1. Introduction

Precision measurements have played an important role in our understanding of the subatomic world. The discovery of an anomalous magnetic moment of electrons is one early example, where the hyperfine structure of hydrogen (HHFS) was found to be too large for the standard theory to be correct [3]. The Dirac equation \[ i(\gamma^\mu A(\mathbf{x}))\psi = m_e \psi \] predicted a magnetic dipole moment (MDM) for the electron

\[ \mu_e = g_e \frac{e}{2m_e} \mathbf{s} \]  
(2)

with the factor \( g_e = 2 \) (and \( e > 0 \)). The increase in the hydrogen hyperfine levels could be accounted for by a term involving an additional magnetic moment. Motivated by the HHFS dilemma, Schwinger [3] carried out the rst "loop" calculation, and predicted that the electron had an additional (anomalous) magnetic moment of

\[ a_e = \frac{g_e}{2} \text{ where } a_e = \frac{(g_e - 2)}{2} \]  
(3)

The subsequent precision spectroscopic measurements of Kusch and Foley [3] obtained a magnetic moment of \( g_e \) that was in good agreement with Schwinger's prediction.

In 1950, Purcell and Ramsey suggested that an electric dipole moment (EDM) would violate parity invariance \( P \), and proposed to search for the neutron electric dipole moment [3]. This was of course the correct New Physics except for one important detail: an EDM would violate time-reversal symmetry, \( T \), and by implication CP. Presumably, new, as yet undiscovered sources of CP violation are responsible for the magnetic moment of the electron, the muon, and possibly the electron neutrino.

2. The Dipole Operators

As mentioned above, the Dirac equation is inadequate to describe the magnetic moment of the electron. It is necessary to add a Pauli term

\[ \frac{e}{4m_e} \alpha d \mathbf{F}(\mathbf{x}) \mathbf{F}(\mathbf{x}) \]  
(4)

which in modern language is a dimension 5 operator that must arise from loops in a renormalizable theory. New Physics (NP) can also contribute through loops, with \( a(\text{NP}) = C (m = )^2 \), where \( C \gtrsim 0 \) and \( '0 ( ) \) in weak coupling loop scenarios. In the same spirit, one could add the following Pauli-like term

\[ \frac{1}{2} \mathbf{d} \mathbf{F}(\mathbf{x}) \mathbf{F}(\mathbf{x}) \]  
(5)

which represents the electric dipole moment interaction, where

\[ \mathbf{d} = \frac{e}{2m_e} \mathbf{s} \]  
(6)

and the quantity \( \mathbf{d} \) plays the role for the EDM that \( g \) plays for the MDM. One way to parametrize the effects of NP on \( a \) and \( d \) is by \( d(\text{NP}) = a(\text{NP})(e=2m) \tan \frac{N P}{2} \). The electric dipole current is given by

\[ f(p^0) J_{\text{em}} f(p) = u_f(p^0) u_e(p) \]  
(7)
where $u_t$ and $u_e$ are Dirac spinor eilds and has the general Lorentz structure

$$F_1 q^2 + i F_2 q^2 q - F_3 q^2 q^2 2m_q q$$

with $F_1(0) = Q e$ the electric charge, $F_2(0) = a(Q e - 2m)$ the anomalous magnetic moment, and $F_3 = dQ$ the electric dipole moment. I will ignore the last term, the anapole moment.

The anomalous part of the dipole moment interaction

$$u = Q e F_1(q^2) + \frac{i Q e}{2 m} F_2(q^2) q u$$

connects states of opposite helicity, i.e. it is chiral changing, giving a unique sensitivity to NP interactions, e.g. the sensitivity to tan $\beta$ in supersymmetry (SUSY) theories. In most SUSY models, the contribution to $a$ depends on the SUSY mass scale, the sign of the parameter $\tan \beta$, and the value of $m_t$. A simple SUSY model with equal mass parameters [14,15] gives the SUSY contribution as:

