MEMORANDUM

To: Ernie Glover

From: Peter Fisher

Subject: Precision Measurement of the Electron Electric Dipole Moment (EDM) in the broader particle physics context

Date: January 24, 2018

---

1 The Electron EDM (eEDM): sensitivity to new physics

A permanent eEDM (or d_e) arises from the quantum mechanical corrections to the interaction of the electron with the electromagnetic field. Virtual particles fill the vacuum and the presence of an electron (or any other charged particle) alerts the configuration of the virtual particles which in turn alter the interaction of an electron with an applied field. Vacuum polarization, first measured by Lamb and Retherford in 1947, provides an example: the electron's electric field polarized the virtual electron positron pairs in the vacuum, slightly decreasing the electric charge when measured far from the electron, Fig. 1a. Fig. 1b shows the quantum mechanical interaction between an electron and virtual particles in electromagnetic field, a quantum correction. Fig. 1c shows the largest component in which the electron interacts directly with the EM field.

The second quantum mechanical diagram shows the photon briefly converts to the an $e^+ - e^-$pair (referred to as a "loop") that recombines back to a photon. This is an example of a quantum correction. Any particle may appear in the loop, making a measurement of the vacuum polarization potentially sensitive to undiscovered particles and their interactions, if a sensitive enough measurement can be performed. The size of the quantum correction is much smaller than the direct interaction and usually there are many other quantum corrections. Quantum mechanics tells us to sum the contributions from all the processes and then square to find the probability of the process occurring. If the calculation does not agree with experimental measurement, some new process or particle must be in play in one of the contributions. The size of as discrepancy (if there is one) may hint at the new particle's mass or interaction strength, but does not tell us what they are the same way direction production does.

eEDM works in a similar way. The electron appears as a point particle in quantum field theory and a dipole moment indicates the positive and negative charges in an electron are not distributed in the same way, requiring the electron to have a "shape" described by the quantum corrections. In addition, the interaction of an eEDM requires both P and CP symmetry be violated, which only occurs with the weak interaction in the Standard Model (SM). Fig. 2a shows an example of the an SM contribution to the eEDM. The very large masses of the $W^{\pm}$ particles makes the SM contribution to the eEDM unobservably small. The small contribution of the SM (relative

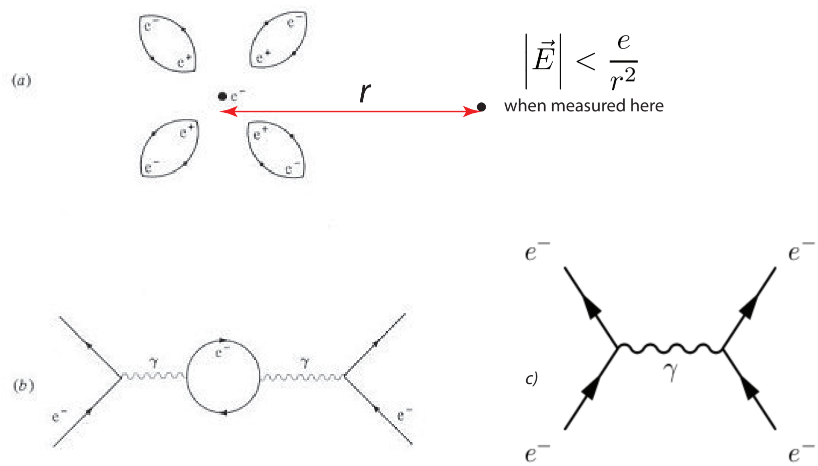

Figure 1: a) "Classical" picture of an electron polarizing virtual $e^+ - e^-$pairs, lowering its apparent charge when measured from the electron. b) Quantum mechanical picture of vacuum polarization with the photon, γ, from the electric field interacting with a virtual $e^+ - e^-$pair "loop". c) The dominant $e^+ - e^-$interaction via photon exchange. The contribution of this diagram is about 100 times the size of the diagram in panel b.

to possible quantum corrections brought about by new interactions) to the eEDM is actually an advantage – large classes of new theories predict large contributions to the eEDM, Fig. 2b and, coupled with the ever increasing sensitivity of experiments, making eEDM a good place to look for evidence for new physics.

2 Constraining new physics

The eEDM is best measured for an electron bound in a heavy atom – atoms are more easily trapped and controlled and there is relativistic enhancement of the EDM for over a factor of 100. The best measurement of eEDM is $(-0.21 \pm 0.37 \pm 0.25) \times 10^{-28}$ e-cm from the measurement of spin precession in ^{232}Th^{16}O from the ACME collaboration [2]. ACME and other groups have plans to improve the experimental sensitivity by a factor of ten in the coming years, making the measurement sensitive to new particles with masses of up to 10 TeV. A caveat is that any new theory requires substantial CP and P violation in the right places for the eEDM to be altered. CP and P violation are not necessary features of a new model. The SM expected value for the eEDM is very difficult to compute, but is bounded by $|d_e| \leq 10^{-37}$ e-cm, ten orders of magnitude lower[1].

