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Heavy Quarks and Light Leptons from Muon Storage Rings

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ABSTRACT

This report briefly describes the current and near-term status of neutrino oscillation experiments, identifies the challenges for the longer term future of oscillation measurements, and describes quantitatively how neutrino beams made at a muon storage ring can meet these challenges. In addition, a few non-oscillation measurements will be described to illustrate how this facility can also usher in a new field of precision nucleon structure and heavy quark measurements.

1 Introduction

Muon colliders have been proposed as a possible path to the high energy frontier. However, merely collecting and storing 20 to 50 GeV muon beams in rings is intriguing both for a first step towards a muon collider, and for the resulting neutrino beams. The neutrino fluxes from proposed rings will be higher than ever achieved before, with a flavor composition far superior to that of conventional neutrino beams. This enables one to consider completely new neutrino measurements. In the realm of oscillation physics, distances between production and detection can now span the globe, and one can map out a plan to measure the neutrino oscillation mixing matrix much like physicists now are measuring the CKM quark mixing matrix. In the realm of heavy quark physics, detectors close to the ring itself can be optimized to use the neutrino beam as a charm factory. Also, new neutrino target materials near the ring can provide nuclear structure measurements quark by quark.

2 Evidence for Neutrino Oscillations

More and more precise evidence has been collected in recent years indicating that neutrinos may be oscillating from one flavor to another. If only two generations of neutrinos are mixing, then those oscillations can be parameterized by a 2×2 mixing matrix, or one mixing angle and one mass squared difference $(m_1^2 - m_2^2)$.

SuperKamiokande has seen evidence for $\nu_\mu \to \nu_X$ in the atmospheric neutrino sample, with a mass squared difference around a few $\times 10^{-3} eV^2$. Further investigation of this sample indicates that ν_X is more likely to be ν_τ than a sterile neutrino or ν_e [1]. This anomaly in atmospheric neutrinos has been seen in several experiments in the past few decades [2], [3], [4], [5], with SuperKamiokande having the largest and most precise data set.

There is also evidence from SuperKamiokande and others that solar neutrinos (ν_e) are disappearing between the sun and the earth, and again this can be interpreted as oscillations with a mass squared difference between $10^{-4} eV^2$ and $10^{-10} eV^2$. Since the data do not indicate a final state neutrino, that signal could be electron neutrinos oscillating to muon, tau, or sterile neutrinos. Again the signal of missing solar electron neutrinos has been observed by a number of exprERIMENTS in recent history [6] [1].

Finally, the LSND experiment at Los Alamos has observed a signal consistent with $\bar{\nu}_\mu \to \bar{\nu}_e$, where because it is an appearance experiment, there is no uncertainty in either the initial or final state neutrino flavor [7]. This experiment has not been confirmed, nor has it been ruled out, although the KARMEN experiment (among others) has ruled out some but not all of the possible parameter space [8]. The remaining available mass squared difference for this signal lies between $\approx 5 \times 10^{-2} eV^2$ and $1 eV^2$.

The three different sets of evidence indicate, however, that there are three different mass differences, and so either there is a fourth (sterile) neutrino, or one of the sets of evidence is being incorrectly interpreted as oscillations.

3 Next Generation of Oscillation Experiments

The next generation of experiments is poised to answer at the very least the oscillation hypothesis through novel detectors, beamlines, or both, as well as to define (or set limits on) the role that sterile neutrinos play in the lepton mixing matrix. If these signals are confirmed, there will be substantial improvements on the measurements of the 2-generation mixing parameters themselves.

K2K, MINOS, and the Cern to Gran Sasso program will provide three very different neutrino beams with very different detectors and systematic errors to explore the atmospheric neutrino anomaly. K2K is already running and has reported from 20% of their expected total data set a 2 sigma deviation between the expected and observed number of neutrino events in their far detector, located 295km away from the production site of the neutrino beam [9].

The SNO experiment will be able for the first time to study both neutral and charged current solar neutrino interactions, both testing the oscillation hypothesis and determining if the solar neutrinos are oscillating to active or sterile neutrinos. Kamland, using several reactors located around Japan, will be sensitivite to ν_e disappearance for mass squared differences above $1 \times 10^{-5} eV^2$. If it measures a disappearance it will be the first reactor experiment to do so.

