Muon Physics

Summary: We discuss a new extensive study of $\mu-e$ conversion at Project-X that will use multi MW of beam at 3 GeV to achieve a single event sensitivity of a few times 10^{-19}, two orders of magnitude beyond the current proposals and 10^{6} beyond the existing experiments. Generating the required muon beam will be challenging, so we will discuss two approaches. The first is based on a muon storage ring based on a fixed field alternating synchrotron (FFAG). The alternative proposal utilizes an ionization cooling channel incorporating ideas similar to those proposed for muon colliders and/or neutrino factories. These two approaches have very different requirements in terms of the primary proton beam. The detector section would be based on an innovative design, consisting of an electron transport with curved solenoids followed by detectors such as electron tracking chambers and calorimeters in a straight solenoid. Because of the huge proposed increase in sensitivity, it is clear that the experimental design will evolve, and the ultimate configuration might change significantly based on lessons learned from the intermediate $\mu-e$ conversion experiments (Mu2e and/or COMET).

1. Introduction

Muon Charged Lepton Flavor Violation: The muon, along with the muon neutrino, belongs to one of three flavors of leptons, the other flavors being the electron, tauon, and their respective neutrinos. In (almost) all interactions, the number of leptons in a given flavor is conserved. The only known exception is when a neutrino of one flavor oscillates into another flavor, for example a muon neutrino oscillating into an electron neutrino. However lepton flavor violation has never been observed in the decay of a charged lepton such as the muon. The remarkable conservation of lepton flavor, and the violation of it by neutrino oscillations, can be incorporated into the Standard Model, but the source of these lepton flavor properties is not understood. Indeed, since there is no known reason, e.g. a symmetry, which would lead to lepton flavor conservation, most physics models beyond the Standard Model readily permit charged lepton flavor violation (CLFV), and the failure to see any CLFV so far is a strong constraint on these models. Given that lepton flavor properties are central to our understanding of lepton behavior and they are sensitive to new physics contributions, yet little is known about them, there is intense experimental interest in discovering or setting new limits on the occurrence of CLFV, with several high-priority experiments planned or under way.

The most obvious and easily accessible place to look for CLFV is in the interactions of the muon. It may be possible to observe electron to muon or tauon conversion, with no accompanying neutrinos, at proposed electron-hadron facilities, however it appears difficult to compete in sensitivity with proposed experiments using muons in the initial state. There are plans to observe CLFV in tau decays at the upcoming tau factories. In a few new physics scenarios, the signal could be seen in tau decays and not seen in muon decays, and these will be important complementary measurements to CLFV in muons. However the branching ratio limits will necessarily be many orders of magnitude less than for muons because the tau fluxes will be many orders of magnitude smaller than for muons.

Currently, the CLFV reaction $\mu \rightarrow e\gamma$ is being studied by the MEG experiment using a muon source at the Paul Scherrer Insitut (PSI) in Switzerland. The previous best limit on the branching ratio is 1.2×10^{-11}. Recently, MEG has announced a preliminary new limit of 1.5×10^{-11} (90% C.L.), and expects to arrive at a goal of a few times 10^{-13} in 3 years of data collection. The ultimate limit of 10^{-13} to 10^{-14} is set by the maximum data rate, which is dictated by the need to resolve the time coincidence of the electron and gamma. A related and complementary CLFV reaction, $\mu \rightarrow eee$, has an experimentally determined branching ratio limit of 1×10^{-12}. Like $\mu \rightarrow e\gamma$, the measurement would require coincidences and backgrounds would be high, limiting the maximum beam intensity and ultimately the sensitivity. There are no current plans to improve on this limit. $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$ experiments might benefit from an intense source of muons from Project-X. A polarized DC muon beam may be helpful in eliminating some background events, but again the maximum muon rates will be limited by accidentals in the coincidences.

The conversion of a muon into an electron, with no accompanying neutrinos, is another example of CLFV. The reaction would have to occur in close proximity to another mass in order to conserve momentum and energy. The experimental approach is to form a muonic atom, in which the muon is bound by the Coulomb force in the ground state of atomic orbits around the target nucleus. It is then energetically possible for the muon to convert into an electron with no neutrinos, $\mu^- + N(A,Z) \rightarrow e^- + N(A,Z)$. The electron is mono-energetic, and has energy well above the majority of background sources. A Project-X version of this experiment, discussed later in this note, could improve on the limits of these two experiments by another 2 orders of magnitude.