With the discovery of the Higgs boson in 2012, the SM is complete: all the particles have been observed and characterized to some degree and all the types of interaction strengths have been measured. The framework of the model is complete. The imperative facing experimentalists now is to find a place where the SM predictions are unfulfilled in a reproducible laboratory measurement. The existence of dark matter, dark energy, and many characteristics of the SM provide clues where to look, but the parameter space is very large. Far example, the class of theories known as Supersymmetry has 105 parameters, most only weakly constrained by experiment. The search for new physics, already thirty years old, requires a broad range of experiments.

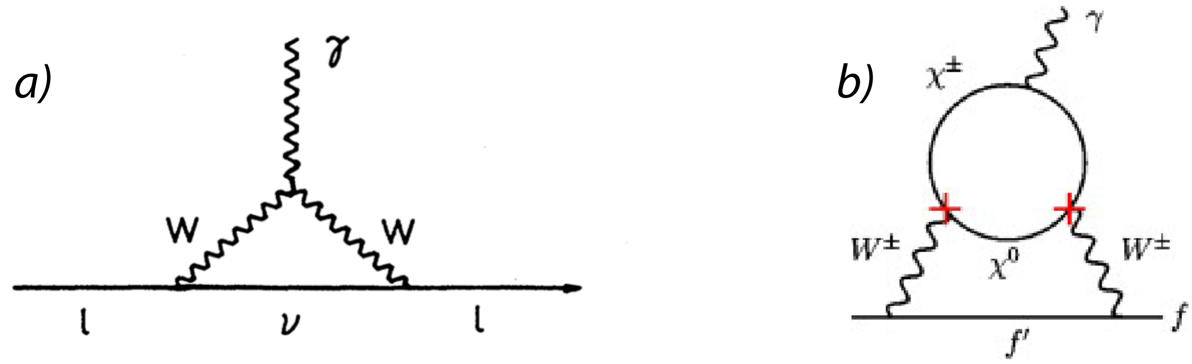

Figure 2: a) SM contribution to d_e. b) New physics contribution to d_e. χ^o and $\chi^{\pm}$ are new particles that could induce a large d_e.

2.1 $g-2$

"Why not just measure $(g-2)_\mu$more precisely?" A cousin to eEDM, g twice the ratio of the precession rate of the magnetic moment to the precession rate of the momentum of a particle in a magnetic field. For classical electrodynamics, $g=2$ and in QED, quantum corrections make g about 1% larger. g may be calculated to very high precision in the SM: $g-2 = (116591823 \pm 1 \pm 34\, pm26) \times 10^{-11}$ while the best measurement gives $(11659209.1 \pm 5.4 \pm 3.3) \times 10^{-10}$, 3.5 standard deviations from the SM prediction [3]. Like eEDM, $(g-2)_\mu$arises from a change in the quantum mechanical shape of the muon and is hence sensitive to new particles appearing in loops via quantum corrections similar to those for eEDM. In contrast to eEDM, the quantum corrections in $(g-2)_\mu$do not require CP or P violation, making $(g-2)_\mu$ sensitive to a broader range of new phenomena, but at lower experimental sensitivity. $(g-2)_e$also provides sensitivity to new physics via quantum corrections, but at lower sensitivity than $(g-2)_\mu$owing to the lower mass of the electron.

2.2 Neutron Electric Dipole Moment (nEDM)

The nEDM (or d_n) measurement gives different sensitivity than eEDM. The neutron is a constituent particle composed of quarks and gluons, giving sensitivity to new particles that connect to the strong interaction. Like eEDM, the new interactions must violate CP and P. Owing to the difficulty of the measurement, including the 880 s lifetime of the neutron, the best nEDM measurement is two orders of magnitude lower than eEDM, $|d_n| = (-0.21 \pm 1.82) \times 10^{-26}$ e-cm[4]. This sensitivity does uniquely constrain a variety new physics models and two new experiments aim to make order of magnitude more sensitive measurements in the coming years.