Finally, LSND will be confirmed or refuted by the Mini-BooNe experiment, which uses a completely new neutrino beamline. The ICARUS experiment in the Cern to Gran Sasso program should also have sensitivity to see the LSND neutrino oscillation transition. Although ICARUS is expected to run a few years after Mini-BooNe, it could produce another independent confirmation of that signal.

4 Three Generation Mixing

A more thorough review of neutrino oscillation mixing parameters can be found in these proceedings [10]. In summary, though, if there are three generations of neutrinos then by definition there is a 3×3 mixing matrix analagous to the CKM matrix describing quark mixing in the weak interaction. This matrix must be unitary and relates the mass eigenstates ($\nu_i, i = 1,3$) to the weak eigenstates ($\nu_\ell, \ell = e, \mu, \tau$) in the following way:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

Since $U_{\ell i}$ is unitary it can be described by three mixing angles ($\theta_{12}, \theta_{13}, \theta_{23}$) and a CP-violating phase (δ). A common representation of this matrix is

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \tag{2}$$

where $c_{ij} = \cos\theta_{ij}$, $s_{ij} = \sin\theta_{ij}$.

The oscillation probabilities depend on these mixing angles and on two independent differences of squared masses, $\delta m^2_{32} = m(\nu_3)^2 - m(\nu_2)^2$ and $\delta m^2_{21} = m(\nu_2)^2 - m(\nu_1)^2$.

If the two mass differences are different by more than an order of magnitude, then one mass difference may dominate at a given experiment (L/E) [11]. Making the pessimistic assumption that LSND is not confirmed and the largest mass squared difference corresponds to that indicated by the atmospheric neutrino anomaly, the probabilities for electron and muon oscillations in vacuum are:

$$\begin{aligned} P(\nu_e \to \nu_\mu) &= S^2_{23} \sin^2 2\theta_{13} \sin^2(\delta m^2_{23} L/4E) \\ P(\nu_e \to \nu_\tau) &= C^2_{23} \sin^2 2\theta_{13} \sin^2(\delta m^2_{23} L/4E) \\ P(\nu_\mu \to \nu_\tau) &= \sin^2 2\theta_{23} C^4_{13} \sin^2(\delta m^2_{23} L/4E) \\ P(\nu_\mu \to \nu_\mu) &= 1 - P(\nu_\mu \to \nu_e) - P(\nu_\mu \to \nu_\tau) \end{aligned}$$

Another quantity of interest is the CP-violating difference in oscillation probabilities, $\mid P(\nu_a \to \nu_b) - P(\bar{\nu}_a \to \bar{\nu}_b) \mid$. It can be shown that this difference is the same for all three combinations of neutrinos, and is equal to (in the above representation, where $\delta m_{23} >> \delta m_{12}^2$) [12]

$$
\begin{aligned}
\mid P(\nu_a \rightarrow \nu_b) - P(\bar{\nu}_a \rightarrow \bar{\nu}_b) \mid & \propto \sin 2\theta_{23} \sin 2\theta_{12} \sin 2\theta_{13} \cos\theta_{13} \sin\delta \\
& \times \sin \delta m_{12}^2 L/2E \times \sin^2 \delta m_{23}^2 L/4E
\end{aligned}
$$

Matter effects, caused by $\nu_e/\bar{\nu}_e$-electron scattering during passage through the earth, can change the probabilities for ν_e and $\bar{\nu}_e$ significantly. This additional diagram changes both the effective mixing angle (θ_{13}) and oscillation length. Matter effects introduce a difference between $P(\nu_e \rightarrow \nu_x) \mid_{\mathrm{matter}}$ and $P(\bar{\nu}_e \rightarrow \nu_x) \mid_{\mathrm{matter}}$ in a way that depends on δm_{23}^2 itself, and not $\sin^2(\delta m_{23}^2 L/2E)$. By measuring that probability difference one can then determine if ν_3 is much heavier or much lighter than ν_1 and ν_2.

After the next generation of experiments is completed we will know a great deal more about two of the mixing angles, θ_{23} and θ_{12}, and possibly $\mid \delta m_{23}^2$ and $\mid \delta m_{12}^2$ there will be very little additional knowlege of the angle θ_{13}, matter effects, and the cp-violating phase δ. The current limit on θ_{13} comes from the CHOOZ experiment, and is $\sin^2 2\theta_{13} < 0.10$ [13].

