PROCEEDINGS OF SCIENCE

Project X and the Intensity Frontier Physics Program at Fermilab

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The Project-X program at Fermilab transforms the existing accelerator into a high intensity facility which is capable of supporting and expanding the physics sensitivities of the long baseline neutrino program. The upgrade program also will establish new high precision programs to search for lepton flavor violation in the muon sector and to make high precision kaon decay measurements. This is made possible through a reference design for the accelerator upgrades that use a continous wave linac to provide a 2 MW class facility with flexibility that can not be matched in a synchrotron-based design.

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1. Introduction

Project-X is the evolution of the existing Fermilab accelerator to use super-conducting RF technology to provide facility capable of providing mega-Watt class beam power to a wide range of experimental programs across both high energy and nuclear physics. The program is collaboration between more than 20 institutions, national labs and research consortiums.

The primary goals of the Project-X program are:

1. To provide a 2 MW class proton source with an energy between 60-120 GeV for the purpose of driving a next generation program of long baseline neutrino oscillation measurements and experiments.
2. To establish high intensity, low energy proton beams to enable a new programs of high precision kaon, muon, nuclei and short baseline neutrino oscillation experiments which can operate simultaneously with the long-baseline neutrino program.
3. Provide a path towards a muon source for a future neutrino factory or muon collider, by providing a facility that can provides 4 MW of beam power at an energy between 5-15 GeV.
4. Address missions beyond particle physics by establishing beam facilities that can be used to investigate basic energy applications and including driven subcritical systems.

Through meeting these goals, the Project-X program will be able to support and expand the world leading intensity frontier physics program that Fermilab has planned for the next decade.

2. The Project X Design

The Project-X reference design, shown in Fig. 1, uses a continuous wave linear accelerator which will replace the current 400 MeV, 35 mA linac that is currently the start of the Fermilab accelerator chain. This new front end to the accelerator complex would use a superconducting continuous wave $H^{-}1$ linac design which will be able to provide 1 mA of average beam current at an energy of 3 GeV. The accelerator is design provides for a programmable beam structure to allow for the simultaneous running of multiple experiments with different requirements on the spill structures that are delivered to each experiment lines. The CW linac is designed to provide a 3 GeV proton beam to drive experiments in the rare kaon and muon programs, which can significantly reduce their background rates by running their production targets in this energy range. At the same time, the CW linac is also allows for extraction at an energy of 1 GeV which can be used run a nuclear energy program that would explore accelerator driven subcritical reactions.

The second accelerator system of the reference design utilizes a pulsed linac design to deliver 300 kW of beam power between 3-8 GeV. This beam line would be used to support a short baseline neutrino program capable of performing precision ν-oscillations and cross section measurements. This accelerator stage would also provide a path towards a high intensity muon facility that would be require for the next generation of lepton flavor violations searches and muon g-2 measurements.

The reference design also include upgrade to both the Fermilab main injector and recycler complexes to allow them to provide a 2+ MW class beam at an energy between 60 to 120 GeV.

