Beyond the Standard Model with Electron and Muon Beams

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Abstract. We describe the current status and future potential of precision low energy experiments using intense electron and muon beams to search for physics beyond the standard model in a manner complementary to direct searches at the Large Hadron Collider. The measurements fall under to broad categories: those that search for small deviations in precision electroweak observables that are measurable with very high precision and have correspondingly accurate calculations at the level of electroweak radiative corrections, and those observables that have very small or vanishing values within the framework of the electroweak theory but are very sensitive to new physics at the TeV scale. We review ongoing efforts and outline future initiatives that are timed to match the physics results from high integrated luminosity at the LHC.

1. Introduction
The SU(2)_L × U(1)_Y gauge structure within the Standard Model, which gives rise to electroweak interactions, has been subject to stringent tests over more than three decades of precision measurements. Consistency has been achieved at ~ 0.1%, a level of precision where “hard” electroweak radiative corrections involving the top quark, the massive vector bosons, and their scalar interactions, become manifest. No compelling signature for an inconsistency has been found to date, with direct access to center of mass energies of order 200 GeV in e^+e^- collisions at CERN’s LEP ring, of order 1 TeV in the hard scattering of partons in pp collisions at Fermilab’s Tevatron, and most recently with the newest data (albeit with very low statistics) with access to several TeV pp collisions at CERN’s LHC.

Nevertheless, compelling theoretical arguments, input from cosmological observations, and the discovery of neutrino mass strongly motivate the continued exploration of the multi-TeV scale. Direct searches at colliders, where one looks for as yet unobserved new interaction amplitudes at the highest possible center of mass energies, are an essential component of this endeavor. However, an equally important part of the package to determine the full extent of validity of the electroweak theory involves indirect probes, where one looks for deviations from theoretical predictions at much lower center of mass energies.

Prominent low energy approaches are those that achieve sufficient sensitivity to TeV scale dynamics and complement high energy experiments in one of two ways: either precision measurements that help distinguish between competing models that explain potential LHC anomalies, or, symmetry violation searches that access new physics well beyond the few TeV energy scale of LHC. After a brief overview of the variety of strategies that are pursued at low energy, we focus on experiments carried out with high intensity electron and muon beams.
2. Experimental Approaches at Low Energy

Low energy experimental approaches that have sensitivity to TeV-scale dynamics and beyond can be divided into four broad categories:

(i) Neutrino Masses and Mixing: e.g. direct neutrino mass measurements, neutrino oscillation measurements from the sun, reactors and accelerators, and neutinoless double-beta decay searches

(ii) Rare and Forbidden Processes: e.g. CP- and T-violation searches in weak decays, searches for EDMs and searches for charged lepton flavor violation

(iii) Dark Matter Searches

(iv) Precision Electroweak Measurements: e.g. precision measurements of weak neutral current amplitudes at $Q^2 \ll M_Z^2$, precision measurement of $(g-2)_\mu$ and precision measurements of weak decays of neutrons and heavy nuclei.

The list above encompasses a broad international program of experimental investigations over a range of experimental techniques. The focus of this review are those subtopics that can be best addressed with intense electron and muon beams. These topics are highlighted in boldface above. A model-independent way to parametrize the physics sensitivity of various approaches is via higher dimensional operators characterizing new contact interactions at or above the TeV-scale. Precision electroweak measurements are typically characterized by flavor-diagonal contact interactions while searches for charged lepton flavor violation are characterized by flavor-violating contact interactions. We discuss each class of searches in sequence below.

3. Flavor-Diagonal Contact Interactions

Many models addressing the shortcomings of the Standard Model predict new particles and interactions above the TeV scale that manifest themselves as new flavor diagonal contact interactions parametrized as follows [1]:

$$\mathcal{L}_{f_1f_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2} \bar{f}_i^1 \gamma_\mu f_1^i \bar{f}_j^2 \gamma_\mu f_2^j,$$

where $f_{1/2}$ are any of the Standard Model fermions, $f^{L/R} = \frac{1}{2}(1 \mp \gamma_5)\psi_f$ are chirality projections of the fermion spinor, $\Lambda$ is the mass scale of the contact interaction, and $g_{ij}$ are coupling constants. To be complementary to LHC direct searches, one needs to reach the sensitivity $\Lambda \gtrsim 10$ TeV for as many different combinations of $f_1f_2$ as possible.