By measuring $\nu_e \leftrightarrow \nu_\mu$ and $\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ transitions we can measure θ_{13} and either the sign of the largest mass splitting (through matter effects), or CP violation, or both, depending on the experiment. The remainder of this report describes a new facility where these measurements could happen, as well as predicted sensitivities to this new physics, and finally, a very brief description of some non-oscillation (i.e. heavy quark!) physics that could be addressed at a muon storage ring.

5 Neutrino Beams from Muon Storage Rings

Traditionally, neutrino beams above a few GeV have been made by taking as many protons as one can find, hitting a target, focusing the resulting pions and kaons to a decay volume pointing toward a far detector. The resulting beam is primarily a ν_μ (or $\bar{\nu}_\mu$) beam with some $\nu_e(\bar{\nu}_e)$ contamination, where the contamination level depends on beamline optics and proton energy, but is typically on the order of a per cent. The neutrino energy spectrum at the far detector depends on such details as the efficiency of the focusing devices and the pion and kaon production spectra for a given target-proton beam combination.

If one were to have instead a muon storage ring with a long straight section pointing toward a far detector, then the resulting neutrino beam would be a roughly equal mixture of $(\bar{\nu}_\mu + \nu_e)$ or $(\nu_\mu + \bar{\nu}_e)$, depending on if there were positive or negatively charged muons in the ring. By simply measuring the muon beam current and the muon energy one would have a precise prediction of the neutrino fluxes at a far detector, which much less uncertainty than what conventional neutrino beams can provide. Furthermore, for muon storage rings above 15GeV and 10^{20} muon decays per year, the neutrino event rates from a muon storage ring are far superior to those of conventional beams. There is already a detailed design report for a facility giving 6×10^{19} muon decays per year [14], and work continues on improving this design.

Although in principle there are six transitions that one can study given a two-flavor initial state beam, this report will focus on the transitions from electron to muon neutrinos. The relevant signal then is a charged current neutrino interaction with a final state muon of opposite charge as that of the muons circulating in the storage ring.

5.1 Long Baselines

Given that one has a very efficient source of neutrinos, whose efficiency scales like the average neutrino energy cubed, one can consider using high energies and going to very long baselines. The advantage from an experimental point of view is that the higher the neutrino energy, the easier it is to detect the final state muon and its charge in a ν_μ or $\bar{\nu}_\mu$ charged current interaction. The theoretical advantages of high baselines are two-fold: for one, matter effects can greatly enhance the signal itself (since the initial state is a ν_e or $\bar{\nu}_e$), so that the effective θ_{13} for either neutrinos or antineutrinos is higher than one would expect from a "short baseline" (700km) experiment [15], and secondly, depending on which probability gets enhanced, neutrinos or antineutrinos, one can measure the sign of the largest mass splitting, and thus determine the mass structure of the neutrino sector.

5.2 Backgrounds to Neutrino Oscillation Searches

Because the neutrino beam produced is purely (ν_μ and $\bar{\nu}_e$) or its cp-congugate, as long as one determines the charge of the final state lepton there is no intrinsic beam-related background to an oscillation search. This is very different from conventional beams, where there is a ν_e component in a mosly ν_μ beam on the order of a per cent. The backgrounds that can arise in neutrino factory searches for "wrong sign muon" events are purely from neutrino interactions themselves. In deep inelastic scattering events (which dominate for neutrinos of energies above 1 GeV) there are typically several secondary particles created, along with the final state (charged or neutral) lepton. There is a non-zero possibility that these secondary particles (pions and kaons, for example) will decay before they interact in the detector, and depending on the charge of secondary that decays, that can give either a right-sign or a wrong-sign muon background. In general, however, the muons that come from these decays are much lower in energy than muons that come from real charged current interactions. Another background comes from charged current charm production, where the primary muon is lost and the charm created in the hadronic shower decays to a muon which is by definition of the opposite charge as the primary muon. Figure 1 shows the fraction of background that persists as a function of the muon momentum cut that is made, for 20 and 50 GeV muon storage rings, for different materials [16]. The probability that a pion or kaon will decay before it interacts depends on the interaction length (which is related to the density) of the target material, and as is shown in 1 the background for a water target is higher than that for a steel/scintillator target, yet for a modest muon momentum cut of 4 GeV in a 20GeV muon storage ring experiment, the background is at the 10^{-4} level. There are other handles on background rejection that can be used, such as the angle between the outgoing muon and the outgoing hadronic shower.