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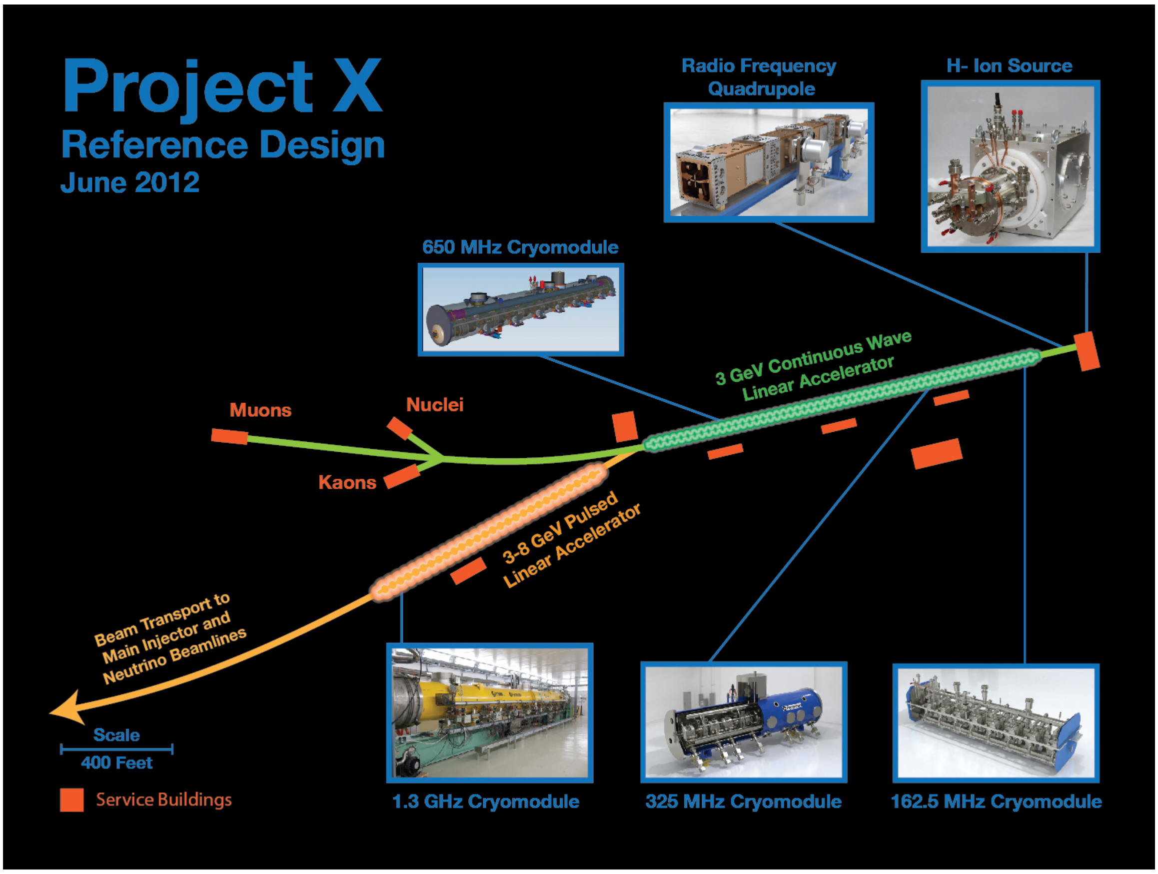

Figure 1: The Project-X reference design uses a 3 GeV continuous wave linac and a 3-8 GeV pulsed linac to drive precision experimental programs in kaon, muon, neutrino physics.

This beam would be essential to support the long baseline neutrino program in a wide band beam configuration, such as that proposed by the LBNE experiment, in order to resolve the neutrino mass hierarchy and place tight constraints on the CP violating phase δ_{CP} in the PMNS neutrino mixing matrix.

Under this design the Fermilab accelerator complex shown in Fig. 2a would be upgraded by replacing the current linac and booster complexes with the new 1-3 GeV continuous wave linac, which would drive a campus of rare decay and precision measurement experiments. The 3-8 GeV pulsed linac would be located inside the Tevatron's main ring and would merge into the existing 8 GeV transport lines to feed the main injector complex as shown in Fig. 2b.

Under this configuration the Project-X accelerator complex would be able to simultaneously deliver 2870 kW, 170 kW and 2450 kW to the 3 GeV, 8 GeV and 120 GeV programs respectively, as shown through the operation parameters in Table 1.