Within the context of the electroweak theory, consistency at the 0.1% level has been established, with the only unknown parameter being the mass of the Higgs boson. Electroweak measurements can thus probe for new contact interactions parametrized in Eqn 1 for the indirect effects of new by making more and more precise measurements of electroweak parameters and searching for deviations from very precise theoretical predictions within the context of the Standard Model [2]. Two classes of low energy measurements that have reached the required level of sensitivity for flavor diagonal interactions are weak neutral current (WNC) measurements and the measurement of the $(g-2)_\mu$ anomaly.

For example, WNC interactions at $Q^2 \ll M_Z^2$ can probe for heavy $Z'$ bosons or leptoquarks whose effects might be highly suppressed in measurements on the $Z$ pole. Since $Z$ pole measurements are imaginary, there are no interference terms with new, real amplitudes. At low $Q^2$ on the other hand, interference effects might be measurable if sufficient accuracy is achieved [3].

Over the past decade, three measurement have reached such sensitivity and set important new constraints on new contact interactions at the TeV scale. The weak charge measurement
in atomic Cesium [4], the NuTeV neutrino deep-inelastic scattering measurement [5] and the measurement of $A_{\text{PV}}$ in electron-electron (Møller) scattering [6] at SLAC. The E158 measurement uses the technique of parity-violating electron scattering requiring intense polarized electron beams, which we discuss next.

3.1. Parity-Violating Electron Scattering

Soon after the discovery of parity violation in beta decay 50 years ago, Zel’dovich speculated that there might be an analogous parity violating neutral current interaction [7]. He noted that if such an interaction existed, then parity violation would be manifested in lepton-nucleon scattering due to the interference between the weak and electromagnetic amplitudes. He predicted that if one scatters longitudinally polarized electrons off unpolarized protons and flipped the sign of the beam polarization, the fractional difference in the cross-section would be:

$$A_{\text{PV}} \equiv \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} \simeq \frac{|A_Z|}{A_\gamma} \simeq \frac{G_F Q_e^2}{4 \pi \alpha} \simeq 10^{-4} Q_e^2$$  \hspace{1cm} (2)

For typical fixed target experiments, $A_{\text{PV}}$ ranges from roughly $10^{-4}$ to as small as $10^{-7}$. In the mid-seventies, parity violation in deep inelastic electron nucleon scattering was first observed at SLAC [8], from which the electron-quark weak neutral current coupling could be extracted. The measurement was an important validation of the Standard Model, and the extracted value of the electroweak mixing angle $\sin^2 \theta_W$ matched the corresponding value obtained from neutral current neutrino scattering experiments.

Over the past 20 years, the experimental techniques employed to measure these tiny left-right asymmetries have been steadily refined such that statistical errors approaching 0.01 parts per million (ppm) and systematic errors of a few parts per billion (ppb) are possible [9]. Depending on the choice of target and kinematic variables, this has facilitated measurements in several important physics topics, such as many-body nuclear physics, nucleon structure and searches for physics beyond the standard model at the TeV scale. The last topic in particular is of interest in the context of this review, and we discuss current and future prospects using electron-electron (Møller) scattering, electron-proton elastic scattering, and electron-deuteron deep inelastic scattering (PVDIS).

3.1.1. The Purely Leptonic Process of Møller Scattering

The Feynman diagrams for Møller scattering involve both direct and exchange diagrams that interfere with each other. $A_{\text{PV}}$ is given by [10]

$$A_{\text{PV}} = mE \frac{G_F}{\sqrt{2} \pi \alpha} \frac{4 \sin^2 \theta}{(3 + \cos^2 \theta)^2} Q_W^e = mE \frac{G_F}{\sqrt{2} \pi \alpha} \frac{2y(1-y)}{1 + y^4 + (1-y)^4} Q_W^e$$  \hspace{1cm} (3)

where $\alpha$ is the fine structure constant, $E$ is the incident beam energy, $m$ is the electron mass, $\theta$ is the scattering angle in the center of mass frame, $y \equiv 1 - E'/E$, $E'$ is the energy of one of the scattered electrons, and $Q_W^e$ (proportional to the product of the electron's vector and axial-vector couplings to the $Z^0$ boson) is the electron’s weak charge.