2.3 Measurements at the highest energies

New particles may manifest themselves through their appearance in high energy collisions. Creating a new particle of mass m requires the annihilation of comparatively massless particles with center of mass energy of at least $2m$, since new particles are typically made in pairs. The highest

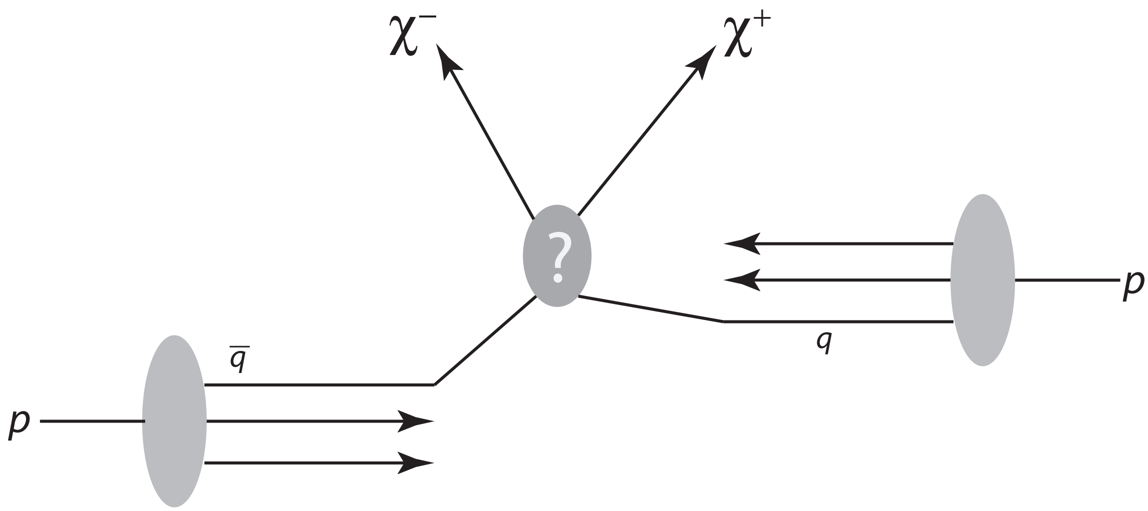

Figure 3: Production of new particles in a proton-proton collision at high energy. The protons are composed of quarks and anti-quarks and, in this case, a quark and and anti-quark have annihilated through a new process (indicated by the grey ellipse with a question mark) to produce a pair of supersymmetric particles χ^+ and χ^-. There are other interactions between the constituants of the protons not shown. The presence of the new particles must be discerned from their subsequent decays and interactions with the experimental apparatus.

energy machines, the Tevatron at Fermilab and the Large Hadron Collider (LHC) at CERN, collide protons with protons (LHC) or anti-protons (Tevatron) and, since protons and anti-protons consist of quarks, anti-quarks, and gluons[1], it is the annihilation of these constituents that leads to the production of new particles, Fig. 3. Since the quarks and gluons carry only a fraction of the momentum of the momentum of the proton, the mass sensitivity is roughly $m \sim E_B/3$, about 4 TeV for the LHC.

New particles produced in pp collisions announce themselves in a variety of ways: unusual topologies of particles emerging from the collision, large missing energy, an exceptional number of long lived particles, and so on. Detecting the production of new particles requires very detailed analysis of the data using simulations of what the SM predicts as well as simulations of a wide variety of possible new interactions. In contrast to eEDM, analysis of high energy collisions requires a testing against many hypotheseses of what new models predict. In the event of the observation of a new particle, high energy collisions could provide a great deal of information about the emergent model.

2.4 Rare decays

Experiments at the LHC, Babar, Belle, and Belle-II colliders, as well as many others, search for new physics by analyzing the decay of known particles to expected and unexpected final states. New particles may appear in the quantum corrections for known decays, altering their expected

[1]Gluons are particles that mediate the strong interaction in a manner similar to photons mediating the electromagnetic ineteraction.

rates, Fig. 4 or allow decays to final states not allowed by the SM. Like eEDM, $(g-2)_\mu$and nEDM, observation of a discrepancy between the SM expected rate and observation indicates the presence of new physics, but, generally, does not greatly constrain the nature of the new process.

3 Summary

The completion of the SM and lack of new data that contradict the SM have created a new imperative for a broad search for new physics. Precision measurements like eEDM, nEDM, and $(g-2)_\mu$play an even more important role than they did before: all these measurements will produce more sensitive results in the coming few years. At the same time, the LHC will continue to collect data and undergo important upgrades, but has covered a large part of the parameter space it was designed to search. Signficant investments have been made in nEDM and $(g-2)_\mu$in recent years, making eEDM ripe for renewal. Since eEDM and nEDM measure a single quantity and compare with SM calculation, having two experiments measuring each quantity with comparable sensitivity is essential. The LHC and rare decay experiments have always had overlapping sensitivities, leading to much higher confidence when two experiments observe the same new phenomenon. The $(g-2)_\mu$situation supports this: their results stand alone – there is no other experiment that measures this important quantity – and their 2009 result lies 4 standard deviations from the SM prediction. The experiment has been dismantled, moved from Brookhaven to Fermilab, re-installed, and will run again soon.

Several first rate groups are pursuing eEDM with higher precision than the current result. The science warrants their support, as does maintaining the experience in this important area of experimental physics.

