Fermilab

Physics at an Upgraded Fermilab Proton Driver

1. Introduction
2. Main Motivation: Neutrino Oscillations
3. Neutrino Scattering
4. Muons
5. Kaons, pions, neutrons, antiprotons …..
6. Summary

Introduction

Neutrino physics provides the primary motivation for a new Fermilab Proton Driver.

The recent APS study on the future of neutrino physics concluded with some recommendations, amongst which:
"We recommend, as a high priority, a comprehensive U.S. program to complete our understanding of neutrino mixing, to determine the character of the neutrino mass spectrum, and to search for CP violation among neutrinos."

The program to do this should have as one of its components:
"A proton driver in the megawatt class or above and neutrino superbeam with an appropriate very large detector capable of observing CP violation and measuring the neutrino mass-squared differences and mixing parameters with high precision."

Neutrinos are Everywhere

Neutrinos outnumber ordinary matter particles in the Universe (electrons, protons, neutrons) by a factor of ten billion.

Depending on their masses they may account for a few % of the unknown "dark matter" in the Universe

Neutrinos are important for stellar dynamics: $\sim 7\times 10^{10}\ cm^{-2}s^{-1}$ stream through the Earth from the sun. Neutrinos also govern Supernovae dynamics, and hence heavy element production.

If there is CP Violation in the neutrino sector, then neutrino physics might ultimately be responsible for Baryogenesis.

To understand the nature of the Universe in which we live we must understand the properties of the neutrino.

We Don’t Know Everything About Neutrinos

From the US APS Multi-Divisional Study on the Physics of Neutrinos

- *What are the masses of the neutrinos?*
- *What is the pattern of mixing among the different types of neutrinos?*
- *Are neutrinos their own antiparticles?*
- *Do neutrinos violate the symmetry CP?*
- *Are there “sterile” neutrinos?*
- *Do neutrinos have unexpected or exotic properties?*
- *What can neutrinos tell us about the models of new physics beyond the Standard Model?*

Neutrino Oscillations are Exciting

Neutrinos have nonzero masses and mixings !

This is exciting because:

The Standard Model needs modification accommodate neutrino mass terms, which require either the existence of right-handed neutrinos → Dirac mass terms, or a violation of lepton number conservation → Majorana mass terms. The physics of neutrino masses & mixings is physics beyond the Standard Model

We don't know the neutrino mass spectrum but we do know that neutrino masses & mass splittings are tiny compared to the masses of the other fundamental fermions. This suggests radically new physics, which perhaps originates at the GUT or Planck Scale, or indicates the existence of new spatial dimensions, or …..

Neutrino Measurements Drive Theoretical Ideas

Although we don't have complete knowledge of the neutrino mixing matrix, we do know it is qualitatively very different from the quark mixing matrix. This necessarily constrains theoretical ideas about the underlying relationship between quarks and leptons.

Over the last few years knowledge of neutrino oscillation parameters has eliminated a previous generation of GUT models, leading to a new set of models designed to accommodate the data.

Further oscillation measurements will necessarily reject the majority of the new models, and hopefully lead to new ideas about physics beyond the Standard Model

Neutrino Oscillation Measurements Drive Theoretical Ideas. This is expected to continue to be the case throughout the Proton Driver era.

Neutrino Mixing

Within the framework of 3-flavor mixing, the 3 known flavor eigenstates (ν_e, ν_μ, ν_τ) are related to 3 neutrino mass eigenstates (ν_1, ν_2, ν_3) :

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \Big(3\times 3 \Big) \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

Specifies the flavor content of the three neutrino mass eigenstates.