Muon Electric Dipole Moment: Many experiments are under way or are being developed to search for electric dipole moments (EDM) of elementary particles. The measurement of a permanent electric dipole moment in an elementary particle would be a violation of T and P symmetries, and under the assumption CPT invariance, would indicate CP violation. It is believed that new sources of CP violation need to be found to help explain baryogenesis. The most accessible EDM for a particle outside the first generation of particles is the muon. The existing limit on the muon EDM is 1.8×10^{-19} e-cm, which is far larger than, for example, the limit on the electron EDM (1.5×10^{-27} e-cm). There have been proposals in the past to measure the muon EDM by storing low energy muon beams in storage rings. The most optimistic sensitivity goal using existing muon facilities is about 10^{-24} e-cm, which is largely limited by the available flux of muons. A pulsed intense muon beam from Project-X (period ~10 times the muon lifetime) could provide a measurement to 10^{-25} e-cm or better. If the EDM follows a 'natural' scaling proportional to the lepton mass, then a 10^{-25} measurement would be comparable to the electron. The 'natural' scaling basically assumes that the muon is a heavy version of the electron and therefore the same physics contributes to both EDM's. As higher energy scales are probed with smaller limit on the EDM, this is not necessarily the case, and a 10^{-25} e-cm limit for the muon may probe physics not accessible to the electron EDM measurement.

Muon Lifetime: A recent experiment (MuLan) is measuring the muon lifetime at PSI with a goal of about 1 ppm uncertainty. Such a measurement will give the best value on the Fermi constant, G_F, one of the important input parameters to the Standard Model. The experiment is best done with a pulsed muon beam, and could be done with much higher statistics and therefore better precision at Project-X. Ideally the pulse period would be about 10 muon lifetimes, or about 20 μ seconds.

Muonium: A conversion of muonium to anti-muonium in vacuum is a class of CLFV process with $\Delta L = 2$. This search would need a pulsed muon beam, and the measurements would be made at a delayed time to remove backgrounds. High precision studies of QED can be extended by Lamb-shift type experiments on muonium, which is a neutral 'atom' formed by a positive muon and an electron. The advantage of muonium over the hydrogen atom is the absence of strong interaction corrections. New methods of producing muonium atoms more efficiently are being developed, and a high flux pulsed muon beam from Project-X could produce an intense source of muonium.

Flagship Experiment of Muon Physics at Project-X: The flagship experiment for the muon physics program at Project-X would be an extensive study of $\mu - e$ conversion, as a follow-on to the approved Mu2e experiment that will use beam from the Fermilab Booster. $\mu - e$ conversion has several advantages over many other processes that could manifest CLFV. The first is that the search for $\mu - e$ conversion is not limited by accidental backgrounds even at Project-X, and therefore the unprecedented intensity of a muon beam available at Project-X can be fully utilized. Other processes such as $\mu \to e\gamma$ and $\mu \to eee$ are limited by accidental backgrounds and could not fully benefit from Project-X. As an example, the sensitivity on the branching ratio of $\mu \to e\gamma$ expected by the MEG experiment at PSI is about $2\mathrm{x}10^{-13}$, whereas the anticipated sensitivity of $\mu - e$ conversion at Project-X could be better than several x 10^{-19}. The second is that $\mu - e$ conversion is sensitive to new physics of four-fermion interactions, in addition to that of the dipole photonic interaction, whereas $\mu \to e\gamma$ is only sensitive to the latter interaction. Therefore $\mu - e$ conversion would be sensitive to more sources of new physics than $\mu \to e\gamma$.

The present experimental upper limit of B($\mu^- + N \to e^- + N$)<$7\mathrm{x}10^{-13}$ was set by the SINDRUM-II experiment at PSI. At the present, two experiments, the aforementioned Mu2e experiment at Fermi National Laboratory and the other in Japan (COMET), are being prepared, aiming at a single event sensitivity of $2\mathrm{x}10^{-17}$, an improvement of a factor of 10,000 over the current limit. Both of them would employ several methods to reduce backgrounds and improve the signal sensitivity, which were not adopted in the SINDRUM-II experiment. Those new methods are:

- **Beam pulsing**: Since a muonic atom has lifetimes of the order of μsec, a pulsed beam with a width that is short compared with these lifetimes would allow one to remove prompt background events by performing measurements in a delayed time window. To eliminate prompt beam-related backgrounds, proton beam extinction is required during the measurement interval. PSI does not have a pulsed beam and therefore had to employ less effective techniques to remove these backgrounds.

- **High Field Solenoids for Pion Capture:** Superconducting solenoid magnets of a high magnetic field surround a proton target will capture pions in a large solid angle. It leads a dramatic increase of muon yields by several orders of magnitude.
- **Curved Solenoids for Muon Transport**: The solenoid system for muon transport has high transmission efficiency, resulting in a significant increase of muon flux. The curved solenoids select charges and momenta of muons. With appropriate placement of collimators, either muon charge can be selected and limits can be set on the momentum range.