$$\tan \beta = 10^{11} \times 10^{-3} \text{rad}$$

2.1. Measurements of the Muon and Electron Anomalies

The electron anomaly has been measured to a precision of 0.24 parts per billion by storing a single electron in a quantum cyclotron and measuring the quantum cyclotron and spin levels in this system [3]. When independent measurements of the non-structure constant available at this precision, this impressively precise measurement could provide a testing ground for the validity of QED down to the $\mu$-loop level, and present an opportunity to search for extra-GeV physics. At present the best independent measurements of $a$ have a precision of 5 ppb [10]. In the absence of such an independent measurement, the electron (g-2) value has been used, along with the QED theory (assumed to be valid), to give the most precise value of $a$.

The muon anomaly, while only measured to an accuracy of 0.54 parts per million (ppm) [13], nevertheless has an increased sensitivity to higher physics that scales as $m = m_{e}^{2}$ = 43,000. This means that at a measurable level the Standard Model contribution to the muon anomaly comes from QED from virtual hadrons in vacuum polarization or hadronic light-by-light scattering loops; and from loops involving the electroweak gauge bosons.

In principle the technique is similar to the experiment of the electron anomaly, where muons are stored in a "trap" consisting of a dipole magnetic field plus an electrostatic quadrupole field. In the muon experiment, an ensemble of muons is injected into a precision storage ring. The observable is the spin precession frequency relative to the muon momentum, which is the difference between the spin precession frequency and the cyclotron frequency:

$$\frac{1}{a} = \frac{1}{a} \tan \beta = \frac{Q e}{m} \frac{a}{\beta} \frac{1}{16} \frac{1}{1} \frac{m_{e}}{c}$$

The second term in brackets represents the effect of the momentary magnetic field on the muon motion. The experiment is operated at the "magic" value of $m_{e} = 10^{-7}$. This value is the use of an electric quadrupole field to provide the vertical focusing.

The measured electron and muon anomalies are

$$a_{e} = \left[1.165918073(18)\right] 10^{-4} 0.24 \text{ppm}$$

$$a = \left[116592089(63)\right] 10^{-11} 0.54 \text{ppm}$$

Interestingly enough, the muon anomaly seems to be slightly larger than the Standard Model value [12].

$$a_{SM} = 116591834(49) = 10^{-11}$$

which uses e⁻⁻ annihilation into hadrons to determine the hadronic contribution, and the value of Prades et al. [13] for the hadronic light-by-light contribution. There is a difference of 3.2 between the two. Hadronic decays are used to determine the lowest-order hadronic contribution (a decay that relies on significant isospin corrections) the difference drops to 2 [13].

Such a deviation could well with the expectations of supersymmetry in the few-hundred GeV mass region, as shown in Eq. 10. Were SUSY particles to be discovered at LHC, the muon anomaly would play an important role in helping to discriminate between the different possible scenarios, and providing a measure of spin. For a thorough review of SUSY and (g-2) see the articles by Stockinger [16].

The precision of the E821 (g-2) measurement was limited by the statistical error of 0.46 ppm, compared to the systematic error of 0.28 ppm. A new experiment has been proposed for Fermilab, P989 [13] with the goal of equal statistical and systematic errors, and a total error of 0.14 ppm, a factor of four in the error over E821.

Significant works on different aspects of hadronic contribution are in progress, both on the experimental side to measure the hadronic electroproduction cross sections better, and on theoretical sides to improve on the hadronic light-by-light contribution [20].

The supersymmetry conjecture has chosen a number of possible scenarios that might be discovered at LHC, the Snowmass points and slopes [17], which
serve as benchmarks for determining the sensitivity to the SUSY parameters. Since $a$ has significant sensitivity to $\tan \beta$ (see Eq. [10]), it is possible to compare the sensitivity to $\tan \beta$ from LHC vs. from $\mu$. Such a comparison is shown in Fig. 2, which assumes that the SPS1a point is realized, typically a SUGRA point with an intermediate value of $\tan \beta$. There is some tension between the new value of $a$ and this model, which predicts $a = 293 \times 10^{11}$, so the minimum from LHC is at 10, the input from SPS1a, and the presence of a value implies a slightly lower value. The lighter blue band shows the in proven ent that could be gained in the new Fermi Lab experiment.