5.3 Neutrino Oscillation Detectors

In a muon storage ring, if one is searching for the transition $\nu_e \to \nu_\mu$ then the experimental signal is simply the presence of a neutrino interaction with a final state muon of opposite charge as that of the muons circulating in the storage ring. Of course the presence of two neutrino flavors of opposite helicity allows for searches of $\nu_{\mu,e} \to \nu_\tau$ as well, but to measure θ_{13}, matter effects, and to search for CP violation it is enough to build massive detectors that do final state muon charge identification.

Three possible kinds of detectors for $\nu_e \to \nu_\mu$ searches at a neutrino factory are considered here: a Liquid Argon TPC such as the ICARUS detector followed by a muon spectrometer, a large water Cerenkov detector such as the

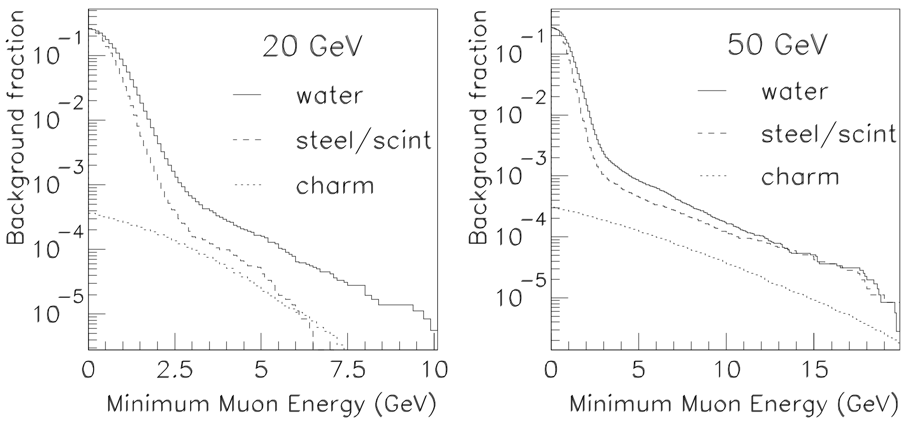

Figure 1: *Background Levels to wrong-sign muon appearance as a function of minimum muon momentum for several different target materials.*

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SuperKamiokande detector, again followed by muon charge identification, and finally a magnetized steel-scintillator sandwhich detector, such as the MINOS detector. They all can do muon charge identification, but they differ in how well they can describe the accompanying hadronic shower in a neutrino deep inelastic scattering interaction, as well as how massive they can ultimately be made. It is hoped that one could make roughly a 10-15 kton fiducial mass Liquid Argon TPC, perhaps a 30-50kton fiducial mass steel scintillator, and there is a proposal for a 450kton fiducial mass water Cerenkov detector, which was initially motivated to extend the search for proton decay [17].

Because the background level is already extremely low above muon momenta of a few GeV, the most important criteria for these detectors are detector mass combined with signal acceptance. These detectors also vary widely in their capabilities for doing complementary measurements, such as ν_τ searches or neutral current analyses. A discussion of what can be gained from these additional analyses for a Liquid Argon TPC detector (the most fine-grained detector listed above, and hence the most sensitive to other channels) can be found in reference [18].

6 Oscillation Physics Potential at Neutrino Factory

The oscillation physics goals considered here are: a measurement of the mixing angle θ_{13}, a determination of the sign of the largest mass splitting, and finally, a search for CP violation. In fact these three steps must be arrived at sequentially–without a measurement of θ_{13} one cannot measure matter effects, and without θ_{13} and matter effects one cannot unambiguously determine CP violation at these energies. The flux of neutrinos that one needs for each of these three measurements is also more and more demanding.

The parameter space for these experiments is large–one can consider going to several different baseline lengths, or using several different muon storage ring energies, and different exposures, which are a product of the detector mass and muon decays per year. For each plot shown in the following sub-sections the choices of baseline length, muon storage ring energy, detector mass, and muon decays per year are specified.