3. Physics Sensitivities

The physics capabilities of the Project-X program can be described through the different power

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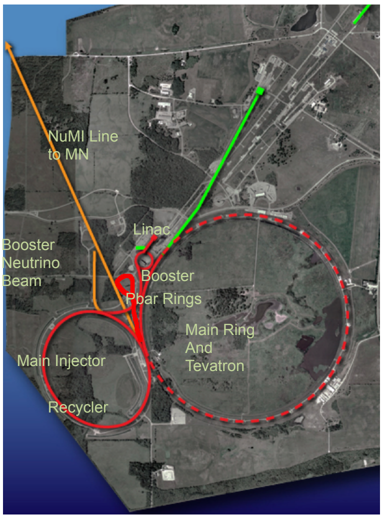
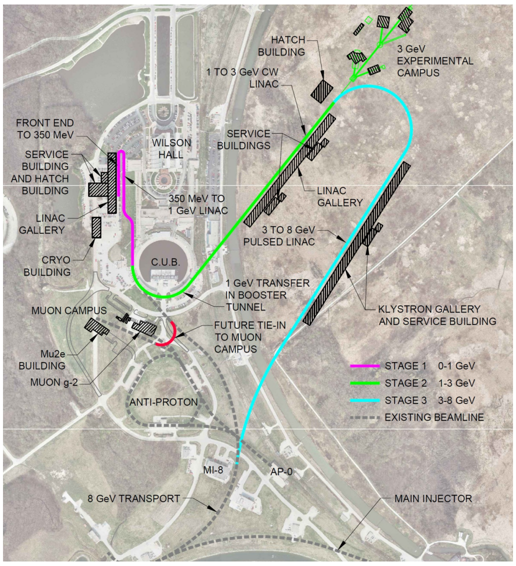


(a) The current configuration of the Fermilab Accelerator Complex utilizing the 400 MeV linac, 8 GeV booster and Main injector ring to drive the 700 kW NuMI neutrino line that provides beam to the MINOS and NOvA experiments.



(b) The Fermilab Accelerator Complex with Project X upgrades which replace the linac and booster complex with a new 3 GeV continuous wave linac and then provides a 3-8 GeV pulsed linac that would connect into the main injector complex.

Figure 2: Evolution of the Fermilab accelerator complex

stages that the program will evolve through. Each of these major stages brings with it new capabilities and new scientific facilities that can be driven by the accelerator systems. The power stages and the beam which they can deliver to each of the physics programs are shown in Fig. 3.

3.1 Stage-0 NOvA Era

The first stage of the Project-X upgrades started in May 2012 with the upgrade of the accelerator complex to double the beam power available to the NuMI (Neutrinos at the Main Injector) beam line from 320 kW to 700 kW. This upgrade ushers in the start of the NOνA era during which the NuMI Off-axis ν_e Appearance (NOνA) experiment will make the measurements of the oscillation probabilities for $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ along the 810 km baseline from Fermilab to the NOνA far detector which is located in northern Minnesota at the Ash River site.

Given the recently established large value of the neutrino mixing angle θ_{13} ($\sin^2\theta_{13} \approx 0.09$) from global fits [1], the NOνA experiment will be able to make independent measurements of $P(\nu_\mu \to \nu_e)$, $P(\bar{\nu}_\mu \to \bar{\nu}_e)$, $P(\nu_\mu \to \nu_\mu)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_\mu)$. When these measurements are combined and compared to the three flavor oscillation predictions (parameterized in the CP violating phase δ_{CP}) they allow for a potential determination of the neutrino mass hierarchy. For the event rates estimated for three years each of neutrino and anti-neutrino beam configuration running at 700 kW, the NOνA experiment can make a 2σ resolution of the neutrino mass hierarchy over 34% of the available parameter space in δ_{CP}. The example 1 and 2σ contours for an example measure-

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CW Linac	
Particle type	H^-
Beam kinetic energy	1.0-3.0 GeV
Average beam current	1 mA
Linac pulse rate	CW
Beam power at 3 GeV	3000 kW
Beam power to 3 GeV program	2870 kW
Pulsed Linac	
Particle type	protons/H^-
Beam kinetic energy	8.0 GeV
Pulse rate	10 Hz
Pulse width	4.3 msec
Cycles to main injector	6
Particles per cycle to recycler	2.6×10^13
Beam Power to 8 GeV program	170 kW
Main Injector/Recycler	
Beam kinetic energy	8.0 GeV
Cycle time	1.3 sec
Particles per cycle	1.6×10^14
Beam Power at 120 GeV	2450 kW