### 3. Electric Dipole Moments

Unlike the magnetic dipole moments, the Standard-M Model values of electric dipole moments are orders of magnitude less than present experimental limits, both of which are shown in Table I. The experimental observation of an EDM would unambiguously signify the presence of new physics.

![Table I: Measured Limits on Electric Dipole Moments, and their Standard M Model values](image)

For hadronic systems, the $\theta$-term in the QCD Lagrangian

$$L_{QCD}^{\text{eff}} = L_{QCD} + \frac{a G_F}{4 \pi^2} \epsilon^{\alpha \beta \gamma} F^{\alpha \beta} F_\gamma$$

violates both parity and time-reversal symmetries, where the physical quantity is the sum of the overall phase in the quark masses, $+ \arg(\det M)$. The non-observation of a neutron EDM restricts the value of $\theta$.

$$\theta \leq \frac{3 \times 10^{-15} \text{ e cm}}{\mu} < 10^{-10}$$

which for a quantity that could be one order of magnitude small and is often referred to as the strong CP problem. While supersymmetry, or other models of New Physics can easily contain new sources of CP violation, the absence of any observation of an EDM, with a significant fraction of the "natural" part of the SUSY CP-violating parameter space already eliminated, is sometimes called the SUSY CP problem.

The isovector and isoscalar combinations of the magnetic dipole moments are:

$$F^{(1=1)}_{2N} = \frac{F_{2p} + F_{2n}}{2}$$

$$F^{(1=0)}_{2N} = \frac{F_{2p} - F_{2n}}{2}$$

we conclude that the isovector dominates the anomalous EDM. Both isoscalar and isovector EDMs are predicted by various models [23], so measuring both the proton and neutron EDMs would help disentangle these two possibilities.

In the traditional EDM experiment, the system is placed in a region of parallel (anti-parallel) electric and magnetic fields. The Larmor frequency is measured, and then the electric field direction is tipped.
An EDM would cause the Lamb or frequency to be higher/lower depending on the direction of the electric field. The EDM is determined by the frequency difference between these two configurations:

\[ \Delta \nu = \frac{4dE}{h} \]  

A new result from the Seattle group places the limit on the EDM of the mercury atom:

\[ d^{(199)\text{Hg}} = (0.09 \pm 1.29_{\text{stat}} \pm 0.76_{\text{syst}}) \times 10^{-29} \text{ cm} \]  

(19)

giving the limit above in Table 1.

Searches are underway worldwide to find an EDM of the electron (24) (Imperial College, Colorado, Harvard, Yale, Amherst, Penn State, Texas, Osaka and Indiana), neutron (23) (ILL, PSI, Oak Ridge), the atom (23)(199)Hg (Seattle) or (252)Xe (Princeton), (225)Ra (Argonne, Garching),

The limit on the muon EDM comes from E821 at Brookhaven (24). If an EDM exists, it is necessary to modify the spin precession formula of Eq. 11 with an extra term, !

\[ \frac{\gamma}{\gamma} = \frac{QeE}{2mc} \cdot \pi \]  

(20)

and the total spin precession frequency is \( \frac{\gamma}{\gamma} = \frac{\gamma}{\gamma} + \frac{\gamma}{\gamma} \). The torsional electric field is proportional to \( \pi \), so the EDM results in an out-of-plane component of the spin, where the (very small) tipping angle relative to \( \frac{\gamma}{\gamma} \) is \( \tan^{-1} \frac{\gamma}{\gamma} = \tan^{-1} \frac{\gamma}{\gamma} \). For spin 1/2, it is related to the EDM, \( d \), by the relationship

\[ d = \frac{eh}{4mc} \]  

(21)

In the (g-2) experiment, \( \frac{\gamma}{\gamma} \) and the resulting motion is an up-down oscillation with frequency \( \frac{\gamma}{\gamma} \), out of phase with the (g-2) oscillation. Such an experiment is largely limited by systematic errors, since the out-of-plane motion is asked by the large-amplitude spin precession from the magnetic moment. Nevertheless, the new Fermilab experiment hopes to achieve one to two orders of magnitude improvement in the muon EDM as a by-product of the improved (g-2) measurement. Significant progress beyond that goal would require to reduce the large background caused by the \( \frac{\gamma}{\gamma} \) precession.