Innovative considerations and approaches on the background reduction, in addition to a higher muon beam intensity, are required to take advantage of the proposed multi MW of beam power from the Project-X linac. Some of these requirements are:

1. **No pion contamination in the muon beam:**
   One of the most critical background sources is pions in a beam. In particular, radiative pion capture by a nucleus followed by photon conversion would cause serious backgrounds. A long muon beam line where all the pions decay away in their long flight is the easiest and cleanest way to reduce this background. Placing materials in a beam line for pion reduction (as, for example, was done in the PSI SINDRUM experiment) could produce backgrounds due to pion interactions with the materials. Another possibility, on the other hand, would be an ionization cooling channel with parameters set to transmit muons could be designed to discriminate strongly against particles of different masses and therefore different velocities and different values of dE/dx at any given momentum.
2. **Tight beam momentum cutoff before a muon-stopping target**
   A very tight momentum selection of muons just before a muon-stopping target is critically important, especially the elimination of high momentum muons. As an example, if the target nucleus in $\mu^- + N \to e^- + N$ is aluminum, the conversion electron has momentum 104.96 MeV/c. A freely decaying muon in flight with momentum > 76 MeV/c can produce an electron at the conversion energy. We will certainly wish to study different Z materials since they could help differentiate among models purporting to explain an observation, which have lower conversion electron energies than aluminum an therefore are susceptible to background decay electrons from muons even lower than 76 MeV/c. We must be able to cut these muons away; further, we could completely eliminate any other electrons in the conversion region coming from the upstream portion of the muon beam line. Additionally, the number of muons that are not stopped in a muon-stopping target should be significantly reduced so that the penetrating muons could not produce any backgrounds and also could not increase the singles rates seen in the detectors. A momentum cut of 40 MeV/c ±3% (or 1.2 MeV) might be needed.
3. **Extra beam extinction for muons**
   In accordance with the aimed sensitivity, the beam extinction between proton beam pulses should be improved correspondingly to reduce beam-related backgrounds during

the measurement time. It might be easier to improve the extinction for low-energy muons. Ionization cooling can also discriminate strongly against particles of different masses. An extra beam extinction of a factor of about 100 or more might be needed, assuming the proton beam extinction required in Mu2e or COMET of 10^{-9} can be achieved.

4. **Increase of the number of muons in the given momentum width**
   To improve the signal acceptance to a sensitivity level of 10^{-19}, the resolution of electron momentum detection should be improved. Therefore the use of a thin muon stopping target would be necessary to reduce smearing of the signal from the stochastic energy loss in the muon stopping target. The signal-to-background ratio improves dramatically as these stochastic sources are lessened. Next, it would eliminate electrons with 100 MeV/c, which would otherwise mimic signals. Finally, we wish to reduce the number of muons not being stopped in the muon-stopping target so that the penetrating muon-stopping target will not produce backgrounds that have to be removed. All these can be accomplished with a narrow muon momentum distribution.
5. **Reduction of charged and neutral background events in the detector**
   At the very high muon-stopping rate expected at Project-X, the instantaneous hit rates at the detector should be reduced so that any false event tracking at the tracking device and pile-up events at the electron calorimeter could be avoided. In particular, any background sources associated with the muons stopped, such as low-energy electrons from decays of muons bound in atomic orbit (a muonic atom), or protons, neutrons and photons emitted from nuclear muon capture, are present at the target position and should be eliminated and prevented from arriving at the detector region. These considerations favor designs that provide high duty factors.

To meet these requirements mentioned above, we consider two potential experimental approaches to delivering the required muon beam:

- **A muon storage ring**: This configuration uses an FFAG as a muon storage ring, as proposed for the PRISM/PRIME experiment at J-PARC. This muon storage ring would provide a long flight length beam to reduce pions in a muon beam (requirement 1). The RF system installed in the muon storage ring can be used to accelerate slow muons and decelerate fast muons to provide an increase of muons in the given momentum width (requirement 4). This technique is referred to as "phase rotation" in accelerator terminology. The fast kicker magnets at the injection/extraction would serve as devices for extra muon extinction (requirement 3) and muon momentum selection (requirement 2).
- **Cooled (RF and ionization, CRFI) beam**: In this approach we will take advantage of recent conceptual developments in the areas of pion/muon collection channels and ionization cooling of muon beams. We imagine a pion collection system analogous to that of a muon collider, but significantly less complex. It would start with a target station capable of handling the 1 MW of beam power, followed by a solenoidal transport and ionization cooling channel. This channel could simultaneously be used to narrow the momentum spread and reduce the average momentum, allowing the experiment to exploit the higher momentum pions, which

have a much higher production cross section. Like the FFAG, the channel would include a phase rotation section based on high frequency RF.

Each of these approaches has significant challenges, and they have very different requirements in terms of the primary proton beam. The detector itself is conceptually identical in the two cases, although the instantaneous rates will be quite different. It turns out that the detector rate, however, would not be problematic with the proposed detector, as discussed later.