Table 1: Operational parameters for the Project-X accelerator components.

ment point (determined by combination of $P(\nu_\mu \to \nu_e)$ and $P(\bar{\nu}_\mu \to \bar{\nu}_e)$ measurements) is shown in Fig. 4a along with the ellipses defining the three neutrino oscillation probabilities with matter effects for the the normal (blue) and inverted (red) mass hierarchies.

In addition to the mass hierarchy measurements, the NOνA experiment will also make precision measurements of θ_{13} and θ_{23}. These measurements have the potential to determine if θ_{23} is non-maximal and if it is non-maximal are able to determine the octant to which θ_{23} lays in which is a determination of whether the third neutrino mass state, ν_3, couples more to ν_μ or ν_τ. NOνA also as the ability to put limits CP violation at 1σ over 30% of the available range in delta.

All of the NOνA sensitivities at stage-0 are statistics limited and can be significantly improved from increasing the beam power to the experiment.

3.2 Stage-1 LBNE Era

The second stage of the Project-X program comes from the installation of the continuous wave linac running at an energy of 1 GeV. This phase of the Project-X program enables the low energy muon programs running with 80 kW of beam power in tandem with the 8 GeV neutrino program and the long baseline 120 GeV program. This phase also enables a new set of programs to investigate nuclear electric dipole moments (EDMs), ultra cold neutron measurements and nuclear energy technologies.

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Program:	**Stage-0:** Proton Improvement Plan	**Stage-1:** 1 GeV CW Linac driving Booster & Muon, EDM programs	**Stage-2:** Upgrade to 3 GeV CW Linac (MI>70 GeV)	**Stage-3:** Project X RDR (MI>60GeV)	**Stage-4:** Beyond RDR: 8 GeV power upgrade to 4MW
MI neutrinos	470-700 kW**	515-1200 kW**	1200 kW	2300 kW	2300-4000 kW
8 GeV Neutrinos	15 kW + 0-50 kW**	0-40 kW* + 0-90 kW**	0-40 kW*	85 kW	3000 kW
8 GeV Muon program e.g, (g-2), Mu2e-1	20 kW	0-20 kW*	0-20 kW*	85 kW	1000 kW
1-3 GeV Muon program	-----	80 kW	1000 kW	1000 kW	1000 kW
Kaon Program	0-30 kW** (<30% df from MI)	0-75 kW** (<45% df from MI)	1100 kW	1100 kW	1100 kW
Nuclear edm ISOL program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Ultra-cold neutron program	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
Nuclear technology applications	none	0-900 kW	0-900 kW	0-900 kW	0-900 kW
# Programs:	4	8	8	8	8
Total* power:	585-735 kW	1660-2240 kW	4230 kW	5490 kW	11300kW

Figure 3: Project-X power staging plan and and the amount of beam power available to physics programs at each stage.

The improvements in physics sensitivities that can be achieved in stage-1 can be examined through the various experiments which will be ready as "Day-1" experiments during this era. These experiments include the Long Baseline Neutrino Experiment (LBNE), NOνA and the MicroBooNE upgrade.

The Project-X upgrades will increase the beam power to the long baseline experiments from 700 kW to 1.2 MW. In the case of the NuMI/Ash River beams options, this increase in beam power would extend the NOνA experiment's run by an additional three years in the ν and $\bar{\nu}$ configurations. The increase in exposure extends NOνA's ability to resolve the mass hierarchy from a 2σ sensitivity to a 3σ sensitivity over 34% of the available parameter space in δ_{CP}. It also extends its 2σ coverage to over 50% of the parameter space in δ_{CP} extending over the ranges $(\pi, 2\pi)$ and $(0, \pi)$ for the normal and inverted hierarchies respectively, as shown in Fig. 4b.