The electroweak theory prediction at tree level in terms of the weak mixing angle is $Q_W^e = 1 - 4 \sin^2 \theta_W$; this is modified at the 1-loop level [11, 12] and becomes dependent on the energy scale at which the measurement is carried out, i.e. $\sin^2 \theta_W$ “runs”. It increases by $\sim 3\%$ compared to its value at the scale of the $Z^0$ boson mass, $M_Z$.

The SLAC E158 experiment carried out the first measurement of parity violation in Møller scattering [6]. The experiment was constructed between 2000 and 2002 and final data collection completed in late 2003. The grand average result for the parity-violating asymmetry in Møller
scattering at $Q^2 = 0.03$ GeV$^2$ was found to be $A_{PV} = -131 \pm 14 \text{(stat)} \pm 10 \text{(syst)} \text{ (ppb)}$. This can be compared to the theoretical prediction within the electroweak framework to put limits on new contact interactions at the TeV scale. Assuming that the only contributing chiral structure comes from the $\Lambda_{LL}$ term, the 95% C.L. limit is 7 TeV or 16 TeV depending on the sign of the contact interaction term.

There is strong motivation to make further improvements in the accuracy of low energy leptonic and semi-leptonic weak neutral current coupling constants at low energy. Improved measurements would keep pace with the improved sensitivity for discovery at the multi-TeV scale by experiments at the Large Hadron Collider. With the upgrade of Jefferson Laboratory to 12 GeV, a new project called MOLLER (Measurement of Lepton-Lepton Electroweak Reaction) is being designed to improve on the SLAC E158 measurement of the weak charge of the electron $Q_e^W$ by a factor of five [13].

Using $\alpha_{EM}, G_F, M_Z$ and $m_t$ as input, precision measurements of electroweak parameters such as $m_W$ and $\sin^2 \theta_W$ can be used to test the electroweak theory at the level of electroweak radiative corrections. Consistency (or lack thereof) of various precision measurements can then be used to constrain $m_H$ and search for indications of physics beyond the Standard Model. While there is no significant conflict between such indirect limits of $m_H$ with direct collider searches, the $m_H$ constraints from the two most precise single measurements of $\sin^2 \theta_W$ are very different [14]. The proposed MOLLER measurement would provide a third independent measurement of $\sin^2 \theta_W$ with comparable precision.

In addition, since MOLLER would be carried out at a very low energy scale in contrast to the two collider measurements, there is greatly enhanced sensitivity to as yet undiscovered superweak interactions at the TeV scale. For the 2.3% total uncertainty envisioned, the sensitivity can be expressed as:

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = \frac{1}{\sqrt{2G_F|\Delta Q_e^W|}} \simeq \frac{246.22 \text{ GeV}}{\sqrt{0.023Q_e^W}} = 7.5 \text{ TeV.}$$

(4)

For example, models of lepton compositeness are characterized by strong coupling dynamics. Taking $\sqrt{|g_{RR}^2 - g_{LL}^2|} = 2\pi$ shows that mass scales as large as $\Lambda = 47$ TeV can be probed, far beyond the center of mass energies of any current or planned high energy accelerator. This allows electron substructure to be studied down to the level of $4 \times 10^{-21}$ m. The strongest constraints on the coefficients in Eqn. (1) come from LEP 2, approaching 5 TeV for specific chiral combinations. However, the parity-conserving cross-sections and forward-backward asymmetries studied at LEP 2 are blind to the parity-violating combination $g_{RR}^2 - g_{LL}^2$ probed by MOLLER.

Using Eqn. (4), it is also straightforward to examine its reach in specific models [2]. The sensitivity to specific R-Parity-violating SUSY interactions would be greatly improved [15]. In addition, the MOLLER measurement would provide unique new constraints on combinations of left- and right-handed leptonic couplings to new neutral gauge bosons between 1 and 2 TeV [16], complimenting LHC measurements [17]. Finally, the sensitivity to lepton-number violating interactions mediated by doubly charged scalars would be greatly extended.

The MOLLER collaboration, a group of $\sim 100$ authors, submitted a proposal to the Jefferson Laboratory Program Advisory Committee in December 2008. The project was awarded stage-I approval with strong endorsement. The collaboration is currently carrying out an R&D plan to develop the technical design of the apparatus. The MOLLER collaboration is about to submit a proposal to the US Department of Energy, Division of Nuclear Physics to obtain primary project funding, and also hope to obtain supplementary funding from the US National Science Foundation and international funding agencies.