Neutrino Mixing Matrix

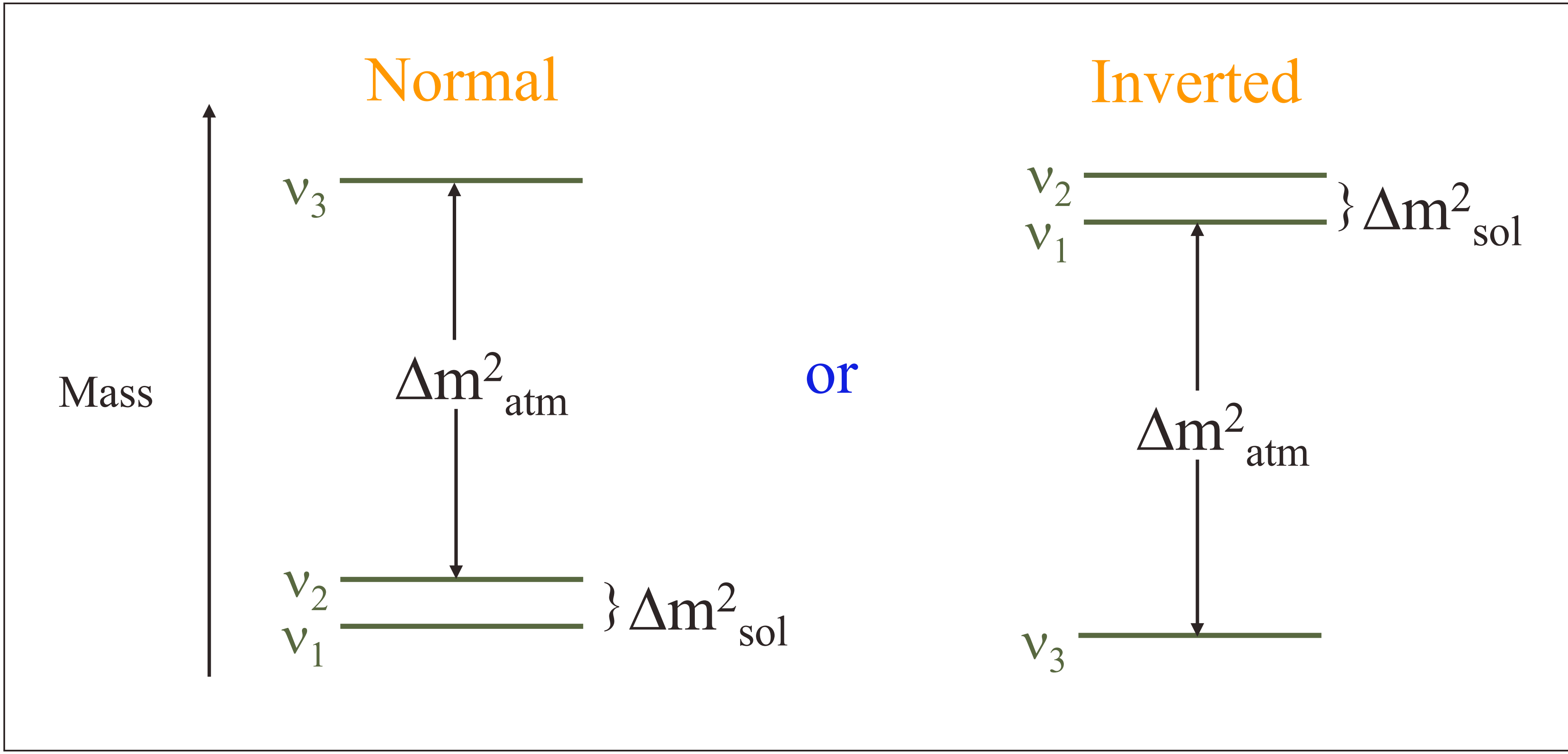
The neutrino mixing matrix can be parameterized using 3 mixing angles (θ_{12} , θ_{23} , θ_{13}) and one complex phase (δ) :

$$\begin{pmatrix} C_{12}C_{23} & S_{12}C_{13} & S_{13}\, e^{-i\delta} \\ -S_{12}C_{23} - C_{12}S_{23}\, S_{13}\, e^{i\delta} & C_{12}C_{23} - S_{12}C_{23}\, S_{13}\, e^{i\delta} & S_{23}C_{13} \\ S_{12}S_{23} - C_{12}C_{23}\, S_{13}\, e^{i\delta} & -C_{12}S_{23} - S_{12}C_{23}\, S_{13}\, e^{i\delta} & C_{23}C_{13} \end{pmatrix}$$

We know the rough values of θ_{12} , θ_{23} but only have an upper limit on θ_{13}, and no knowledge of δ.

Neutrino Mass Spectrum

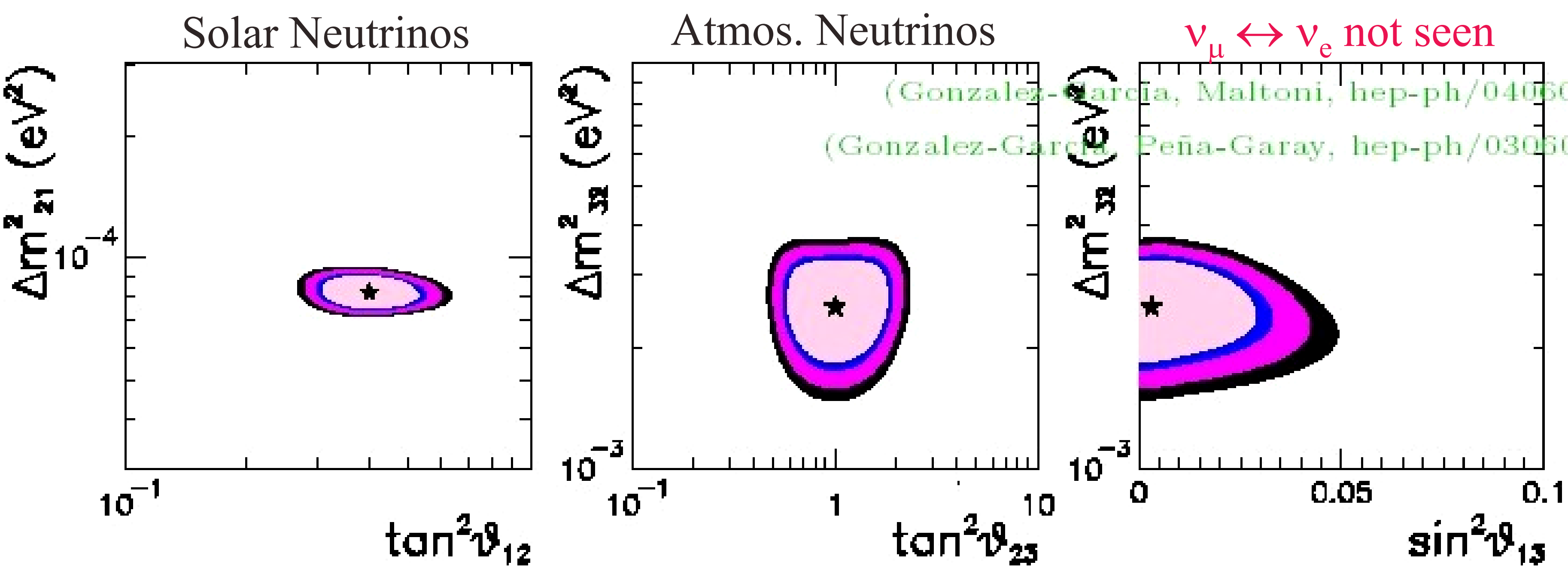
The oscillations are driven by the mass splittings: $\Delta m^2_{ij} \equiv m^2_i - m^2_j$



