generated when the R parity quantum number $P_R = (-1)^{3(B-L)+2S}$ is not conserved, with $B$, $L$, and $S$ denoting, respectively,
the baryon number, lepton number, and spin of a given particle. In order to avoid unacceptably large contributions to the proton decay rate, we do not allow for any $\Delta B \neq 0$, $\Delta L = 0$ R parity violating (RPV) interactions. Those which violate $L$ are parameterized by the couplings $\lambda_{ijk}$ and $\lambda'_{ijk}$ appearing in the superpotential, where the former involve purely leptonic interactions and the latter corresponding to semileptonic effects. The subscripts denote the generations of the three particles in the interaction. The corresponding contributions to the $C_{iq}$ arise from the Feynman diagrams of Fig. 2 and involve the positive, semi-definite, dimensionless quantities:

$$\Delta_{ijk}(\tilde{f}) = \frac{|\lambda_{ijk}|^2}{4\sqrt{2}G_\mu M_{f_k}^2},$$

where $\tilde{f}_k$ is the scalar superpartner of fermion $f_k$ and where an analogous expression applies for the semi-leptonic corrections, $\Delta'_{ijk}(\tilde{f})$. Note that one must consider both the purely leptonic and semileptonic corrections, as the former modify the relative normalization of neutral and charged current amplitudes as well as the predicted value of the weak mixing angle $\theta_W$.

In terms of the $\Delta_{ijk}(\tilde{f})$ and $\Delta'_{ijk}(\tilde{f})$, one has the following shifts in the $C_{iq}$:

$$\Delta C_{1u}^{RPV} = -[C_{1u} - \frac{4}{3}\lambda_x] \Delta_{12k}(\tilde{e}_R^k) - \Delta'_{11k}(\tilde{d}_R^k)$$

$$\Delta C_{1d}^{RPV} = -[C_{1d} + \frac{2}{3}\lambda_x] \Delta_{12k}(\tilde{e}_R^k) + \Delta'_{1k1}(\tilde{q}_L^k)$$

$$\Delta C_{2u}^{RPV} = -[C_{2u} - 2\lambda_x] \Delta_{12k}(\tilde{e}_R^k) - \Delta'_{11k}(\tilde{d}_R^k)$$

$$\Delta C_{2d}^{RPV} = -[C_{2d} + 2\lambda_x] \Delta_{12k}(\tilde{e}_R^k) - \Delta'_{1k1}(\tilde{q}_L^k),$$

where

$$\lambda_x = \frac{s^2(1 - s^2)}{1 - 2s^2} \frac{1}{1 - \Delta\tilde{r}^{SM}} \approx 0.35$$

with $\Delta\tilde{r}^{SM}$ being a radiative correction to the $\alpha - G_\mu - M_Z - \sin^2 \theta_W$ relation in the SM:

$$s^2c^2 = \frac{\pi\alpha}{\sqrt{2}M_Z^2 G_\mu (1 - \Delta\tilde{r}^{SM})}.$$

We first analyze the SUSY corrections to the $C_{iq}$ and $A_{LR}^{\mu \nu}$ assuming conservation of R parity. To do so, we randomly generate $\sim 5000$ different sets of soft SUSY-breaking parameters, chosen from a flat distribution in the SUSY-breaking mass parameters and a logarithmic distribution in $\tan \beta$. The ranges chosen for the parameters are given in Table III.
TABLE I: Range of MSSM parameters chosen for computation of SUSY radiative corrections. Here \( \tilde{M} \) denotes any of the gaugino masses, sfermion masses or the \( \mu \) parameter, while \( A_f \) denotes the triscalar couplings that enter the off-diagonal term in the mass-squared matrix for scalar fermion \( \tilde{f} \).

| parameter | range       |
|-----------|-------------|
| \( \tan \beta \) | \( 1.4 \rightarrow 60 \) |
| \( \tilde{M} \) | \( (50 \rightarrow 1000) \) GeV |
| \( A_f \) | \( (-1000 \rightarrow 1000) \) GeV |