6.1 Reach in θ_{13}

Figure 2 shows the reach in $\sin^2 2\theta_{13}$ as a function of the largest mass splitting (δm^2_{23}) that a 10kton Liquid Argon Calorimeter would have by looking for $\nu_e \to \nu_\mu$ and $\bar{\nu}_e \to \bar{\nu}_\mu$ [18]. Although the coutours shown are for 10kton and 2×10^{20} or 2×10^{21} muon decays, the same contours would be applicable for a 50kton detector and 4×10^{19} or 4×10^{20} muon decays, which would be less than a 2 year run at an entry level neutrino factory. The detector is assumed to sit 7400km from the muon storage ring, to take advantage of matter effects, and it is assumed that the run would be for the same number of muon decays with positive 30GeV muons in the ring, and with negative 30GeV muons in the ring. Note that with just a 2-year run and a 50kton detector, one could improve the θ_{13} reach by about two orders of magnitude beyond what is currently known.

6.2 Matter Effects

Given the fact that the neutrino factories being considered are for 20GeV muons and above, the mean neutrino energies will be above 10GeV. This means that the expected baseline lengths that one would want to use are on the order of several thousand kilometers, which is more than enough to measure matter effects clearly. Below 1000km matter effects change the oscillation probabilities

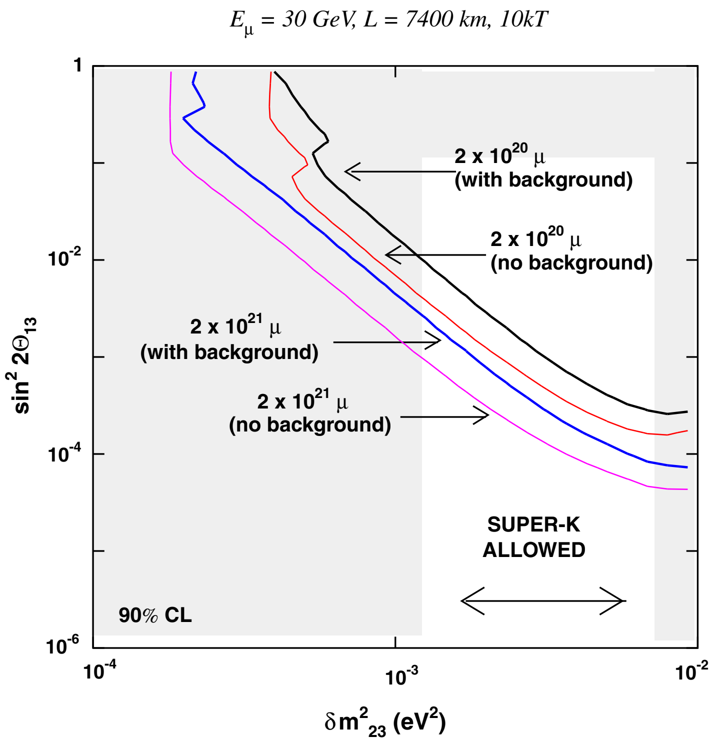

Figure 2: *Reach in the mixing angle θ_{13} as a function of the largest mass squared difference, for the large mixing angle solution for the solar neutrinos, and detector and beamline parameters as described in the text.*

between ν_e and $\bar{\nu}_e$ very little, but at baseines of 2000km and above there are large differences between ν_e and $\bar{\nu}_e$ probabilities [15], so that it will be straightforward to see 3σ differences between the two probabilities. In reference [19] it is shown that for baselines of 2500km and above, for a 20GeV muon storage ring and a 50kton detector, one can make a 3σ determination of the sign of δm^2_{23} if one collects 10^{20} μ^+ and μ^- decays and $\sin^2 2\theta_{13}$ is above 10^{-3}, or if one collects 10^{19} μ^+ and μ^- decays and $\sin^2 2\theta_{13}$ is above 10^{-2}. Recall the current limit on $\sin^2 2\theta_{13}$ comes from the CHOOZ experiment and is $\sin^2 2\theta_{13} < 0.10$ [13].

6.3 CP-violation

As was stated above, the size of CP violation that one would expect in neutrino oscillations depends on all of the mixing angles in the matrix, as well as both of

Table 1: Event rates on 40cm radius targets for a neutrino factory which comes from 10^{20} 50GeV muon decays per year.