The goal is to launch MOLLER with significant R&D funding by late 2011, so that construction of the apparatus can begin in 2013. The MOLLER experiment could then be
constructed by 2015, soon after full luminosity beams become available.

3.1.2. Semi-leptonic Processes The interactions of the Z-boson and heavier particles can be approximated by four-fermion contact interactions. The parity-violating part of the electron-hadron interaction can then be given in terms of phenomenological couplings $C_{ij}$

$$L^{PV} = \frac{G_F}{\sqrt{2}} \left[ \bar{e} \gamma^\mu \gamma_5 e (C_{1u} \bar{e} \gamma_\mu e + C_{1d} \bar{d} \gamma_\mu d) + \bar{\nu} \gamma^\mu \nu (C_{2u} \bar{\nu} \gamma_\mu \nu + C_{2d} \bar{d} \gamma_\mu d) \right]$$

(5)

with additional terms as required for the heavy quarks. Here $C_{1j}$ ($C_{2j}$) gives the vector (axial-vector) coupling to the $j^{th}$ quark. Within the framework of the Standard Model, these four couplings are purely a function of $\sin^2 \theta_W$. The atomic Cs weak charge measurement [4] measured one combination of $C_{1u}$ and $C_{1d}$ precisely.

At sufficiently forward angles and low $Q^2$, the hadronic structure uncertainty in the WNC elastic electron-proton amplitude becomes small enough such that one can measure the underlying coherent $2u + d$ e-q amplitude combination to high precision, thus precisely constraining $2C_{1u} + C_{1d}$. This combination is proportional to $1 - 4 \sin^2 \theta_W$, so that a 4% measurement of $A_{PV}$ would achieve a precision of $\delta(\sin^2 \theta_W) = 0.0007$.

Such a measurement is being carried out by the Qweak collaboration in Hall C at Jefferson Lab [18]. Qweak was recently successfully commissioned and is in the process of collecting the first physics data. It is hoped the full statistics will be accumulated by 2012, before Jefferson Laboratory shuts down to upgrade its beam energy to 12 GeV. If successful, the combination of APV in $^{133}$Cs and Qweak will precisely constrain both $C_{1u}$ and $C_{1d}$, providing new, unique sensitivity to TeV scale dynamics.

$A_{PV}$ in deep inelastic scattering (DIS) can be written as

$$A_{PV} = Q^2 \frac{G_F}{2\sqrt{2}\pi a} \left[ a(x) + \frac{1 - (1 - y)^2}{1 + (1 - y)^2} b(x) \right],$$

(6)

$$a(x) = \frac{1}{x} \sum_i f_i(x) C_{1i} q_i / \sum_i f_i(x) q_i^2,$$

(7)

$$b(x) = \frac{1}{x} \sum_i f_i(x) C_{2i} q_i / \sum_i f_i(x) q_i^2.$$  

(8)

Here, $x$ is the fraction of the nucleon momentum carried by the struck quark, $f_i(x)$ are parton distribution functions and $q_i$ are the electromagnetic charges. The $a(x)$ term, which are functions of $C_{1i}$, is the dominant term. For an isoscalar target such as deuterium, the dependence on structure largely cancels out in the $A_{PV}$ ratio of the weak and electromagnetic amplitudes:

$$a(x) = \frac{6}{5} \left[ (C_{1u} - \frac{1}{2} C_{1d}) + \text{corrections} \right];$$

(9)

$$b(x) = \frac{6}{5} \left[ (C_{2u} - \frac{1}{2} C_{2d}) \frac{q(x) - \bar{q}(x)}{q(x) + \bar{q}(x)} + \text{corrections} \right],$$

(10)

where $q(x) = u(x) + d(x)$.

In trying to make precision measurements of $A_{PV}$ in PVDIS, several important issues should be taken under consideration. The $a(x)$ term is a factor of 5 to 10 larger than the $b(x)$ term because the latter involves the vector coupling of the electron, which is small in the electroweak theory. In order to be relevant in constraining new physics at the TeV scale, $A_{PV}$ must be measured to 1% relative accuracy or better. To avoid uncertainties from sea-quark distributions and higher-twist effects, it is important to have $Q^2 \geq 2$ GeV$^2$ and $x \geq 0.35$. The DIS cross-section is steeply falling as $x$ increases. The above factors have precluded a followup precision measurement to E122 for the past two decades.
The upgrade of Jefferson Laboratory (Jlab) to 11 GeV incident energy will allow precision measurements for the first time. While the first measurements were carried out at 6 GeV [19] and a 11 GeV experiment has been proposed for Hall C [20], a dedicated spectrometer could for the first time allow the accumulation of high statistics at high $x \sim 0.7$. PV DIS provides access to novel aspects of nucleon structure, such as charge symmetry violation and investigation of higher-twist effects [21, 22]. Most importantly, PV DIS allows the isolation of the linear combination $2C_{2u} + C_{2d}$, which is difficult to measure using elastic scattering.