The parameters varied include the gaugino masses, Higgs bilinear mass parameter \( \mu \), \( \tan \beta \), sfermion masses, and the triscalar couplings \( A_f \). The latter enter the off-diagonal entries in the mass-squared matrix for scalar fermion \( \tilde{f} \):

\[
(M_f^2)_{LR}^i = \begin{cases} 
  m_f(A_f - \mu \cot \beta), & Q_f > 0 \\
  m_f(A_f - \mu \tan \beta), & Q_f < 0 
\end{cases}
\]  

The lower limit on \( \tan \beta \) is derived from an analysis of electroweak symmetry-breaking and direct bounds on the lightest SUSY Higgs searches from LEP. The lower bounds on the gaugino and sfermion mass parameters correspond roughly to direct search lower bounds on SUSY masses, while the limits on \( A_f \) is taken from naturalness bound.

For each parameter set, we compute the SUSY radiative corrections to the \( C_{iq} \). In order to incorporate what is known phenomenologically, we impose several constraints on the acceptable parameter sets. First, to avoid unacceptably large flavor-changing neutral currents, we do not allow for generation mixing\(^4\). Second, we retain only those parameter sets that give values for \( S \) and \( T \) consistent with current constraints on these parameters. As discussed in Ref. [18], neglecting the non-oblique corrections to the \( Z \)-pole precision observables entails some lack of self-consistency, but does not distort the qualitative conclusions.

\(^4\) In practice, we have also taken the CKM matrix for quarks to be diagonal. For the observables of interest here, this approximation introduces negligible error.
FIG. 3: SUSY loop correction to the relative shift in $A_{L,R}^{e D, DIS}(y = 1)$ vs. the relative shifts in the electron (dark dots) and proton weak charges (light dots).

In presenting our results, we follow the spirit of our previous work and plot in Fig. 3 the relative shift in $A_{L,R}^{e D, DIS}$ vs. the relative shifts in the electron and proton weak charges. The weak charge, $Q_W^f$, of particle $f$ characterizes the effective $A(e) \times V(f)$ neutral current interaction:

$$L_{e f}^{PV, \, eff} = -\frac{G_F}{2\sqrt{2}} Q_W^f A(e) \cdot V(f),$$  \hspace{1cm} (18)$$

which can be measured in PV $ee$ and elastic PV $ep$ scattering experiments. In terms of the $C_{i q}$ one has for the proton $Q_W^p = -2(2C_{1u} + C_{1d})$. In the SM, the weak charges of the proton and electron are suppressed, making them relatively transparent to the effects of new physics.

As with the SUSY loop effects in $Q_W^e$ and $Q_W^p$, the shifts induced in $A_{L,R}^{e D, DIS}$ are highly correlated with those in the electron and proton weak charges. In contrast, the loop SUSY contributions to the weak charge of cesium are negligible as a result of cancellations between up and down quark contributions\[18\]. Thus, the present agreement of atomic PV with the SM does not preclude substantial SUSY loop contributions to $A_{L,R}^{e D, DIS}$. Indeed, the magnitude of the corrections can be as much as one percent of the SM asymmetry for sufficiently
light SUSY mass parameters or large tan \( \beta \). From a practical standpoint, one would need to perform a measurement with precision better than \( \sim 0.5\% \) in order to be sensitive to the effects of SUSY radiative corrections. A recent Letter of Intent for a measurement at SLAC proposed a combined statistical and systematic error of 0.8 %, suggesting that, with further refinements, a sensitive probe of SUSY loop contributions may be feasible in the future.

\[
\begin{align*}
\text{FIG. 4: SUSY contributions to } A_{L,R}^{eD,\text{DIS}}(y = 1) \text{ from } \delta \rho_{PV} \text{ (dashed line), } \delta \kappa_{PV} \text{ (dash-dotted line)} \text{ and } \delta \lambda \text{ (dotted line). The solid line is the sum of all the contributions to } A_{L,R}^{eD,\text{DIS}}. \text{ The } x\text{-axis is the common first and second generation slepton mass. The other MSSM parameters are chosen to be } \tan \beta = 10, \ 2M_1 = M_2 = \mu = 200 \text{ GeV. The mass for the squarks and third generation slepton are taken to be 1000 GeV. Note that neutralinos and charginos are light, which leads to a non-decoupling effect in } A_{L,R}^{eD,\text{DIS}} \text{ even when squarks and sleptons are heavy.}
\end{align*}
\]