$\Delta m^2_{sol} \cong 8 \times 10^{-5}\ eV^2$, $\quad |\Delta m^2_{atm}| \cong 2.5 \times 10^{-3}\ eV^2$

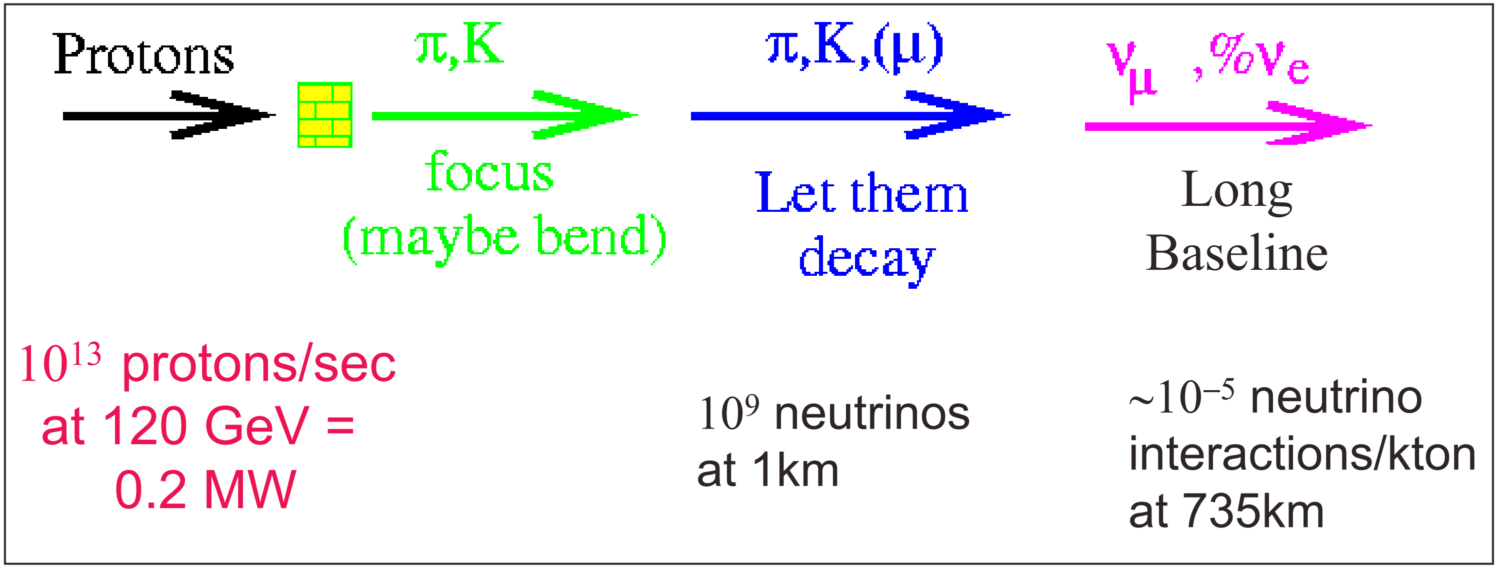
Measured Parameters

From the solar-, atmospheric-, and reactor-neutrino data we already know a lot about the mixing matrix and mass splittings:



… but note that we have only an upper limit on θ_{13}, and know nothing about δ. We need to search for $\nu_\mu \leftrightarrow \nu_e$ oscillations !

Why Do We Need High Intensity Proton Beams



We want to study rare processes. The upper limit on the all important $\nu_\mu \rightarrow \nu_e$ oscillation amplitude is ~5% !