2. Beam Line and Beam Structure Needed

The detailed beam requirements are quite different in the two scenarios.

Muon Storage Ring Option

In the case of the muon-storage-ring proposal, the muon beam should be pulsed and accordingly the proton beam should be pulsed too. The timing width of the proton beam is determined by the performance required for phase rotation. If one aims for a final momentum width of 3% starting with about about 30%, using the phase rotation method, a time width of a beam pulse should be about 10 nsec. It is desirable to have higher beam repetition, but at this moment, a repetition rate as fast as 1 kHz is the maximum which is technically feasible now. This is determined by the technology of injection and extraction kickers to not more than 1 kHz, but as shown later, it would not cause any serious problems on the detector rates.

As the requirements, a proton beam should be bunched with pulse width of about 10 nsec and repetition of 1 kHz. Making such a beam time structure would require high-performance MW-class 3-GeV accumulation/buncher rings for the protons. Such a ring would also need corresponding extraction kickers as well as a challenging charge-stripping injection system. One possible scenario is to have an accumulator ring with quasi-continuous stripping injection from the CW proton linac, with a gap in the incoming proton beam for the extraction kicker of about 100 nsec. The accumulator ring would be isochronous or close to isochronous with some RF for keeping a proton beam bunched. A separate compressor ring, which would do phase rotation with RF, might be needed. It can operate above its transition or with imaginary gamma transition. The proton beam in this ring can be accelerated to higher energy to increase beam power. The both rings can be placed in the same tunnel. These accelerator ring complex might serve later to a proton beam for the muon colliders or neutrino factories. Thereby, the development of such rings would be synergistic with the proton driver needs for and may also be synergistic with neutrino factory and muon collider R&D.

CRFT (Ionization Cooling Channel) Option

In the case of CRFI proposal, the required proton bunches could be produced directly by the linac. The H- ions could be used directly on the production target, with no stripping required. A baseline Project-X proton beam would have short proton bunches at 325 MHz (~50 ps long bunches spaced at 3.1 ns.) At 10 mA total current each bunch would have $\sim 2\times 10^{8}$ protons. To study muons captured on Aluminum (τ~900ns), a 500 kHz, 1MW beam to the experiment could be created by sending 22 bunches every 2 μs, for a total of $\sim 4\text{x}10^{9}$ protons on target in a 68 ns FW bunch, satisfying all of the requirements outlined in the introduction. A follow-up experiment may explore $\mu - e$ conversion in a high-Z atom, such as Au, where the lifetime would be ~80ns. In this case, the spacing between the bunch trains could be reduced by up to a factor of 3.

3. Beam line to Detector

We will now discuss in some detail the two-muon delivery schemes presented in the introduction.

Muon Storage Ring Option

A proton beam strikes a target to produce pions. The pions are captured by a solenoid magnetic field of such as 16 Tesla produced by superconducting solenoid magnets. The pion capture by a high magnetic field is critical to increase the phase space density of a muon beam. The muons from pion decays in flight will be collected and transported through a combination of curved and straight solenoid magnets. The section of the muon transport is not necessarily long once a muon storage ring is included in the muon beamline.

This configuration uses a muon storage ring, as proposed for the PRISM/PRIME experiment at J-PARC. The central momentum of the muon storage ring is about 40 MeV/c. The requirements for a muon storage ring are that (1) it should have a large beam acceptance, and (2) quick acceleration (or deceleration) can be possible. One of the candidates of the muon storage ring is a FFAG synchrotron with straight section inserted.

This muon storage ring would provide a long flight length to reduce pion contaminations in the muon beam (requirement 1). The circumference of the muon storage ring could be about 50 meters. With 5-6 turns, a total flight length would be about 300 meter long. Then a pion survival rate would be about less than 10^{-20} for pions with momentum of 40 MeV/c. Furthermore, by using the RF system installed in the muon storage ring, slow muons are accelerated and fast muons are decelerated so that the net momentum width of a muon beam gets narrower (requirement 4). It is called "phase rotation" in accelerator terminology. After phase rotation, the momentum width could be $\pm 3\%$. The fast kicker magnets at the injection/extraction would serve as devices for extra muon extinction (requirement 3) and the muon momentum selection (requirement 2). This whole concept is called PRISM (Phase Rotated Intense Slow Muon source). The main advantage of the muon storage ring compared to a long solenoid beam line is cost. Another advantage that fewer RF cavities and less RF power are needed. The proposed 1 kHz injection and extraction kickers are beyond the current state of the art and will present a technical challenge. A study of this FFAG storage ring is being undertaken in the framework of the PRISM-FFAG Task Force, formed by the UK and Japanese groups. The status report on the PRISM-FFAG Task Force is attached as a supplement document. A schematic layout of the muon storage ring option is shown in Fig.1.

