1 Report of Muons at Project X Working Group

The Muon Working Group set two goals:

1. Identify, from the current state of theory, a compelling set of questions best answered using muons at Project X;
2. Define a set of experiments that can address those questions and determine how to develop them given the Project X staging plans.

The group met over the nine days of the Summer Study. There were six theory talks along with six talks on muon experiments and beam formation. The Muon Working Group also had productive joint sessions with the EDM and calorimetry groups. Finally, there were considerable informal discussions we attempt to capture in this summary.

1.1 Theory

The main theory focus of the Muon Working Group was charged lepton flavor violation (CLFV). Rare muon decays provide exceptional probes of beyond the Standard Model physics. In the Standard Model, the predicted rates for $\mu \to e$ processes resulting from a neutrino mass mixing insertion are absolutely tiny: Babu [1] reminded us $BR(\mu \to e\gamma) \sim 10^{-52}$ given existing neutrino masses and mixings.

If the scale of lepton flavor physics is much lower, Bernstein [2] set the stage by providing the well-known parameterization of the CLFV dimension-6 operators,

$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)\,, \tag{1}$$

and showing that CLFV is presently constrained to be $\Lambda \gtrsim 10^3$ TeV based on the MEG experiment and the SINDRUM-II experiment. This is already nearly 3 orders of magnitude higher than the LHC collision energy, with the next generation experiments at Mu2e (Project X) expected to improve the sensitivity by a factor of $\simeq 7$ ($\simeq 20$) above this scale [2].

Intriguingly, several theorists suggested that this level of sensitivity to CLFV would have direct impact on several models beyond the Standard Model. Fok [3] discussed a supersymmetric model incorporating an R-symmetry, based on [4]. Ordinarily, supersymmetry is *highly* constrained by flavor physics, so much so that entire model edifices have been constructed ("CMSSSM", "mSUGRA", etc.) precisely to *avoid* these constraints. Interestingly, much of the strong constraints on the superpartner-induced flavor violation can be mitigated when supersymmetry is extended to include an approximate R-symmetry with heavy Dirac gauginos. Fok pointed out that this scenario is presently only weakly constrained by existing $\mu \to e\gamma$ and $\mu \to e$ conversion bounds. However, with the improvments expected from future experiments, the slepton mixing angles go from being constrained to be roughly order one (with existing experimental bounds), down to $\mathcal{O}(10^{-3})$ (with Project X). Fok showed that there is a complementarity between $\mu \to e\gamma$ and $\mu \to e$ conversion, in which measurements of both processes are required to fully probe the parameter space.

Tsai [5] discussed a warped extra dimenional model with anarchic Yukawa couplings. One intesesting development from warped extra dimensional model building has been recasting the flavor structure of the Standard Model into higher dimensional fermion field wavefunction overlaps of the "Higgs brane". Exponential hierarchies are generic, determined by the fermion wave function localization. Tsai showed us that, like the R-symmetric supersymmetric model, the bounds from $\mu \to e$ conversion are complementary to $\mu \to e\gamma$. Unfortunately for the LHC, these bounds are already strong enough to force the mass of the first KK excitation to be above 5-6 TeV. This again demonstrates the remarkable sensitivity of CLFV towards new physics.

Chang [7] and Julio [6] told us of two models that attempt to explain the neutrino mass hierarchy in two quite different scenarios. Chang [7] presented a warped extra dimensional model in which the fermion hierarchy is determined by a five-dimensional Zee model, with ordinary Yukawas determined by extra dimensional fermion wave function overlap, somewhat analogous to [5]. The best probes of this scenario were found to be $\mu \to 3e$ and $\mu \to e$ conversion, but *not* $\mu \to e\gamma$. Several separate parameter regions were identified, with the scale of $\mu \to e$ conversion near $\Lambda \sim 4 \times 10^3$ TeV and $B(\mu \to 3e)$ near 10^{-13}. This is beyond the current bounds, but definitely can be probed by the next generation experiments. Julio [6] mainly concentrated on a model of neutrino mass generation through leptoquarks. Julio identified the full set of operators leading to $\Delta L = 2$ processes, and considered several cases. One choice, $\mathcal{O}_8$, lead to neutrino masses from leptoquark exchange, where the leptoquarks are constrained to be less than about 800 GeV. There was an interesting complementarity between the LHC probe of leptoquarks and the $\mu \to e$ processes. Generally, smaller leptoquark masses led to *much* smaller rates for $\mu \to 3e$ and $\mu \to e$ conversion. The strong dependence on the leptoquark mass is due to the higher dimensional nature of the operator generating neutrino massses. The exciting prospect from this scenario is that, as LHC continues to increase the bounds on the mass of leptoquarks, the predicted rates for $\mu \to e$ processes *increase*.

Finally, there were several joint sessions with the lattice working group, which is of direct relevance to $g-2$ of the muon. Blum [8] presented several preliminary lattice calculations of the light-by-light contribution to $g-2$. It was intriguing that the sign of this contribution is not *a priori* determined by lattice. Early calculations obtained a negative contribution, contradicting the "Glasgow consensus", while ongoing calculations appear now to be positive, but much work remains. It seems clear that this is the biggest obsticle to interpretations of the $g-2$ measurements, and we look forward to future improvements in the lattice calculations.

1.2 Experiment and Technology

There was a consensus that a suite of experiments searching for (or measuring) charged lepton flavor violations in a number of channels was necessary to probe the physics. We discuss each experiment in turn, together with relevant talks on both the technology and beam requirements.