NEED MW-CLASS MULTI-GeV PROTON SOURCES

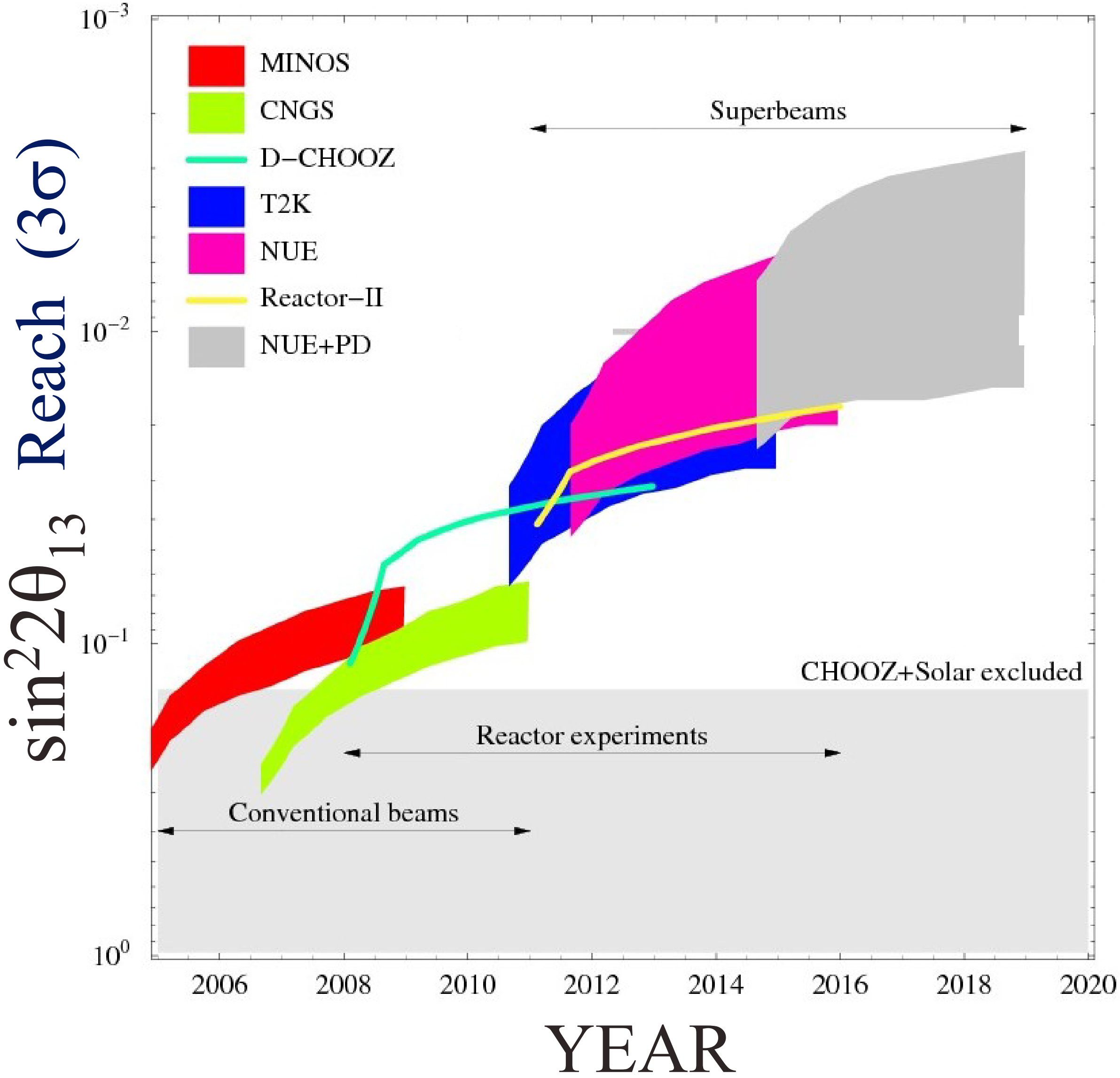
Why Fermilab ?

Fermilab hosts the present U.S. accelerator based neutrino program, and with the completion of the NuMI beamline, operates the longest-baseline neutrino beam in the World.

The NuMI baseline is the only accelerator-based baseline long enough (& with the right energy) for matter effects to have a significant impact on the measured oscillation probablilities … & these matter effects provide the key for determining the pattern of neutrino masses.

The NuMI beam is unique …. it can do what no other beam can do, namely exploit matter effects … provided the beam intensity is sufficient (2MW primary protons or more) , and the detector is large enough (few times 10kt).