At the extraction section, there should be a momentum slit to select a narrow momentum range (±3%) of charged particles from the muon storage ring. Since the muon beam extracted from the FFAG muon storage ring has a large momentum dispersion, this momentum slit would be quite useful to eliminate any electrons of 100 MeV/c coming from the upstream of the muon beam line, and also muons which would penetrate the muon-stopping target. The kicker magnet would provide additional beam extinctions of about a factor of 100 for a muon beam of 40 MeV/c in momentum. In addition to the proton beam extinction of 10^{-9}, a total beam extinction of 10^{-11} is conceivable.

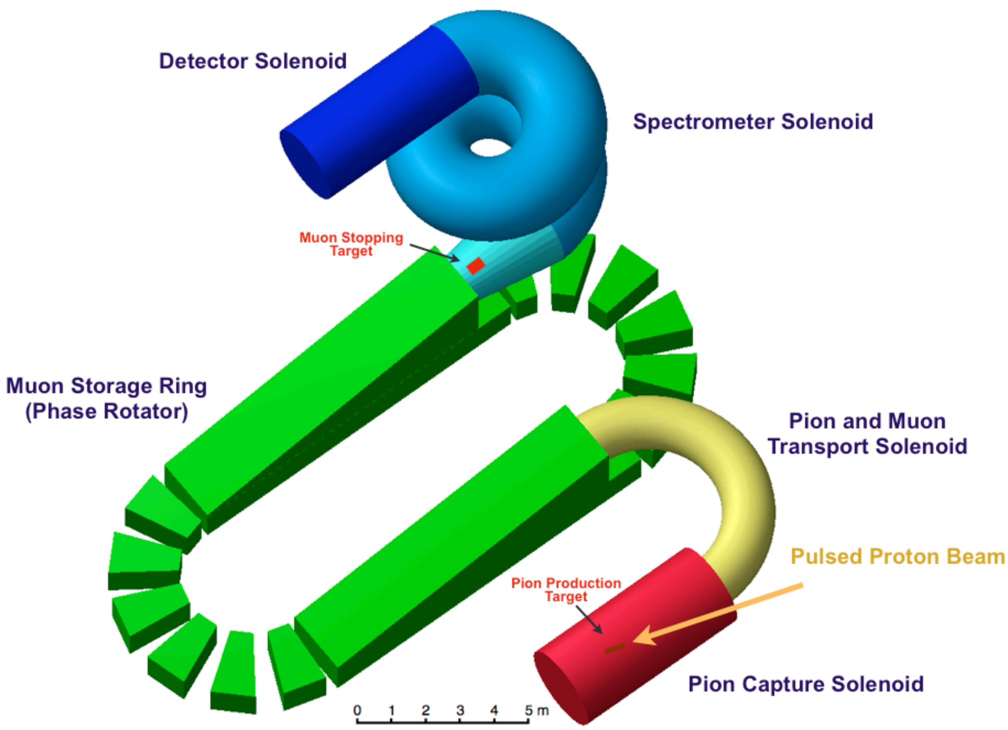

Fig.1 Layout of the muon storage ring proposal (PRISM/FFAG proposal). It consists of the pion capture solenoid section, the pion and muon transport solenoid section, the muon storage ring (PRISM-FFAG phase rotator), the electron spectrometer section, and the detector section.

CRFI- Ionization Cooling Channel

In this approach we will take advantage of recent conceptual developments in the areas of pion/muon collection channels and ionization cooling of muon beams. We imagine a pion collection system analogous to that of a muon collider, but less complex. It would start with a target station capable of handling 1 MW of beam power, The target would consist of a high-Z material in a solenoid whose field tapers from about 10 to 4 Tesla. The pions would be collected in the forward direction, and the tapered field has the effect of folding the production angles forward.

The system developed for a muon collider provides a ratio of about 0.1 useful muons (of each polarity) per incident 8-GeV proton. That is to be compared with a ratio of about 0.0025 for the Mu2e experiment. That difference, a factor of 40, suggests that there is room for improvement in the collection system for a muon-to-electron conversion experiment in the Project-X era. Of course with 3-GeV protons instead of 8 GeV, the ratio will be less, by about a factor of three. But the results per unit beam power should be comparable.

The design concepts described here deviate from the ones developed for a muon collider in some important respects. The systems would be CW instead of pulsed, the experiment needs only negative muons, and the proton bunches would be considerably shorter. That latter feature suggests capturing the produced pions in RF buckets operating at a high frequency synchronous with that of the proton beam. The resulting decay muons would mostly remain in the same buckets for subsequent processing. That obviates the need for a long muon capture section. So the proposed channel would consist of:

1) The target solenoid for pion collection;
2) a decay volume, about 30 meters long, including rf cavities running at a frequency synchronous with the linac frequency (e.g. 325 MHz) to hold the pions in rf buckets until they decay;
3) a system of rf cavities at a lower frequency (e.g 162.5 MHz) to bunch-rotate the muons in longitudinal phase space to reduce their momentum spread;
4) a transverse cooling system for the decay muons, followed by a matching section to…
5) a six-D cooling section, followed by a matching section to…
6) a transport system that uses rf cavities to decelerate the bunches to the stopping target.