The combination of the NOνA detector with the LBNE 30 kt liquid argon detector located at Ash River option yield significantly improvements on the hierarchy and CPV measures and are able to make the 3σ determination of the neutrino mass hierarchy over 45% of available space in δ_{CP}, with greater than 5σ sensitivities in the regions around $\delta_{CP} = 3\pi/2$ (normal) and $\delta_{CP} = \pi/2$ (inverted). These sensitivities are shown in Fig. 5a.

Similarly the ability of the combined experiments to resolve the octant of the θ_{23} for the MINOS best fit value $\theta_{23} = 0.96$ [2] with the 1.2 MW and three years each neutrino and anti-neutrino running are shown in Fig. .5b and allow for a 3σ determination of the octant over all values of δ_{CP}.

The Ash River configurations are limited by their use of a narrow band beam and baseline distance. These combine to give a region of degeneracy where the oscillation solutions for the

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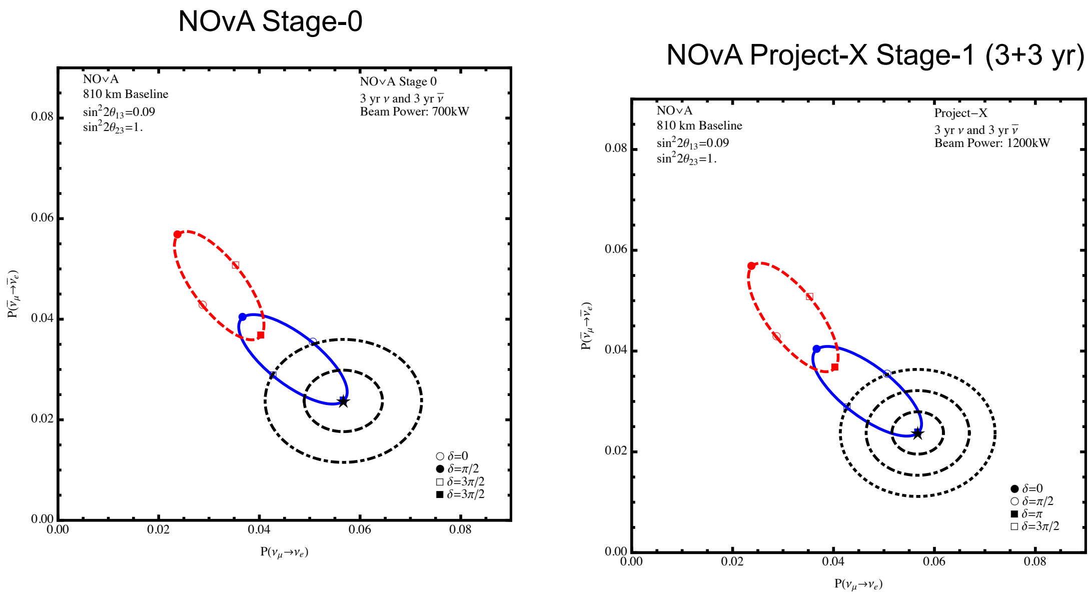

(a) Baseline Nova Sensitivities (700 kw) (b) Project X sensitivities for NOvA.

Figure 4: Evolution of NOvA sensitivities (15 kt)

normal and the inverted mass hierarchies overlap. Since the off-axis configuration used for the Ash River site is specifically tuned to the first oscillation maxima to reject background events, there is only limited coverage of the first oscillation node and there is very little shape based information available to the fits. This significantly limits the Ash River configuration even under Project-X beam powers if δ_{CP} is near $\pi/2$ (normal hierarchy) or $3\pi/2$ (inverted hierarchy).