Target	Thickness (cm)	events
Liquid H_2	100	12.1M
Liquid D_2	100	29.0M
Solid HD	50	9.3M
C	5.3	20.7M
Fe	2.3	31.6M

the mass squared differences. So if the two mass differences are very different from each other or if one of the mixing angles is close to zero, then CP violation will be too small to measure, even if the CP violating phase is maximal. However, if the solar neutrino anomaly is confirmed to be the large mixing angle solution, so the smaller mass squared difference is only a factor of 10-20 smaller than the atmospheric neutrino mass squared difference, and the mixing angle is maximal, then there is a possibility of measuring a non-zero cp-violating phase. The two unknowns left in determining the expected size of CP-violation would then be θ_{13} and the phase δ itself. Figure 3 shows, for the four combinations of the sign of δm^2_{23} and the sign of δ, how small $\sin^2 2\theta_{13}$ can be where one would still see a 3σ difference between 0 and maximal CP violation [20], as a function of baseline, for a 50kton neutrino detector, 10^{21} muon decays in each of μ^+ and μ^- running, and assuming the large mixing angle solution for the solar neutrino anomaly ($\delta m^2_{12} = 5 \times 10^{-5} eV^2, \delta m^2_{23} = 3.5 \times 10^{-3} eV^2$).

7 High Rate Neutrino Physics

A very intriguing field which would be introduced by a muon storage ring would be that of high rate neutrino physics. If one were to put 30m of shielding downstream of the straight section of a muon storage ring, and then place a fine-grained detector, one would see event rates on small ($0.5 \times 0.5 m^2$ and a few kg) targets that are comparable or larger than those seen at neutrino scattering experiments of the past which had targets on the order of one kton, and spanning $3 \times 3 m^2$. Table 1 gives a sample of targets that could be studied, and the expected event rates at a near detector measuring $40 cm$ in radius [16].