The system must include collimation schemes to restrict transmission to the μ-conversion target and detector to the desired band of muon momenta, and eliminate spurious sources of 100MeV decay electrons.

The optimistic expectation is that such a channel would provide the following advantages relative to the Mu2e experiment:

- a better muon-to-proton ratio than the Mu2e system would obtain at the same proton energy;

- much smaller momentum spread for the muons headed for the stopping target, allowing the use of much thinner stopping foils;
- a much tighter time distribution of the stopping muons, allowing the use of higher-Z stopping targets;
- very good hadron (especially pion) rejection, greatly reducing the flash that occurs when the muons stop.

Obviously, simulations are necessary to verify these expectations. Concomitant design work may result in significant changes from these initial concepts

The proton beam energy of 3 GeV or higher provided by Project-X is easily sufficiently high enough to produce negative pions and muons. Since the cross section of pion production is roughly proportional to proton beam energy, the pion yield is almost proportional to the total proton beam power.

4. Detector

One candidate detector for the both options is a COMET-like detector, which consists of the electron transport with curved solenoids and the detector region with a straight solenoid following the electron transport. This electron transport would reduce neutral particles and charged particles of low energy coming into the detector region (requirement 5). The detector is called PRIME (PRIsm's Muon to Electron conversion detector). The principle of background reduction is as follows. In a curved solenoidal magnetic field, a center of the helical trajectory of a charged particle is shifted perpendicular to the curved plane. The shift, whose amount and direction are given as a function of momentum and its charge respectively, makes a dispersive beam. The shift is also proportional to a total bending angle. With an appropriate vertical compensation magnetic field perpendicular to the bending plane, charged particles of interest can stay in the mid-plane and can go through the spectrometer to the detectors, while unnecessary particles would hit collimators. The PRIME detector with more than 360 degree turn would have better momentum selection than the original 180 degree turn concept in the COMET detector, owing to its large bending angle. And, more importantly, a large bending angle would eliminate secondary (and tertiary) particles produced by the primary background particles hitting the collimator. Without this curved spectrometer, the detector rate cannot be at a manageable level.

4.1 Muon Stopping Target

The stopping target itself must be thinner than the Mu2e/COMET design. Currently conversion electrons lose approximately 250 keV from energy loss passing through the target. We would also like to demand that the reconstructed track pass through the stopping target at a well-defined position along the solenoid axis. This is impossible with the current stopping target designs and rates at either the FNAL Booster or J-PARC. If we make the stopping target thinner, we lose rate unless we also reduce the momentum spread of the muon beam: therefore the muons must be phase-rotated or cooled so that they will stop in as short a distance as possible. In the case that we are improving on a limit, making the target thinner will also help separate conversion electrons from the tail of the decay-in-orbit background; with the current target thickness we could not achieve a single-event sensitivity that takes advantage of Project-X statistics. At Project-X, the net thickness of the muon-stopping target could be about 1/10 of the ones considered in Mu2e and COMET.

4.2 Detector Resolution

Using the statistical power available at Project-X for a $\mu - e$ conversion experiment is a formidable challenge. We perform an illustrative calculation as follows. This discussion focuses on the challenges arising from many stopping muons in the same running time as Mu2e or COMET: what rates must a detector withstand? What resolution is required? The answers also depend on whether we are attempting to set a limit or study a signal. If we are attempting to improve on a limit resolution is far more important than if we have a substantial signal and are examining different Z targets in order to distinguish among models.

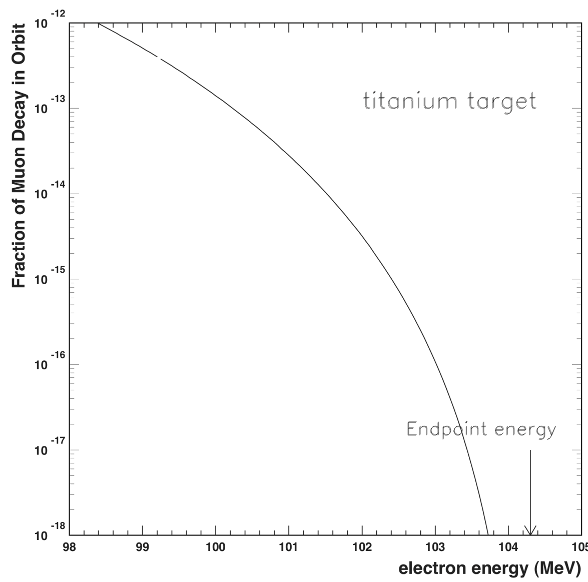

Fig.2 Background spectrum from muon decays in orbit as a function of electron energy.