Ability to observe non-zero θ_{13} versus time



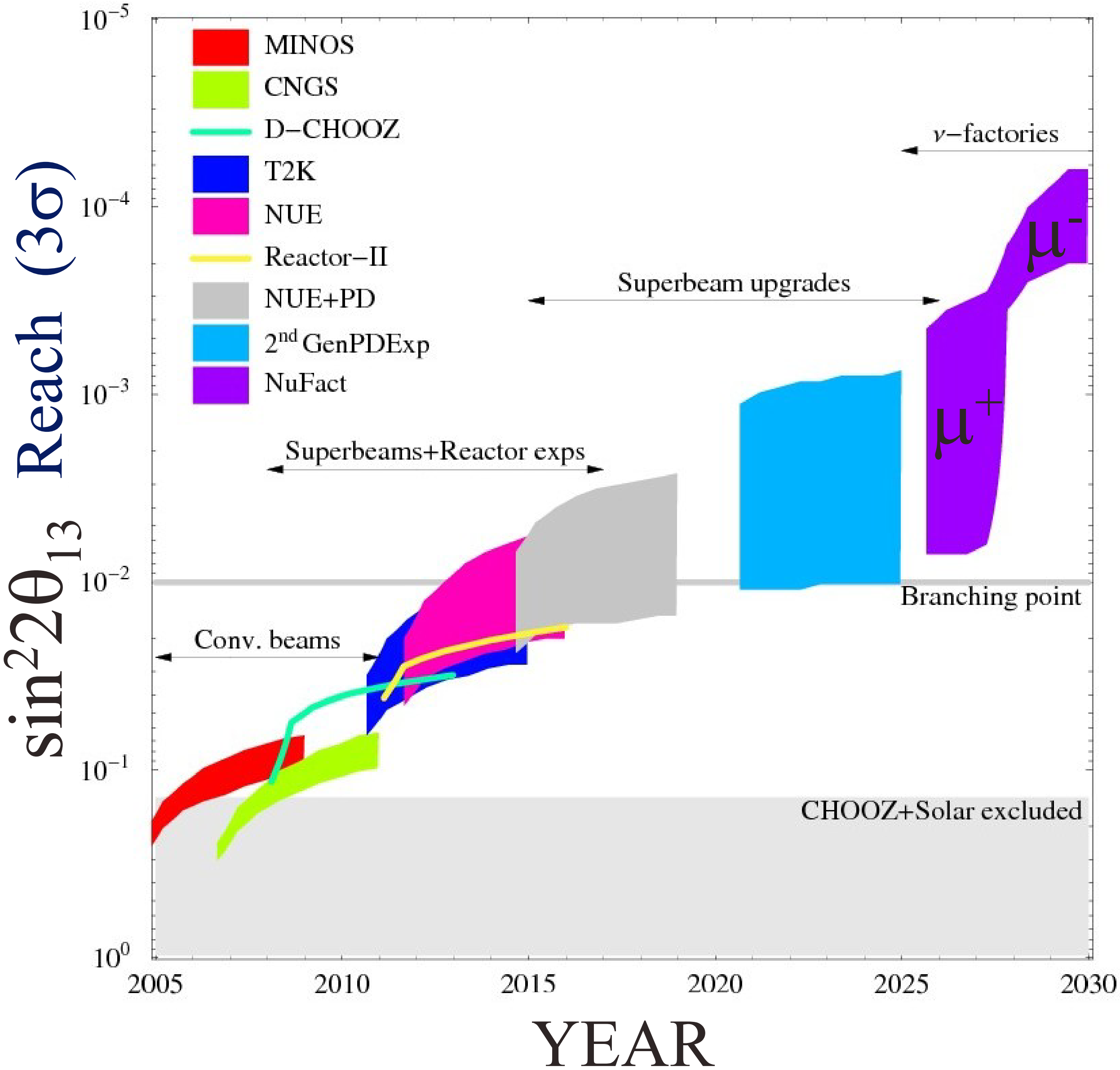
Calculations include statistical & systematic uncertainties, & correlations etc.

Sensitivity depends on δ, which is varies within the bands. Other parameters correspond to current central values+normal mass hierarchy.

NUE = NOvA or equivalent.
PD = Fermilab Prot. Driver

Note: Reactor experiments are disappearance experiments limited by systematics. Accelerator experiments are appearance experiments limited by statistics.

Long-Term $\sin^2 2\theta_{13}$ Evolution



If the short/medium-term experiments tell us that θ_{13} is very small the Fermilab Proton Driver will provide a way to continue the search in the longer term … by supporting upgraded neutrino beams and experiments, or driving a neutrino factory.