To achieve this reduction, the "frozen spin" technique has been proposed (23). Recall the point of choosing the magic parameter \( \lambda \) was to eliminate the effect of the focusing electric field on the spin precession. If, however, a storage ring were to be operated at a different momentum, then a radial electric field could be used to counter the spin precession from the magnetic field (see Eq. 11), viz., it could be chosen such that \( \frac{\gamma}{\gamma} = 0 \). The E-field required to freeze the muon spin is

\[ E = \frac{aBr^2}{1 + a^2 r^2} \]  

(22)

Possible parameters of such an experiment are \( E = 2 \text{ MV/m}, p = 500 \text{ MeV/c}, \rho = 5, R_0 = 7 \text{ m} \) (23, 33), although a much smaller ring has been suggested for the Paul Scherrer Institut (31). The spin technique, along with a very high-\( \times \) facility could permit a sensitivity of \( 10^{-22} \) cm or better for the muon EDM, providing a unique opportunity to measure the EDM of a second generation particle.

The error on such a measurement is given by (24)

\[ \frac{P}{P} = \frac{P}{P} \]  

(24)

which implies that one needs \( P = 10^{-16} \) for \( P = 10^{-23} \) cm. The polarization enters directly into the asymmetry, thus the muon beam for the EDM experiments must have high polarization.

![Figure 3: Present and projected limits on the muon EDM.](Image)

Figure 3: Present and projected limits on the muon EDM. To progress beyond the projection for the new (g-2) experiment at Fermilab, dedicated storage rings will be required, as described in the text. (Modified from a figure courtesy of Thomas Schietinger)

In closing this section, one additional point needs to be made. Should convincing evidence for any EDM be found, it will be imperative that all other EDMs be possible be measured to help sort out the source of this new CP violation.
4. Transition Moments

One of the most important discoveries in the past decade was the definitive evidence that neutrinos mix. In the Standard Model, this implies that charged leptons will also mix, and when one calculates the transition rate for $^+!^-$ one nds:

$$B r(\mu^+\mu^-) = \frac{3}{32} X V_{\mu e}^2 \frac{m^2}{M_W^2} \times 10^{34}$$

which is m easurable under the m ost optimistic scenario. Thus the observation of any process that violates lepton lepton avor would herald the discovery of new physics.

Just as the diagonal m atrix elem ents of the electrom agnetic current were connected with the electric and m agnetic dipole moments, we have the o -diagonal elem ents of the current that give transition m oments:

$$f_j(p^0) \rightarrow f_i(p) = u_j(p^0) i^j u_i(p);$$

where $i^j$ is given by

$$i^j = q^2 g^0 q q r_{E0}^j q_i + s r_{M0}^j q_i i^j q q r_{M1}^j q_i + s r_{E1}^j q_i$$

The first term gives rise to chiral-conserving avor-changing amplitudes at $q^2 < 0$, e.g., $K^+ \rightarrow ^+!^-$, $^+!^-$, and the second term gives rise to chiral-changing, avor-changing amplitudes, e.g., $b ! s$, $^+! e$ and $^+! e$.

Here I con m yself to the muon sector, where possible reactions include:

$$^+!e$$

$$^+!e^+e^-e^-$$

$$N!eN$$

$$^+!e^-$$

There is a long experimental history of searches for these reactions, going back to the search for $\mu^- e^+$ in 1947 by Hinks and Pontecorvo, who showed the branching ratio was less than $10^{-6}$. In the intervening years, the limits for all these processes have lowered to $10^{-10}$ $10^{-12}$, as shown in Fig. 4. Ambitious experiments planned or in preparation have goals of $10^{-18}$ or below.