What might the detector itself look like? The tracker resolution of approximately 150 keV (0.15%) in the current generation will likely suffice at 10^{-18}, as shown in Fig. 2. The calorimeter to measure an electron energy, but at this low energy, neither the energy nor the position resolution of a crystal calorimeter can match the tracker; calorimeters simply do not reach the 0.15% level of resolution. However, it would provide redundancy to eliminate false signals in comparison with the tracking information. We also speculate a silicon system that provides position resolution, along with a system to provide timing and particle ID, will be necessary and it may be that a complementary calorimetric energy measurement will have to be sacrificed.

4.3 Detector Rate

In the case of muon storage ring option, the detector rate is estimated as follows. Assuming a factor of 20 increase in a muon beam intensity (see section 5), and the fact that the muon storage ring can operate at 1 kHz, one can easily calculate that the rate of stopped muons at Project-X is ~2x10^9 muons/pulse, compared to Mu2e's ~10^5 muons/pulse. Each stopped muon produces approximately two neutrons, 0.1 protons, and two photons. Most of all these background particles with their low momentum could be removed by the curved electron transport, and the remaining particles passing through the electron transport are the electrons from muon decay in orbit (DIO), whose momentum are more than the momentum threshold set at the electron transport. The rate of these DIO electrons, for instance with more than 80 MeV/c, is estimated to be about 10^{-8} /stopped-muon for aluminum. Therefore, in this case, an expected number of tracks at the detector would be about 20/pulse. It would not be a problem.

The ionization cooling channel option could potentially have a somewhat higher yield of muons per proton. But, the instantaneous rate would be about a factor of 500 lower. The momentum spread and collimation needs are still under study.

5. Physics Opportunities

At Project-X, an experiment to search for $\mu - e$ conversion in a muonic atom at a single event sensitivity of a few x 10^{-19} could be envisaged. It is a factor of 100 better than the next generation experiments such as Mu2e and COMET.

One of the physics motivations for a search for charged lepton flavor violation is to study physics at very high-energy scales which accelerators cannot reach directly, such as the GUT energy scale. Fig. 3 shows the prediction of the constrained SUSY-GUT prediction for $\mu - e$ conversion on Ti as a function of $M_{1/2}$ with all the SUSY parameters accessible by the LHC. The green points are for the PMNS type mixing, and the red points are for the CKM type mixing for sleptons. From these, it is evident that the search with sensitivity of 10^{-18} would cover all the SUSY parameters by the LHC, and would make discoveries for the scenarios of SUSY-GUT and/or SUSY-seesaw models, after SUSY is found by the LHC.

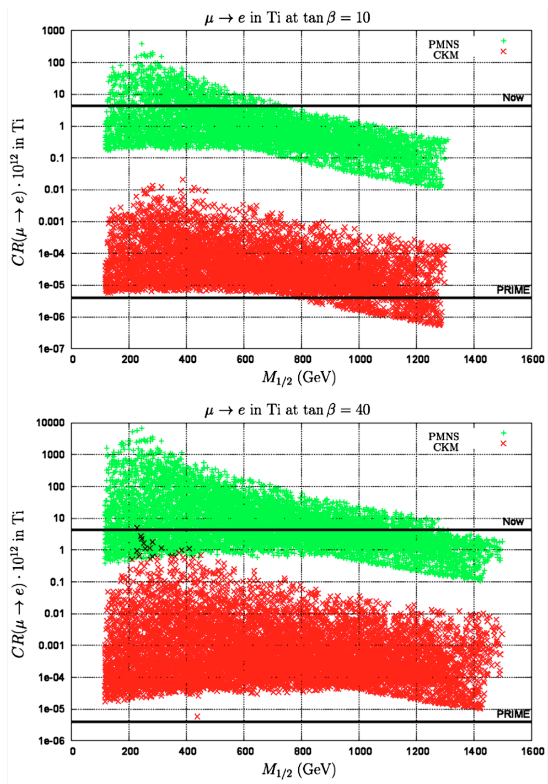

Fig.3 $\mu - e$ conversion in Ti as a probe of SUSY-GUT scenarios. The plots are obtained by scanning the LHC accessible parameter space. The horizontal lines are the present (SINDRUM II) bound and the planned (PRISM /PRIME) sensitivity to the process. We see that PRIME would be able to severely constrain the low tan β, low mixing angles case and to completely test the other scenarios. The green points are for the PMNS type (optimistic case) and the red points are for the CKM type (pessimistic case). From [1]

It is also important to know which types of the interaction are responsible for CLFV. To study this, one method is to change the material of the muon-stopping target. Fig.4 shows the rates for different effective interactions, normalized at Z=13 (aluminum). Comparing light nuclei and heavy nuclei could distinguish among potential sources of CLFV. However, it is known that a lifetime of a muonic atom becomes shorter as the atomic number increases, from 864 nsec in Al to 79 nsec in Au. In the next-generation experiments like Mu2e and COMET, to remove the prompt beam-related backgrounds, in particular from pions, the time window of measurements starts about 700 nsec after the beam prompt. Therefore, the choice of target materials is currently constrained to light materials. To have a heavy material with a large atomic number, a pion-free beam is needed. And that can be done only at Project-X.