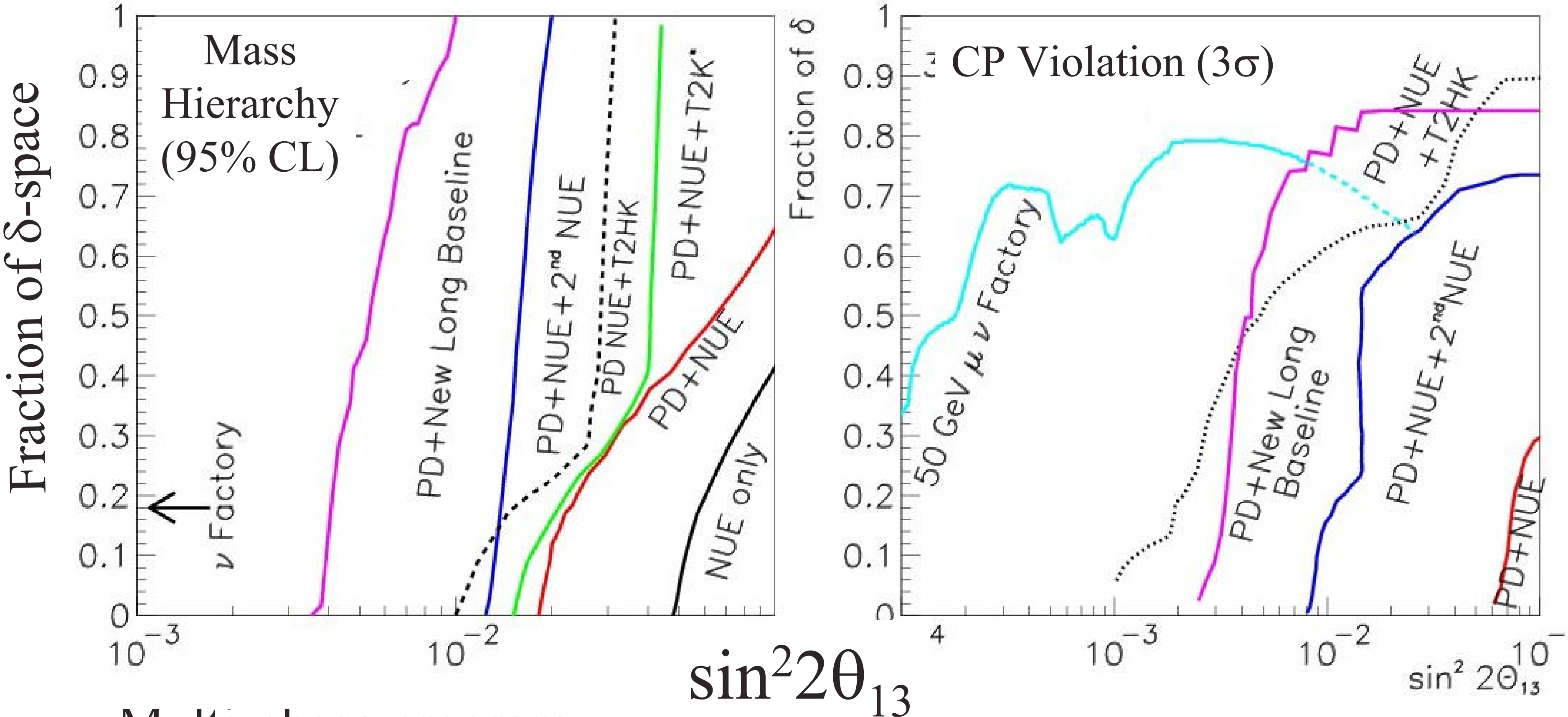
From Searches to Measurements

Although we don't know the magnitude of θ_{13} we have no good reason to suspect it is very small.

Hence at any point along the future path our focus on searching for a non-zero of θ_{13} might be changed to a focus on measuring its value precisely, determining the mass hierarchy, and searching for CP violation.

The Fermilab Proton Driver has critical roles to play in both the search and the measurement phases of the global program.

A Long-Baseline Fermilab Proton Driver Program would make Critical Contributions to the Global Program