1.2.1 Muon-to-Electron Conversion and $\mu^- N \rightarrow e^+ N$

A next-generation muon-to-electron conversion experiment (the neutrinoless process $\mu^- N \rightarrow e^- N$) is required regardless of the results of the Booster-era Mu2e experiment. One can imagine two possibilities:

1. Mu2e sees a signal. In this case, as shown in Sec. 1.1 it will be necessary to change the Z of the capturing nucleus to differentiate among models. The primary experimental difficulty is then beam-related: the lifetime of the muonic atom decreases with increasing Z, and the separation between beam pulses has to be large on the time scale of the muonic lifetime because of backgrounds from radiative pion capture.[2] The Booster-era Mu2e will use Al; the lifetime in aluminum is 864 nsec and the beam spacing is given by the existing complex at 1.7 μsec. The pulse width is approximately 200 nsec. In a promising high-Z material such as gold ($Z = 79$) the lifetime is only about 73 nsec. Making proton pulses and muon beams with the required beam structure would be possible with the Project X CW linac.[9]

2. Mu2e does not see a signal. In this case setting a better limit will require a concomitant increase in statistics, but there are experimental problems that must be addressed. At this conference we noted a requirement on the absolute calibration of the magnetic field and tracking system of order 10 ppm or less.[2]. One talk presented a design for a small electron accelerator that could conceivably meet the needs of such an experiment.[10] It was clear that development of this concept is imperative.

It is not clear how much of Mu2e can be re-used to save money and time. The design of Mu2e has been optimized for an 8 GeV kinetic energy proton beam; it is not clear at this time if the 1 GeV kinetic energy protons of Project X Phase I can be used without rebuilding the Mu2e apparatus. Nonetheless, there was general agreement that a 3–4 GeV kinetic energy beam was optimum primarily because such protons are below threshold for the production of antiprotons; antiprotons can yield background and the Mu2e design at 8 GeV takes care and a significant loss in rate to keep that background at acceptable levels. Since later stages of Project X will use a 3 GeV proton beam, the participants found that an excellent match. Calorimeters for muon-electron conversion were discussed in a joint session with the Calorimetry group.[11]

The design of Mu2e is based on the MELC concept of Vladimir Lobashev.[12] It is likely that design will need to be substantially changed for a Project X experiment. Here, advanced concepts in muon cooling are likely required and those techniques share considerable overlap with the technologies for neutrino factories and muon colliders. Several talks addressed those topics.[13, 14]

The transition $\mu^- N(A, Z) \rightarrow e^+ N'(A, Z - 2)$ was discussed as well. It is particularly sensitive to leptoquarks and comes "for free" with a muon-electron conversion experiment. Since the nucleus changes state, this process presents two difficulties: (1) it does not have the coherent enhancement with Z of muon-to-electron conversion, and (2) the final state nucleus is a combination of a ground and excited states, making calculations difficult. The ability to determine the relative frequency of ground and excited-state transitions, along with a calculation of the *incoherent* contribution to muon-to-electron conversion, were covered as well in both talks and plans for future work.[15]

1.2.2 $\mu^+ \to e^+\gamma$ and $\mu^+ \to e^+e^-e^-$

The MEG experiment sets the current state of the art in $\mu \to e\gamma$ at $\mathcal{B} < 2.4 \times 10^{-12}$.[16] The limitations of that experiment were discussed in a joint session with the Calorimetry group.[17] MEG is writing a proposal to PSI to reach beyond the current design to as low as $\mathcal{B}(5 \times 10^{-14})$.[18] The discussion at this Study centered on whether to convert the photon and track an electron and the resultant electron-positron pair or whether to continue to use calorimetric methods. One tradeoff is obviously the better resolution of tracking vs. the loss in rate from the conversion (assuming a thin enough converter to avoid spoiling the experiment with poor resolution from energy loss). If the experiment requires a converter with $\approx .01X_o$ in order to achieve the desired resolution, it may be better to forgo a converter and use internal conversions, $\mu^+ \to e^+e^+e^-$ instead (which will of course require separation from $\mu \to 3e$). However, many other technical problems come into play and designing an experiment that takes advantage of Project X muon beams will require considerable study. One informal conclusion was that it would be highly advantageous for FNAL to collaborate with the MEG collaboration on their PSI upgrades to gain first-hand experience in the measurement.

The decay $\mu^+ \to e^+e^+e^-$ is ripe for improvement and the measurement is not too dissimilar to the $\mu^{\to}e\gamma$ search, especially in the case of a converted-photon design. A pre-conceptual design was presented and the current LOI at PSI were discussed.[19]

1.3 Other Physics: $g-2$, the Proton Charge Radius, and the Muon EDM

If $g-2$ measurements continue to use the "magic momentum" technique at $p_\mu = 3.09$ GeV/c, then improvements in $g - 2$ measurements require waiting until past Phase I of Project X. "Frozen-spin", an alternative method, was discussed in a joint session with the Lattice QCD group.[20] In any case, running negative muons would be a priority for some combination of systematics (and CPT-violation) checks. Unfortunately, the production cross section from 8 GeV protons is 4.5 times lower in μ^- than from the $pN \to \pi^+ \to \mu^+$ chain.

Despite the current emphasis on neutron and atomic electric dipole moments, there is considerable room for advances in the muon EDM measurement and potential improvements to 10^{-21} e-cm were deemed worthy of study. We refer the reader to the EDM group writeup for details.

Finally, there is a perplexing and potentially revolutionary problem in the measurement of the proton charge radius.[21] There exists a 5σ discrepancy between muon and electron measurements that could be addressed with intense muon beams from Project X in both HFS and scattering experiments.

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