We observe, however, that the strong correlation of loop effects between \( A_{L,R}^{eD,\text{DIS}} \) and the weak charges makes the combination of all three measurements a potentially interesting probe of SUSY radiative corrections. The reason for this correlation is that the contributions to \( \delta \kappa_{PV} \) – and, thus, the shift in the effective weak mixing angle – dominate the loop-induced corrections to the asymmetry (see Fig. 4). A similar statement applies to the electron and proton weak charges. Given the precision anticipated for the measurements of \( Q_W^e \)
and $Q^p_W$ as well as the precision proposed in \cite{9} for $A^{eD,\text{DIS}}_{LR}$, the combination of all three measurements would be nearly a factor of two more sensitive to SUSY loop-induced shifts in $\sin^2\theta_{W}^{\text{eff}} = \kappa_{PV} \hat{s}^2$ than of the measurements individually.

In Fig. 5 we illustrate the sensitivity of $A^{eD,\text{DIS}}_{LR}$ to the effects of RPV interactions. Here, we plot the relative shifts in $A^{eD,\text{DIS}}_{LR}$ vs. those in $Q^e_W$ and $Q^p_W$ due to both SUSY loops as well as RPV interactions. The interior of the truncated ellipse gives the 95% C.L. region from RPV effects allowed by other precision electroweak data. The latter include $\mu$-decay, $\beta$-decay, $\pi$-decay, cesium atomic PV, and $M_W$. The constraints from $Z^0$-pole observables are fairly insensitive to these RPV effects since they generate off-resonance tree-level contributions to $e^+e^-$ annihilation amplitudes. The truncation of the elliptical region results from the requirement that the corrections $\Delta_{ijk}$ and $\Delta'_{ijk}$ be non-negative.

![Figure 5](image-url)

**FIG. 5:** 95 % CL allowed region for PRV contribution to $A^{eD,\text{DIS}}_{LR}(y = 1)$ vs. electron weak charge (a) and proton weak charge (b). The dots indicate the SUSY loop corrections.

As illustrated in by Fig. 5 (a), the presence of RPV effects would induce negative relative shifts in both $A^{eD,\text{DIS}}_{LR}$ and $Q^e_W$, whereas the relative sign of the loop corrections is positive in both cases. Moreover, the maximum correction to $A^{eD,\text{DIS}}_{LR}$ would be $-1.5\%$, corresponding to about $2\sigma$ for the precision proposed in Ref. \cite{9}. The corresponding comparison of the corrections to $A^{eD,\text{DIS}}_{LR}$ and $Q^p_W$ are shown in Fig. 5 (b). Note that in this case, a sizable positive shift in $Q^p_W$ [up to $3\sigma$ for the proposed $A_{LR}(ep)$ measurement] due to RPV contributions could correspond to a tiny effect on $A^{eD,\text{DIS}}_{LR}$ whereas a substantial negative shift in
the proton weak charge could also occur in tandem with a substantial negative correction to $A_{LR}^{eD,DIS}$. On the other hand, even a result for $Q_W^p$ consistent with the SM would not rule out a sizable effect on $A_{LR}^{eD,DIS}$.

In summary, we conclude that a combination of PV electron scattering measurements at kinematics below the $Z^0$ pole may provide an interesting probe of SUSY. Given the correlations between the SUSY loop and RPV effects among the different observables, a comparison of PV elastic $ee$, elastic $ep$ and deep-inelastic $eD$ scattering would provide substantially more information than any one alone. In this context, the addition of an $A_{LR}^{eD,DIS}$ measurement would provide a useful complement to the PV $ee$ and elastic $ep$ measurements, assuming it can be performed with $\sim 0.5\%$ precision or better. More generally, a comprehensive program of PV electron scattering experiments – when combined with the results of atomic PV deep-inelastic $\nu$-nucleus scattering – could help determine which versions of SUSY remain the most viable.

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