5.1 Sensitivity and Backgrounds

Muon Storage Ring Option

In the case of the muon storage ring proposal, an improvement factor of the signal sensitivity of 100 would come from an increase of the number of muons stopped in the muon-stopping target of a factor of 20, and that of the signal acceptance of more than 5. The latter factor is attributed to the wider time window of measurements (from time zero) and the better momentum acceptance of the measurement, etc. as shown in Table 1.

Table 1. Expected improvement factors for the signal acceptance

Item	Improvement factor	Comments
Measurement time window	X 2.5 (for Al)	No pions in a beam
No muon beam stop	X 1.7	Narrow beam energy width
Measurement momentum window	X1.3	Thinner target thickness
Total	X 5.6	

Table 2 shows a preliminary estimation of a net background event rate, which is about less than 0.1 at a sensitivity of better than 10^{-18}, although detailed simulation are needed.

Table 2. preliminary estimation of background events at a sensitivity of 10^{-18}

Item	rate	Comments
Muon decay in orbit	0.05	350 keV (FWHM) resolution
Radiative muon capture	0.01	
Pion related backgrounds	~0	No pions
Muon decay in flight	~0	Momentum cut at extraction
Cosmic rays	0.002	
Total	0.06	

Conclusion

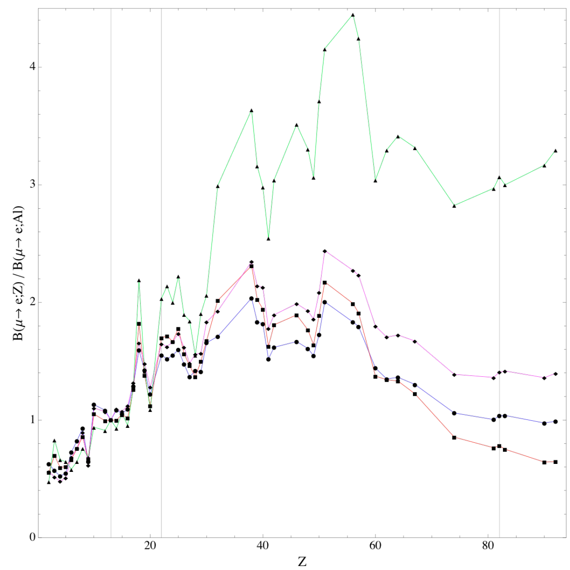

Fig.4 The rate of $\mu - e$ conversion as a function of atomic number for different types of interaction. The rate is normalized to unity for aluminum (Z=13). [2]

In summary, searches for CLFV and precision studies of muon properties are of fundamental importance for advancing the understanding of fundamental questions of 21st century particle physics. They will play a key role in revealing the source of neutrino masses (seesaw mechanism) and other related phenomena, including leptogenesis. They are complementary to direct searches at the energy frontier and to precision measurements in the quark sector. In the event that new particles are all very heavy and beyond the reach of the LHC, CLFV searches are among a handful of particle physics means available to explore nature at the smallest scales.

A new innovative approach to search for $\mu - e$ conversion which will effectively utilize a high intensity proton source such as the one envisioned at Project-X, aiming at sensitivity of better than 10^{-18}, is proposed. Two very different proposals are being considered to generate the required muon beam. One is based on an FFAG muon storage ring, while the other is based on an ionization cooling channel. In the former, the muon storage ring runs in a pulsed mode, and the proton beam should have appropriate pulsed time structure. Such a source would also be of great use in measurements of, for example, the muon EDM, the muonium properties, and the muon lifetime. On the other hand, the CRFI options use a DC proton beam. They have very different beam requirements, so it will be important to select down to the base line approach as early as possible in the project.

In any case, the muon physics program at Project-X is most exciting and will be robust at the LHC era, and furthermore the developments of a highly intense muon source at low energy would also have technical synergies with the muon collider and neutrino factory.

References:

[1] L. Calibbi, A. Faccia, A. Masiero and S.K. Vempati, “Lepton flavor violation from supersymmetric grand unified theories; Where do we stand for MEG, PRISM/PRIME, and a super flavor factory”, Physical Review D 74, 116002 (2006).

[2] V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. D80:013002, 2009.