Fermilab

Physics at an Upgraded Fermilab Proton Driver

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3. Proton Driver Options
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Introduction – Fermilab Long Range Planning Report

The basic recommendation: Aggressively pursue two options for Fermilab's future: A LC & a high−intensity Proton Driver.

Proton Driver Recommendations

1) We recommend that Fermilab prepare a case sufficient to achieve a statement of mission need (CD−0) for a 2 MW proton source (Proton Driver).

2) We recommend that Fermilab elaborate the physics case for a Proton Driver & develop the design for a superconducting linear accelerator to replace the existing Linac−Booster system. … Cost & schedule estimates for Proton Driver based on a new booster synchrotron & new linac should be produced for comparison. A Technical Design Report should be prepared for the chosen technology.

Introduction – Response to the Recommendations

The Fermilab Director has requested:

"Preparation of documentation sufficient to establish mission need for the Proton Driver as defined by the Department of Energy CD−0 process."

"Development and documentation of the physics case. I would like this to include both support for a forefront neutrino program at Fermilab in the decade 2010 and beyond, and identification of other opportunities that could potentially be enabled with a Proton driver facility."

"I am hopeful that the assignment described above can be completed by the end of 2004."

- **Charge is headed by Steve Geer at Fermilab.**

Fermilab Proton Driver Upgrade Physics Study

We are in the middle of setting up an organization and planning a workshop to explore the physics case.

http://www−td.fnal.gov/projects/PD/PD2.html

http://www−td.fnal.gov/projects/PD/PHYSICS.html

Workshop will be at Fermilab October 6–9th.

Neutrino Oscillations

Stunning experimental results have established that neutrinos change flavor and have nonzero, but very small masses, implying profound changes to the Standard Model.

Neutrino masses (i.e. right−handed neutrinos) must be added to the Standard Model. We can now expect Lepton Flavor Violation to happen.

If we add Dirac mass terms, then there is no SM principle preventing us from adding also Majorana mass terms.

Majorana mass terms $\rightarrow$ Lepton Number Violation

Neutrino masses & mass splittings are tiny compared to the masses of the other fundamental fermions $\rightarrow$ Window to Physics at GUT or Planck Scale, or indicates the existence of new spatial dimensions.

Neutrino Oscillation Physics: First Round of Questions

Is three−flavor mixing the whole story ?
Light sterile neutrinos ? Other deviations from three−flavor mixing?

There is one unmeasured angle (θ_{13}) in the mixing matrix.

Is θ_{13} non−zero?

We don't know the mass−ordering of the neutrino mass eigenstates. There are two possibilities, the so−called "normal" hierarchy or the "inverted" hierarchy. Which mass hierarchy applies?

There is one complex phase (δ) in the mixing matrix accessible to ν oscillation measurements. If θ_{13} & sin δ are non−zero there will be CP Violation in the ν−sector.
Is there CP Violation in the Neutrino Sector ?

A World−Class Accelerator−based Neutrino Program at Fermilab

MiniBooNE: Confirmation of LSND oscillation

MIPP: (partial motivation) Particle production related to ν beam systematics

Minerva: Proposal for neutrino cross−sections at low energy

MUCOOL: Neutrino Factory R&D

MINOS: Long−baseline, on−axis, neutrino disappearance at frequencies seen by the SK atmospheric neutrino result

NOνA: Proposal for Long−baseline, off−axis, neutrino appearance at frequencies seen by the SK atmospheric neutrino result

Next Steps for Accelerator−Based Long Baseline Neutrino Experiments

Step 1: A very massive (possibly off−axis ?) "Superbeam" experiment to probe $\sin^2 2\theta_{13}$ down to ~0.001−0.002 and if the result is positive, determine the mass hierarchy and begin the search for CP Violation.

Step 2: A second generation Superbeam experiment optimized to complete the physics program of step 1

OR

A "Neutrino Factory" to complete the program of step 1 if $\sin^2 2\theta_{13}$ is as small as 10^{-4} .

These scenarios require a new High Intensity (2MW) Proton Driver

Physics Reach of Current and Planned Long Baseline Experiments

Beam Name	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.[a]	δ[b] CPV	Mass Hierarchy
OPERA[g]	1.8	0.15	0.04	-	–
ICARUS[g]	2.4	0.15	0.03	-	–
MINOS[m]	5	0.25 → 0.4	0.05	-	–
CNGS**	2.35	.15	~ 0.02**		–
T2K	22.5	0.8	0.006	-	-
NOνA	50	0.4	0.004	-	Yes
T2HK	450	4	~ 0.001[g]	$\lvert\delta\rvert > 20°$	–
Super-NOνA	100	2	~ 0.001[g]	135 ± 20	Yes
BNL2NUSL	500	1	0.004	45 ± 20	Yes
CERN SPL	400	4	0.0016	90 ± 30	–
β Beam	400	.04		T viol.	–
ν Factory	50	4	$< 10^{-4}$	90 ± 20	Yes

[a] at $\Delta m^2_{32} = 3 \times 10^{-3} eV^2$, at 90% CL

[b] all evaluated at different regions of parameter space!