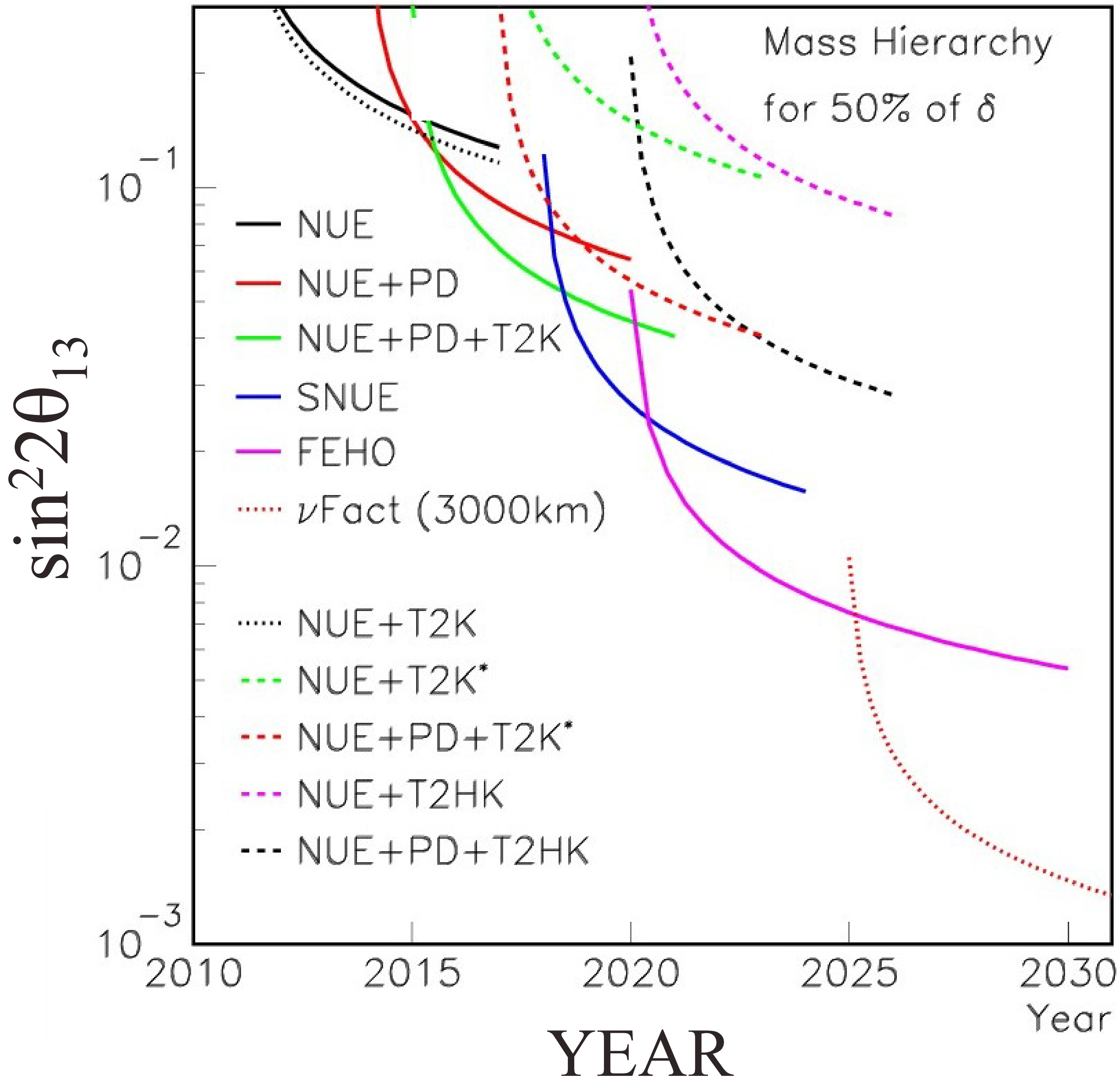


Multi-phase program.

In all scenarios the Proton Driver has a critical role to play.

The NuMI longer-than-T2K baseline is needed to disentangle the mass hierarchy from CP violation.

Mass Hierarchy Evolution



Neutrino Scattering Motivation

High precision neutrino and antineutrino measurements with nuclear & nucleon targets are needed for the oscillation physics program to reduce systematics from cross-section uncertainties.

Neutrino scattering measurements are of interest in their own right:

CC QE Scattering → Nucleon structure & binding of the nucleons within the nucleus

NC Elastic Scattering → Spin structure of the nucleon & the strange quark contribution

Resonant & coherent production of pions → Resonant structure of the nucleon & non-perturbative QCD tests

Strange Particle Production → Understand backgrounds for proton decay searches

Neutrino-Electron Elastic Scattering → Neutrino magnetic moment

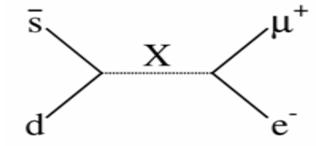
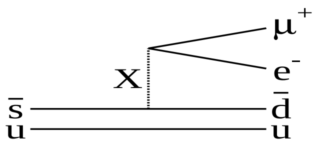
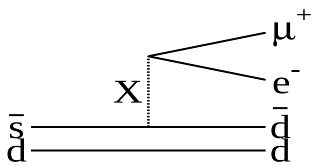
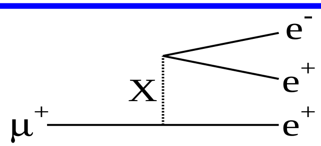
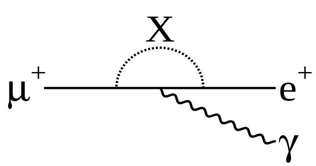
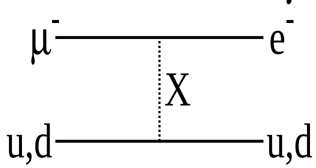
Neutrino Scattering: Need for Higher Intensity

In the pre-Proton Driver era we expect high precision neutrino measurements of CC & NC (quasi)elastic scattering, and CC & NC producion of pions and strange particles off nuclear targets.

However: (i) The antineutrino event rate is down by a factor of 3-5 (depending on energy) compared to the neutrino rate … due to the cross-sections and the π^+/π^- production ratio, and (ii) The H_2 & D_2 target rates are down by an order of magnitude compared to nuclear target rates.

We will need the Proton Driver to make high-precision measurements with antineutrino beams on nuclear targets, and with both neutrino and antineutrino beams on nucleon targets (H_2,D_2), using both the MI beam and the 8 GeV beam – motivates high power (2 MW) at 8 GeV.

Low Energy Probes of High Mass Scales

		Mass Limit
	$B(K_L \to \mu e) < 4.7 \times 10^{-12}$	150 TeV/c^2
	$B(K^+ \to \pi^+ \mu^+ e^-) < 4 \times 10^{-11}$	31 TeV/c^2
	$B(K_L \to \pi^\circ \mu^+ e^-) < 3.2 \times 10^{-10}$	37 TeV/c^2
	$B(\mu^+ \to eee) < 1 \times 10^{-12}$	86 TeV/c^2
	$B(\mu^+ \to e^+\gamma) < 1.2 \times 10^{-11}$	21 TeV/c^2
	Normalized Rate $< 6.1 \times 10^{-13}$	365 TeV/c^2

Many of these experiments are rate limited. Progress requires new beams and progress with detectors and/or readout

Muon Physics - Sensitivity

The estimated number of low energy muons that could be provided with a 2MW Proton beam at 8 GeV is very large (3×10^{21} per year) … but utilization of these Muons will be very inefficient (large phase space).