Moving to a longer baseline of 1300 km and placing the far detector on-axis to utilize a broad-band beam allows for significant coverage of both the first and second oscillation maxima and allows for shape based fits to determine the phase δ_{CP}. This is possible in the case of the LBNE homestake option since the Project-X stage-1 beam power is high enough to exploit running in a low energy (60 GeV) beam configuration which allows for greater coverage of the second oscillation maxima as shown in Fig. 6 and allows for the full determination of the mass hierarchy across the full range of δ_{CP}.

This configuration also allows for a 3σ determination of CP violation over more than 27% of δ_{CP}.

3.3 Stage-2 Muon Era

Stage-2 of the Project-X power staging plan upgrades the linac to 3 GeV and provides 1000 kW of beam power to a new 1-3 GeV rare muon and kaon decays program. This will permit the next generation of muon to electron conversion experiments which will use new techniques to reach sensitivities for $B(\mu N \to eN) \sim (O)(10^{-19})$. These beam power will also allow the measurements to be carried out over a wide range of nuclei such as Al, Ti and Au which through the comparison of the observed rates would allow for a separation of the vector coupling that are present.

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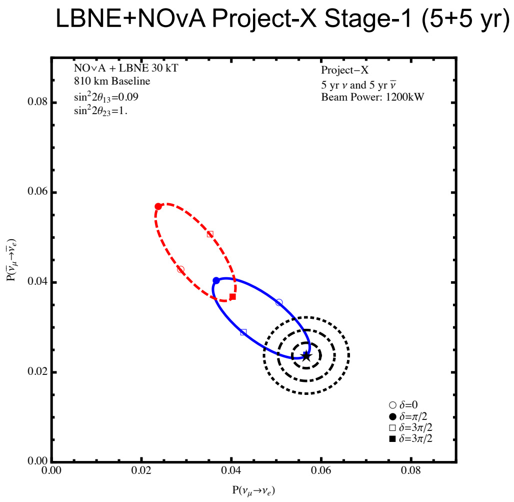
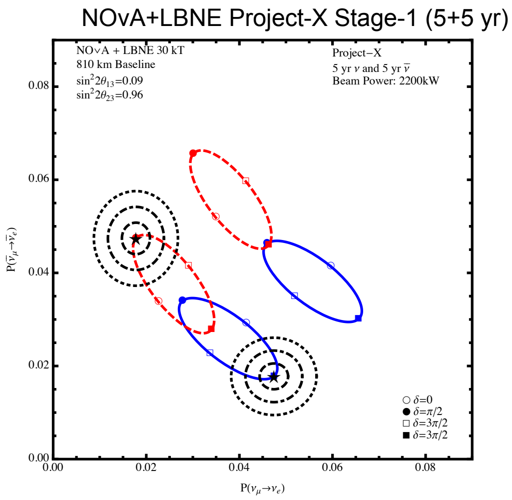


(a) Combined NOνA/LBNE 30 kt sensitivities to the resolution of the neutrino mass hierarchy for the test point δ_{CP} =$3\pi/2$.



(b) Combined NOνA/LBNE 30 kt sensitivities to the determination of the octant of the mixing angle θ_{23}.

Figure 5: NOνA/LBNE sensitivities under Ash River site configuration.

This beam power also permits the next generation of (g-2)$_\mu$ if it is motivated by the next round of theory or LHC data. Many of the new techniques being proposed for these measurements are beam-power hungry and can not be done without megawatt class beams.

The physics reach that Project-X provides to the next generation of muon to electron conversion experiments can be shown by considering a generalized charge lepton flavor violation Lagrangian.

$$\mathscr{L}_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L) \tag{3.1}$$

The first term is identified as the contribution coming from loop like interactions diagrams, shown in Fig. 7a, while the second term is identified as the contribution from contact like interactions. This breaks out the dipole, vector and scalar nature of the interaction and parameters the strength of the interactions in terms of the effective energy scale Λ and the relative dominance κ of the contact like interactions.