[g] Komatsu, Migliozzi, Terranova J.Phys.**G29** 443, 2003 [m] Diwan, Messier, Viren, L.Wai, NUMI-L-714

[g] Assume 5% systematic uncertainty!

[**] modified, Rubbia, Sala, hep-ph/0207084

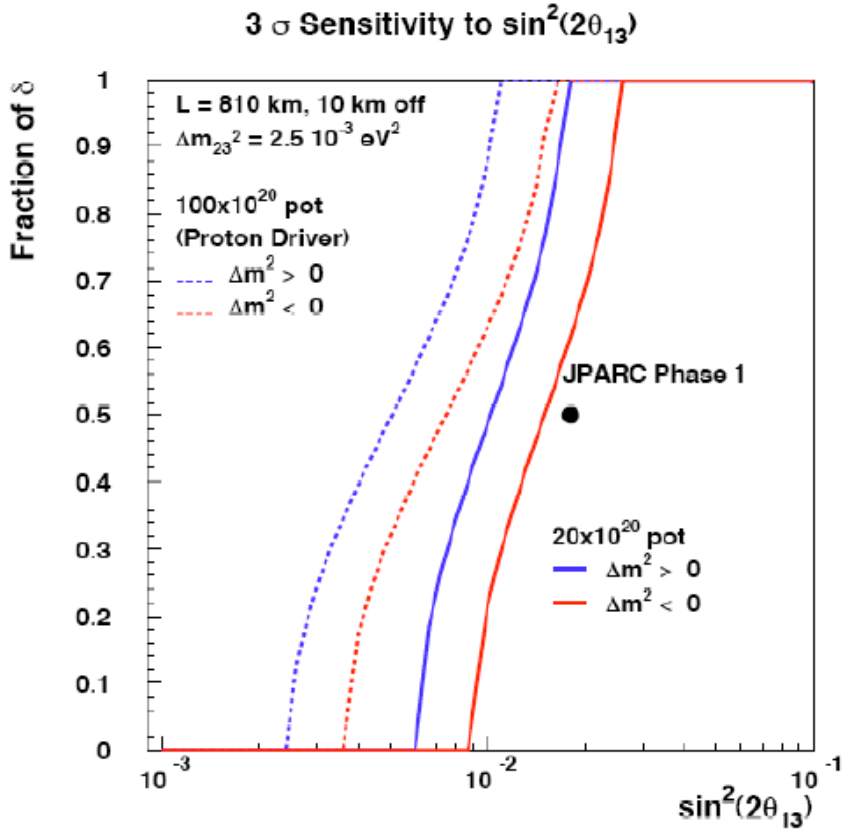
Near−term program: no sensitivity to CPV or mass hierarchy (matter effects)

Superbeam program: order of magnitude improved θ_{13} sensitivity, & increasing chance of observing CPV & mass hierarchy.