Muon Source Requirements to Needed Make Progress

Experiment	q_μ	$\int I_\mu dt$	I_0/I_m	δT [ns]	ΔT [μs]	E_μ [MeV]	$\Delta p_\mu/p_\mu$ [%]
$\mu^- N \to e^- N^\dagger$	$-$	10^{21}	$< 10^{-10}$	≤ 100	≥ 1	< 20	< 10
$\mu^- N \to e^- N^\ddagger$	$-$	10^{20}	n/a	n/a	n/a	< 20	< 10
$\mu \to e\gamma$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu \to eee$	$+$	10^{17}	n/a	n/a	n/a	1...4	< 10
$\mu^+ e^- \to \mu^- e^+$	$+$	10^{16}	$< 10^{-4}$	< 1000	≥ 20	1...4	1...2
τ_μ	$+$	10^{14}	$< 10^{-4}$	< 100	≥ 20	4	1...10
transvers. polariz.	$+$	10^{16}	$< 10^{-4}$	< 0.5	> 0.02	30-40	1...3
$g_\mu - 2$	$\pm$	10^{15}	$< 10^{-7}$	≤ 50	$\geq 10^3$	3100	10^{-2}
edm_μ	$\pm$	10^{16}	$< 10^{-6}$	≤ 50	$\geq 10^3$	$\leq$1000	$\leq 10^{-3}$
M_{HFS}	$+$	10^{15}	$< 10^{-4}$	≤ 1000	≥ 20	4	1...3
M_{1s2s}	$+$	10^{14}	$< 10^{-3}$	≤ 500	$\geq 10^3$	1...4	1...2
μ^- atoms	$-$	10^{14}	$< 10^{-3}$	≤ 500	≥ 20	1...4	1...5
condensed matter (incl. bio sciences)	$\pm$	10^{14}	$< 10^{-3}$	< 50	≥ 20	1...4	1...5

Most experiments require p < 29 MeV/c, good extinction factors, small Δp/p.

To make progress we need to try to design a cost-effective muon source, the matching to the candidate experiments → evaluate cost & performance.

Cost may be the make or break issue.

Pions

Use 8 GeV proton beam + Recycler (?) as a stretcher.

Interface between particle & nuclear physics: Meson & baryon spectroscopy & Lattice Gauge Theory tests. Would complement the JLab program. Baryon spectroscopy requires a 2.5 GeV/c π/K tagged secondary beam.

$\pi e2$ & $\pi\mu 2$ decays $\rightarrow$ precise probe of e-μ universality in the weak interaction. Theoretical predictions 40 $\times$ more precise than experiment.

$\pi^{+} \rightarrow e + \nu \pi^{0}$ potentially offers improved V_{ud} measurement.

Kaons

Mode	Sample	Physics	Number of Protons on Target
$K^+ \rightarrow \pi^+ \nu\nu$	1000	3% $(V_{ts}{}^*V_{td})$	1.5×10^{20}
$K_L \rightarrow \pi^0 \nu\nu$	1000	1.5% $Im(V_{ts}{}^*V_{td})$	1.6×10^{21}
$K_L \rightarrow \pi^0 ee$	$2\text{x}10^4$	10% $Im(V_{ts}{}^*V_{td})$	2.5×10^{20}
$K_S\text{-}K_L \rightarrow \pi^0 ee$	TBD	10% $Im(V_{ts}{}^*V_{td})$	TBD

Present generation of rare kaon decay experiments are already rate limited. Future experiments at the Proton Driver would need to benefit from a DC beam with a large duty cycle (refit Tevatron Ring with permanent magnet dipoles ?) & the improvements in instrumentation expected in the next few years. If this can be accomplished the Proton Driver would offer the possibility of advances in kaon decay sensitivity.

Neutrons

Proton Driver would be comparable in its neutron capabilities with an upgraded SNS. There are some physics topics that will not be covered by the SNS program, and could be unique to the Proton Driver: (i) Production of ultra-cold neutrons $\rightarrow$ neutron EDM and lifetime, (ii) neutron induced "upsets" in semiconductors, (iii) n-nbar oscillations (improve sensitivity by $\times 100$)

Antiprotons

The antiproton source could be used with the Proton Driver for a continuation of the low energy antiproton program: (i) Bottom-onium formation (?), (ii) CP Violation in hyperon decays – order of magnitude improvement in sensitivity over HyperCP, (iii) Light hadron spectroscopy (?)

SUMMARY - 1

Neutrino Oscillation physics is exciting $\rightarrow$ World Class, multi-phase, with the potential for further discoveries

A Proton Driver program yielding 2MW at MI energies would make critical contributions to the Global neutrino program in all θ_{13} scenarios, & (within reason) independent of exactly what else is built and when. The NuMI beam is the longest-baseline beam in the World with the right energy range for significant matter effects!

Neutrino scattering measurements are important for the oscillation program, & broaden the program $\rightarrow$ Needs 2MW or more at 8 GeV.

The potential 8 GeV-based program includes neutrino scattering, low energy muon, pion & neutron experiments, & perhaps a 2nd low energy neutrino beam going to the long-baseline detector. Even at 2MW the 8 GeV proton beam would probably be over-subscribed.

SUMMARY - 2: The Proton Driver could support a diverse physics program

Physics of LFV $\leftrightarrow$ Probing the GUT scale:
Neutrino Oscillations, precision muon experiments.

Physics at the TeV-scale (complementary to the LHC program):
Precision muon and kaon experiments, neutron experiments (?)

Interface between particle and nuclear physics (complementary to Jlab program):
Neutrino scattering, hadron spectroscopy ….

Other possibilities:
Neutrons, antiprotons, …