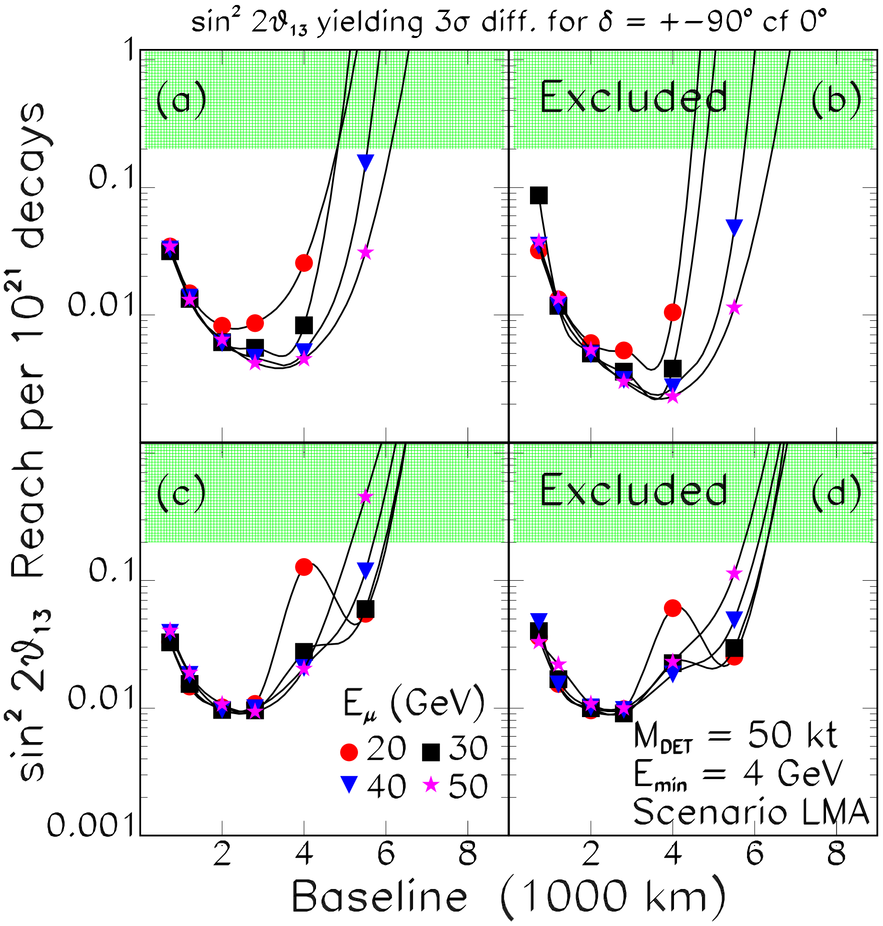

Figure 3: *For four different cominations of the sign of the largest mass squared difference and the sign of the CP-violating phase delta, as well as for four different muon storage ring energies (20 through 50 GeV), these plots show how small* θ_{13} *could be where one would still see a three sigma difference between* $\delta = 0$ *and* $\delta = 90$ *(assuming* $\delta m^2_{23} = 3.5 \times 10^{-3} eV^2$ *and* $\delta m^2_{12} = 5 \times 10^{-5}$*, and the solar neutrino solution is the large mixing angle solution). There is a minimum muon energy cut of 4GeV to remove wrong-sign muon backgrounds. The detector and beamline parameters are described in detail in the text.*

7.1 Measuring Protons Quark by Quark

Because of the very high neutrino fluxes at a muon storage ring one can begin to consider targets of different isoscalarity. By scattering off hydrogen (p) and deuterium ($(p+n)/2$) separately, one can pick out the different quark distributions flavor by flavor by extracting sums and differences of structure functions, as is shown in the equations below:

$$\begin{aligned}
(xF_3^{\nu-\bar\nu})_p - (xF_3^{\nu-\bar\nu})_n &= -2x(u+\bar u - (d+\bar d)),\\
(xF_3^{\nu-\bar\nu})_p + (xF_3^{\nu-\bar\nu})_n &= -2x(s+\bar s - (c+\bar c)),\\
(F_2^{\nu-\bar\nu})_p - (F_2^{\nu-\bar\nu})_n &= -2x(u-\bar u - (d-\bar d)),\\
(F_2^{\nu-\bar\nu})_p + (F_2^{\nu-\bar\nu})_n &= -2x(s-\bar s - (c-\bar c))),
\end{aligned}$$

The errors on the above sums and differences as a function of fractional quark momentum and momentum transfer squared (x, Q^2) are shown in figure 4. These errors assume a $10g/cm^2$ fiducial target for both hydrogen and deuterium, which has already been achieved even for polarized cryogenic targets. The muon storage ring parameters are 10^{20} 50 GeV muons decaying in the straight section in each mode (μ^+ and μ^-), and for a target of radius 50cm. So in summary, with a 4 year run and only a modest target size one could measure quark by quark the contributions to the proton structure functions to better than 0.01! Although the kinematic range of a low-energy neutrino factory is not large, these experiments can access the region of x where many interesting nuclear effects have arisen ($.01 < x < 1.$) and the Q^2 range allows one to probe both the perturbative regime and the non-perturbative regime. [21]

With polarized targets such as the one that was already used for the Spin Muon Collaboration [23] (or the one currently being studied for the LEGS collaboration [22]) one can even map out the spin composition of the proton and neutron, again quark by quark. This would give us unprecedented precision in our understanding of the nucleon.

7.2 Neutrino Charm Factory

Again because of the high fluxes of neutrinos at a muon storage ring, one can consider using much more fine-grained neutrino targets in order to study (or take advantage of) charm production in neutrino scattering. Charm production