To comprehensively address these physics topics experimentally, a series of $A_{PV}$ measurements with better than 1% accuracy are required for the $x$ range from 0.3 to 0.7, with a lever arm of a factor of 2 in $Q^2$ while keeping $W^2_{\text{min}} > 4$ and $Q^2_{\text{min}} > 1$. However, to achieve sufficient statistics at the highest possible $Q^2$, a spectrometer with at least 50% acceptance in the azimuth is required. It turns out that the central tracking magnetic field of one of the collider experiments BaBar, CDF or CLEO would be ideal for this purpose. A proposal [23] exploiting this idea was recently approved by the JLab PAC for this comprehensive program. An engineering design of the detectors and support structures inside the solenoid are under way. It is hoped that this project will be funded in a similar fashion to the MOLLER project, roughly one to two years afterward.

3.2. The Muon Anomalous Magnetic Moment

One of the most precisely measured, accurately calculated and rather sensitive test of TeV scale physics is the muon anomalous magnetic moment. The difference of $g$ from 2 (the anomaly $a_\mu = (g - 2)_\mu$) arises from virtual loops, where those involving pure QED or electroweak interactions are calculated very precisely. Loops involving strongly interacting particles are less well known. However, a variety of analytical and lattice techniques, coupled with precise low energy data on $e^+e^- \rightarrow$ hadrons cross-sections have controlled theoretical uncertainties on the anomaly to an impressive 0.48 ppm [24].

The most precise experimental measurement is from the E821 experiment at Brookhaven National Laboratory (BNL); the final cumulative error is 0.54 ppm [25]. The difference between theory and experiment is $\Delta a_\mu(\text{Expt} - \text{SM}) = 295\pm88 \times 10^{-11}$, a $3.4\sigma$ effect; a 2.5 ppm difference with a cumulative error of 0.75 ppm. The dynamics of the loop corrections contributing to the anomaly are such that supersymmetric (SUSY) extensions of the standard model provide a natural explanation for this deviation. There is tremendous motivation therefore to improve the theoretical prediction as well as design a new experiment to reduce the experimental uncertainties.

There are theoretical efforts under way that should improve the theoretical prediction uncertainty by more than a factor of 2 [26]. Even if the theoretical prediction with improved uncertainty brings the experimental measurement more in line with theory, an improved comparison of theory and experiment remains compelling if a new improved measurement can be carried out in the next decade. For example, consider a situation where new mass states have been found at the LHC, which are compatible with various extensions of the Standard Model such as SUSY or Universal Extra Dimensions (UED). The impact of TeV-scale UED on $a_\mu$ is typically much smaller than that of SUSY, providing discriminating power.

The goal of a future measurement, recently proposed and approved at Fermilab [27], is to reduce both the statistical as well as systematic error, each to $\sim 0.1$ ppm. A scheme to provide an increased muon flux has been devised for three accelerator facilities: BNL, FNAL and JPARC. The plan is the reuse the old muon storage ring, even if the experiment is to be situated at FNAL or JPARC. The time scale to mount any new effort will take several years. Nevertheless, the time-scale is well-suited to provide important complementary input at the same time that high statistics data become available from the LHC.
4. Flavor-Violating Contact Interactions

With the discovery of neutrino oscillations, it became evident that neutrinos are massive and that lepton flavor is not an exact symmetry of nature. The concept of charged lepton flavor violation (cLFV) has historically provided important insights during the development of the Standard Model. Given the small size of neutrino masses, the Standard Model rate for cLFV is too small to observe experimentally.

However, most theoretical approaches that try to naturally explain the uncharacteristically small neutrino masses must introduce new physics at high energy scales, parametrized by a cutoff parameter $\Lambda$. In the process, new higher dimensional operators are introduced, such as that required to provide neutrinos with Majorana masses. In this scenario, new cLFV operators are a very sensitive probe of new dynamics well beyond the TeV scale [28].