In the case of the Mu2e experiment running during the Project-X era, the experiment would be able to reach on ^{27}Al, beyond a branching fraction B($\mu \to e$) = 10^{-17}. This would then equate to an effective energy scale for new physics arising from contact term dominated interactions of greater than 20,000 TeV. This sensitivity is shown in Fig. 7c across the full range of κ.

Stage 2 of Project-X also enables a rich and varied range of experimental opportunities in the kaon sector by providing high enough event rates to make precision measurements of event the

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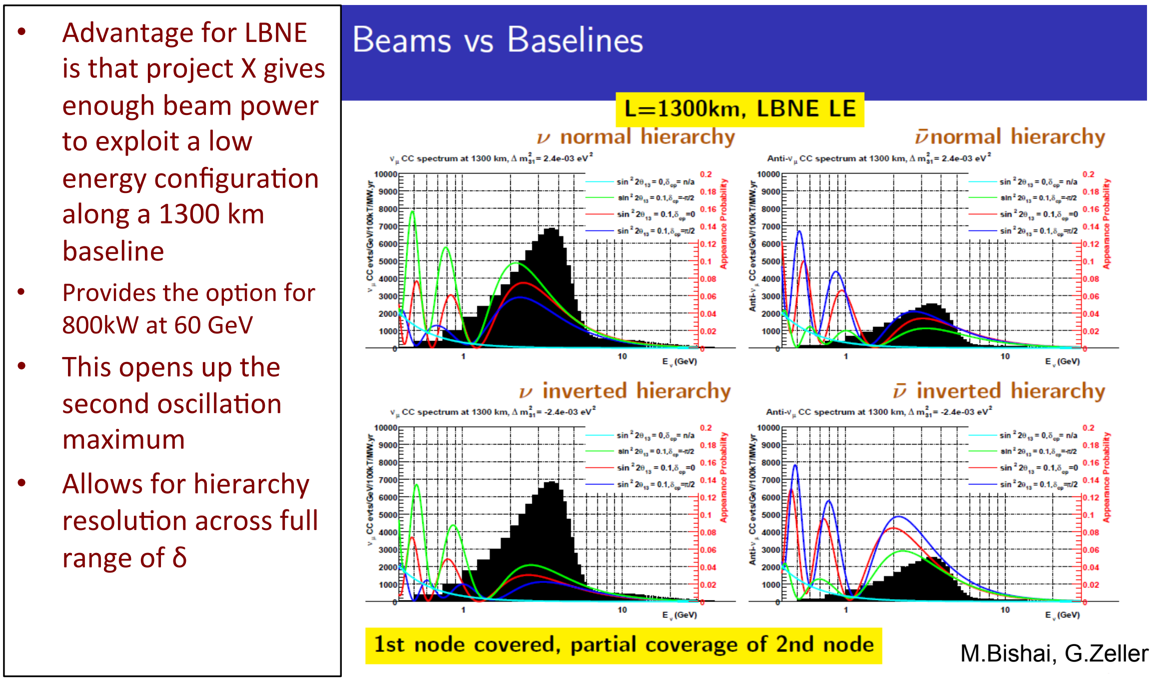

Figure 6: The broadband beam configuration of LBNE at the Homestake site in conjunction with the Project-X beam profile that permits running a power of 800 kW at 60 GeV, opens up coverage of the second oscillation maxima.

rares decay modes. Of particular significance, Project-X would permit the measurement of both:

$$K^+ \to \pi^+ \nu \bar{\nu} \tag{3.2}$$

$$K_L^0 \to \pi^0 \nu \bar{\nu} \tag{3.3}$$

With more than 1000 events per channel. This permits precision rate and form factor measurements which are not possible with lower flux beam facilities or facilities who's beams structures do not allow for the precision time of flight. Additionally the rare kaon program would be able to perform measurements and searches for:

$$K^+ \to \pi^0 \mu^+ \nu \tag{3.4}$$

$$K^+ \to (\pi, \mu)^+ \nu_x \tag{3.5}$$

$$K^0 \to \pi^- e^+ e^- \tag{3.6}$$

$$K^0 \to \pi^- \mu^+ \mu^- \tag{3.7}$$

$$K^0 \to X \tag{3.8}$$

$$K_L \to \mu^\pm e^\mp \tag{3.9}$$

$$K^0, K^+ \to LFV \tag{3.10}$$

As well as improve measurements of the other rare FCNC and CPV decay modes.