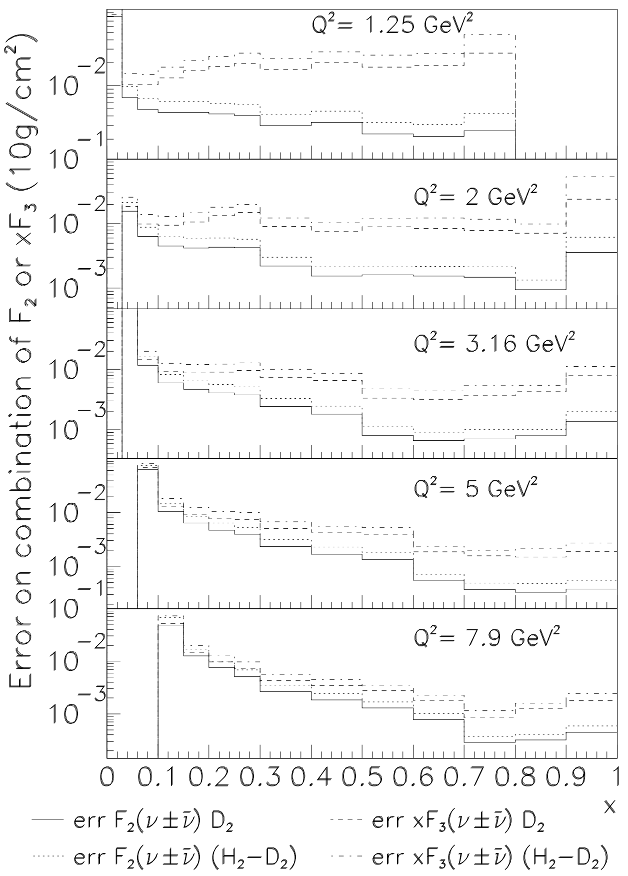

Figure 4: *Errors as a function of x and Q^2 on interesting sums and differences of structure functions.*

occurs in neutrino scattering from charged current interactions with either the strange or (Cabibbo suppressed) down quark. For antineutrino scattering, the largest contribution is from scattering off the anti-strange quark. There is a clean tag of charm production in ν_μ scattering when the charm decays to a muon. The event itself then has (assuming no $D-\bar{D}$ mixing) two oppositely-charged muons. For a 50cm radius target in a 25(50)GeV muon ring, one would expect 700K(7200K) two-muon tagged charm events per kg/cm^2 per year (or 10^{20} muon decays). For a 5cm radius target in a 25(50)GeV muon ring, the statistics are reduced to 27K(380K) two-muon tagged charm events per kg/cm^2. With silicon CCD targets surrounded by particle identification one could do final state reconstruction at a very precise level.

Not only would measurements of the strange sea be available at an impressive precision (see reference [24]) for the most recent results for this type of measurement) but one could also use two-muon events to study charm physics. Specifically, by looking for the presence of two same-sign two-muon events, and comparing to the number of opposite-sign two-muon events, one would have a clean signature of $D^0-\bar{D}^0$ mixing. Although one would not be able to study the time dependence of this mixing, with an exposure of a few kg-years one could have a search sensitivity at the 10^{-5} level.

8 Conclusions

If oscillations are confirmed in the currently-planned generation of neutrino oscillation experiments, an entirely new matrix must be introduced to describe the phenomenon. There are several Grand Unified Theories which make predictions about what these matrices look like, and so not only is it important to study this matrix because it tells us the structure of the lepton sector, but also because these measurements will constrain the GUT's themselves. Neutrino beams coming from muon storage rings like the ones currently being proposed are extremely promising in terms of their capability of mapping out that matrix. If θ_{13} is larger than 2 orders of magnitude below current experimental limits, one can see evidence for its being non-zero at an entry level neutrino factory of 10^{20} muon decays. Measuring the sign of the largest mass squared difference would require only a small upgrade for the smallest value of θ_{13} measurable. In that same range of θ_{13}, if the solar neutrino anomaly is confirmed to be oscillations with the large mixing angle solution, then one has also a hope of seeing CP violation, with an upgraded muon storage ring and again if θ_{13} is at least 1.5 orders of magnitude below current experimental limits.

Although the studies in this report all assume that the LSND signal is not confirmed, if it is confirmed and a fourth neutrino must be introduced, then a neutrino factory becomes even more exciting, because of its unique abilitity to provide two different neutrino species, with the very important detail that those two species are of opposite polarity. Being able to study both ν_μ and ν_e transition probabilities means having much more information about the sterile neutrino sector.

Finally, because of the nature of these new neutrino beams, one can begin to consider very different target materials from what has traditionally been used in neutrino deep inelastic scattering experiments. One can finally study quark by quark the structure of the nucleon, check for nuclear effects, and get very precise measurements of the strange sea using a two-muon event tag (at the very least!). Because even at these low energies charm production in neutrino scattering is not negligible, one can also envision using silicon CCD targets to study charm physics in much more detail than could ever be done in neutrino scattering before. Although this field of heavy quarks at neutrino factories is in its infancy, preliminary studies of the sensitivity to $D^0\bar{D}^0$ mixing show it to be very promising.

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