References

[1] Bernreuther, W. and Mahiko Suzuji, "The electric dipole moment of the electron", *Reviews of Modern Physics* 65 (1991) 313.

[2] The ACME Collaboration, "Order of Magnitude Smaller Limit on the Electric Dipole Moment of the Electron", *Science* 343 (2014) 269.

[3] C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016) and 2017 update.

[4] Pendlebury, J.M., et al., *Phys. Rev. D* 92(2015) 092003.

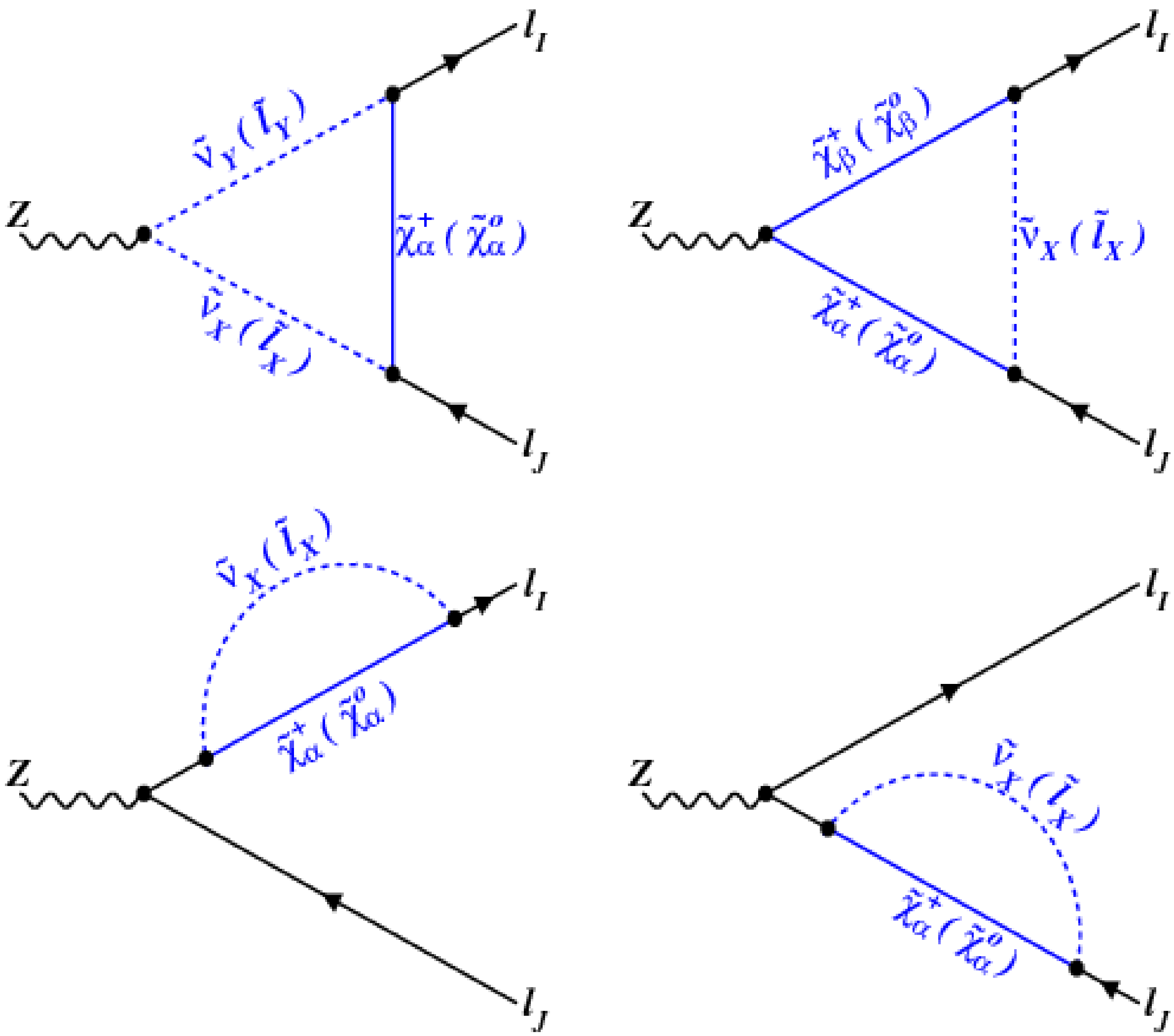

Figure 4: Examples of quantum corrections involving supersymmetric particles that can lead to changes in the decay rate of a heavy photon Z^o to a lepton pair ($l = e^{\pm}, \mu^{\pm}, ...$). The particles with a tilde on top are supersymmetric and have not been observed. There presence would change the observed rate of $Z^o \to e^+e^-$ from what the SM predicts.