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4. Conclusions

Project-X is the key to the Intensity Frontier. It provides the beam power that is required to probe deep into our understand of the neutrino oscillations and indirect searches for new physics. It transforms the existing Fermilab complex into a new facility that can host the next generation of high precision experiments through the long baseline neutrino programs and LBNE, through the new precision muon physics programs with g-2 and Mu2e and through a new generation of precision kaon measurements with the ORKA experiment and the other opportunities that the new beam lines and rare decay programs will provide.

References

[1] D. Forero, M. Tortola, J. Valle, *Global status of neutrino oscillation parameters after recent reactor measurements*, arXiv:1205.4018v2 [hep-ph].

[2] R. Nichol, *Results from Minos*, talk given at Neutrino 2012, June 2012.

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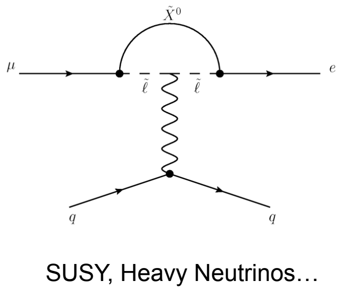
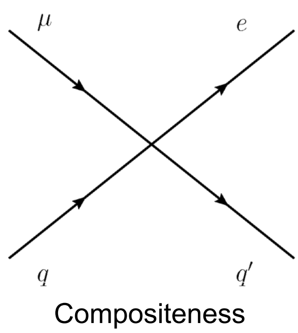
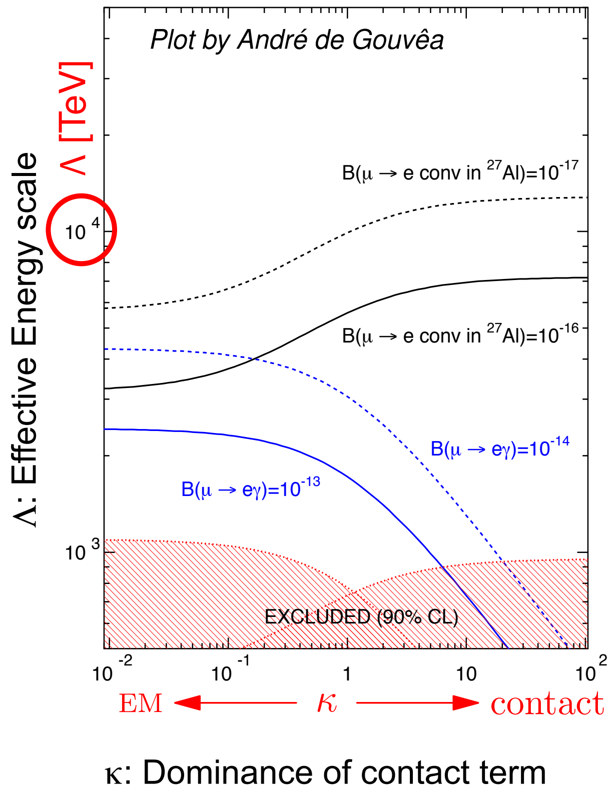


(a) Dipole like loop interaction contributing to μ to e conversion.



(b) Contact interactions contributing to μ to e conversion.



(c) Sensitivity of the muon to electron conversion to the effective energy scale of new physics when parameterized in terms of the dominate interaction process.

Figure 7: Mu2e sensitivities to dipole and contact interaction dominated new physics with Project-X Stage 2 beam power.

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