A wide range of NP could produce such transitions. One channel which permits the highest experimental sensitivity is the muon to electron conversion reaction, Eq. 30. If negative muons are stopped in matter, they come to rest and get captured into atomic orbits in the stopping material. They then cascade down to the atomic 1s state. Ordinarily the decay of these muons in orbit, or are captured weakly on the atom's nucleus, which is analogous to $K$ capture of atomic electrons. In the coherent conversion to an electron with no neutrinos, the signal is a mono-energetic electron with an energy equal to the muon mass less the atom's binding energy of the muon in the ground state of the muonic atom. While this process is forbidden in the Standard Model, it is possible in a large number of Standard-Model extensions, some of which are shown diagrammatically in Fig. 4.

The muon-electron conversion (MEC) is especially interesting because of the broad range of physics which it addresses. The interaction Lagrangian $L_{int}$ is given by [35]:

$$\frac{4G_F}{2} (m A_R P_L e^- + m A_L P_R e^- + A_R A_L P_L e^- + A_R A_L P_R e^- + A_R A_L P_L e^- + A_R A_L P_R e^- + A_R A_L P_L e^- + A_R A_L P_R e^-)$$

where the three terms in the Lagrangian represent dipole, scalar and vector interactions respectively. If the dipole term dominates, then muon-electron conversion is suppressed by $2 \times 10^{-6}$ relative to $\mu^- e^+$, however, for the other operators, MEC is much more sensitive. This is illustrated in Fig. 5, where the sensitivity to different mass scales is shown as a function of the amoun of the non-dipole contribution [35]. While $\mu^- e^+$ is much more sensitive if the dipole contribution dominates, for non-dipole interactions, the conversion event has an enormous mass reach, well beyond what could be in a single shell. The muon-electron conversion rate depends both on the
operator, and on the nucleus [25]. If it becomes possible to measure MEC for a range of nuclei, the $Z$ dependence will help disentangle which operators are responsible. Furthermore, the observation of several CLFV processes will help further, perhaps along with the electric and magnetic dipole moment information.

At present there is one running experiment in the muon sector, the MEG experiment at the Paul Scherrer Institute, which aims for a sensitivity of $R_\mu < 10^{13}$ for the process $\mu \rightarrow e\gamma$. Of course, experimentally, this channel is quite challenging. The two-body final state uniquely determines the kinematics, so at rest the photon and electron are back-to-back, sharing the muon mass energy. However, photons in the 50 MeV energy region are difficult to detect with good position and directional information on the photon. A preliminary result from MEG reported a $3 \times 10^{11}$ 90% confidence level limit [25], which is not yet competitive with the present limit of $1.2 \times 10^{14}$ [24].

The muon-electron conversion experiment is rather special, since the signal of a single mono-energetic electron is unique, and in principle resolved from background. The muon-electron conversion experiment at Fermilab, the solid being for the phase using the present booster accelerator, and the dashed being for the Project X era. (Figure courtesy of Andrew Norman)

5. Conclusions

I have described a set of experiments from the precision/intensity frontier which have the potential in equal to the discoveries we hope for, and expect to see at the LHC. The discovery of a perm anent electric dipole moment would herald, at long last, a new source of CP violation that might explain the matter-antimatter asymmetry of the universe, and partially explain why we are here. The discovery of charged lepton flavor violation would also herald New Physics at...
work in the lepton sector. A confirmation of the muon (g - 2) discrepancy would also signify new physics at the loop level. All of these experiments will help guide our interpretation of the new phenomena we hope to discover at LHC. Perhaps the most important message from this talk is that many different additional experimental results will be necessary to help guide our interpretation of the discoveries made at the LHC. It is crucial for the future health of the field that a diverse program, exploring both the precision and energy frontiers, be strongly supported.

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