One class is electromagnetic transition operators, which leads to the decay $l_i \to l_j \gamma$. Current constraints on $\mu \to e\gamma$ and $\tau \to \mu\gamma$ will be improved by an order of magnitude, accessing $\Lambda$ in the 50 to 100 TeV range. A second class is four-lepton contact interactions which has similar experimental reach (the strongest being $\mu \to eee$) leading to comparable constraints. A third class is 2-quark-2-lepton contact interactions that can lead to decays such as $\tau \to \mu\pi$, $K_L \to \mu e$ and coherent $\mu^{-}e$ conversion in nuclei.

4.1. Muon-Electron Flavor Violation

While the scales probed by the measurements mentioned above might still be orders of magnitude away from the scale of new physics, it is interesting to note that TeV scale physics could be responsible for mediating the heavy scales motivated by natural explanations of small neutrino mass. One example is SUSY, where cLFV terms can be naturally introduced in a variety of ways. Many experimental probes of cLFV are quite sensitive to SUSY-motivated signals that are not too far from current bounds. However, $\mu \to e\gamma$ and $\mu^{-}e$ conversion have the best potential for future improvements [29].

The MEG experiment at PSI, which recently published its first result [30] on $\mu \to e\gamma$, has the statistics and the experimental design to approach a branching ratio limit of $10^{-14}$ which is an extremely interesting level of sensitivity if there are SUSY particles at around the 1 TeV scale. But by far the experimental probe with the greatest future potential in $\mu^{-}e$ conversion. Theoretically, it is sensitive to both the first and third class of cLFV operators mentioned above, as opposed to $\mu \to e\gamma$, which is only sensitive to the first class.

Experimentally as well, $\mu^{-}e$ conversion is likely to be the only probe that has the potential to go well beyond the next generation of experimental designs. Unlike other experimental signatures that need to identify and reconstruct multi-particle final states, $\mu^{-}e$ conversion looks for a single mono-energetic electron that carries away the full rest energy of the muon save for the recoil kinetic energy of the parent nucleus. The experimental signature is best searched for after bringing an intense low energy muon beam to rest in a nuclear target.

The current best limit of $7 \times 10^{-13}$, using a gold target, is given by the SINDRUM-II experiment at PSI. That experiment was limited by backgrounds from cosmic rays and from pion contamination in the muon beam. New experiments must make several improvements to reach better sensitivity, such as employing a pulsed muon beam, obtaining significantly higher average muon beam intensity, reducing pion contamination, employing an active cosmic ray veto shield, and improving the recoil electron energy resolution.

There are two large initiatives being pursued, one in Japan at the new J-PARC facility and one in the US at Fermilab. At JPARC [31], a first stage experiment called COMET is being designed to reach a sensitivity of $10^{-16}$. This is to be followed by a new experiment called PRISM that will employ a novel muon storage ring and achieve a sensitivity of $10^{-18}$. At Fermilab, the Mu2e experiment [32] is also being designed with a sensitivity goal of $10^{-16}$. An upgrade to $10^{-18}$ is envisioned in the far future as the centerpiece of a proton driver program.
The Mu2e experiment is currently undergoing intense R&D, design and prototyping. Construction is envisioned to begin in 2-3 years and should take about 4 years. Running should take 2-3 years, so that the first data and results should be available before the end of the decade.

In the long run, Fermilab is proposing to replace the 8 GeV proton Booster with an ILC-style linear accelerator such that an order of magnitude increase in the total beam power might be feasible. With the experience gained from the first stage measurement as well as the higher muon flux available, the long term goal of $10^{-18}$ might be come feasible. At that level of sensitivity, this technique will be unmatched by any other project to probe for flavor violation and thus complement direct searches for new physics at colliders.

5. Conclusions
There are compelling arguments for why it is likely that new dynamics will become evident in the LHC data over the next decade. In order to decipher the underlying theory that is responsible for these dynamics, targeted high sensitivity low energy experimental measurements are likely to prove indispensable. Intense electron and muon beams that are envisioned in beam facilities over the next few years provides new opportunities to design experiments that will provide the needed sensitivity and complementarity. With electron beams, parity-violating electron scattering will provide unprecedented access to flavor-diagonal contact interactions. With muon beams, a new measurement of the muon magnetic moment anomaly and new highly sensitive searches for $\mu - e$ conversion will provide access to new physics scales well beyond the reach of the LHC.

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