Superbeams open the way to the ultimate neutrino factory sensitivity

NOνA

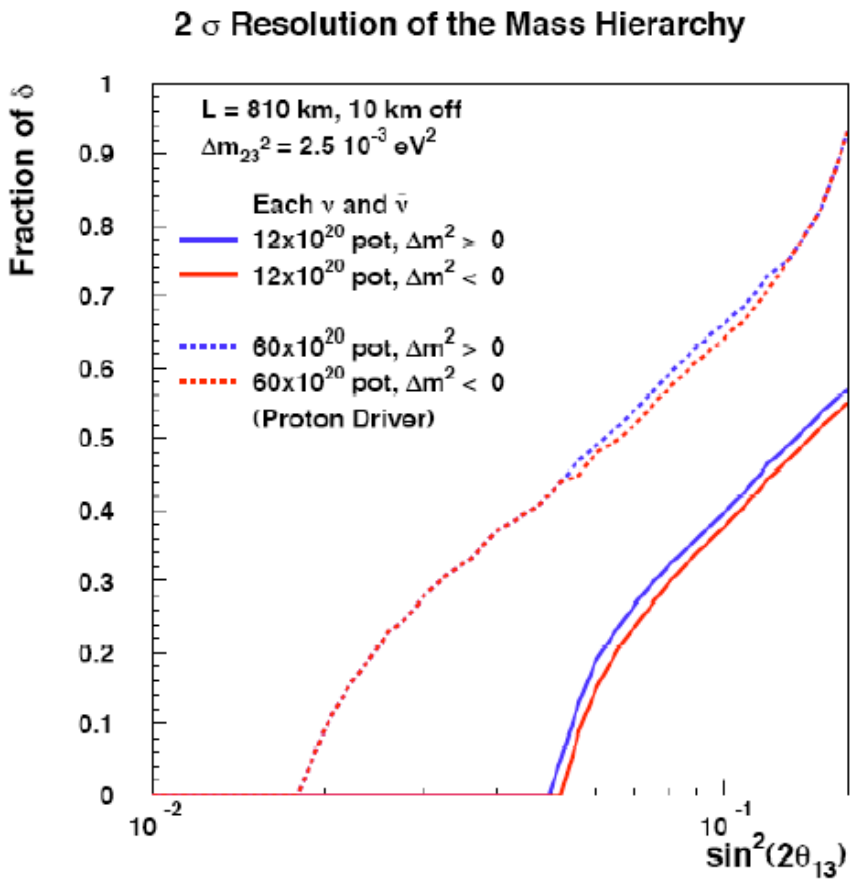
3 σ Discovery Potential for $\nu_\mu \rightarrow \nu_e$



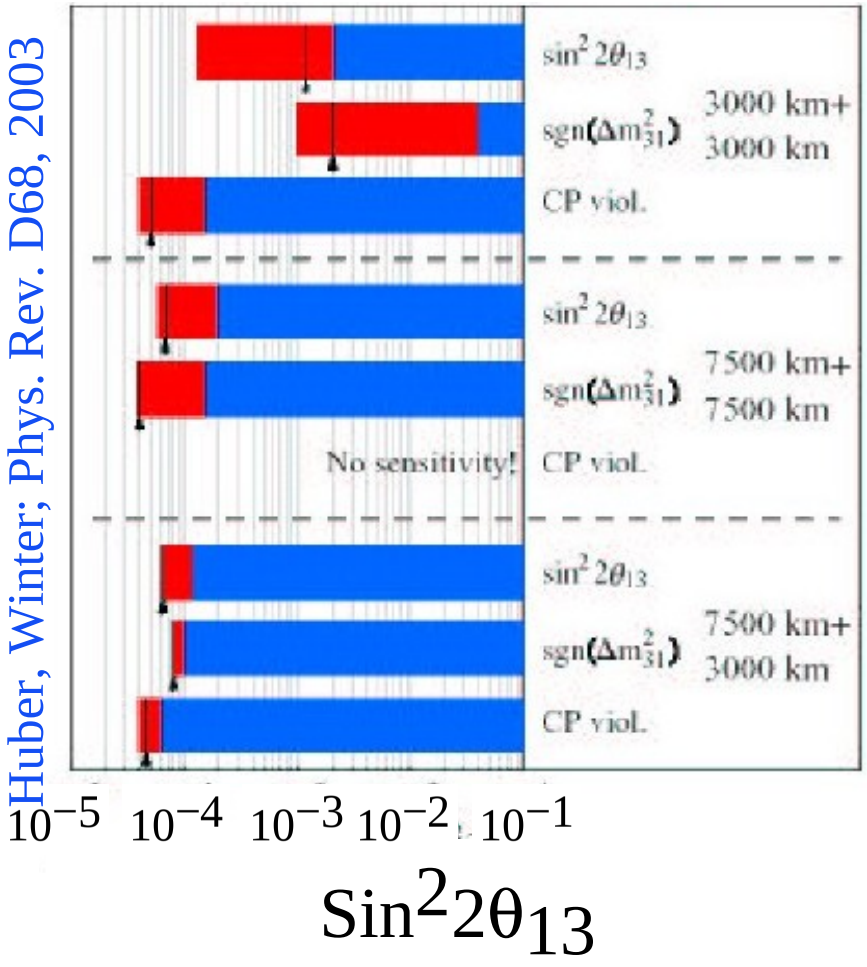
Case Study by the NOνA Collaboration

NOnA

95% CL Resolution of the Mass Hierarchy



Ultimate Reach with a MW Proton Driver as Injector for a Neutrino Factory



The full physics program (Establishing the magnitude of θ_{13}, determining the mass hierarchy, & searching for CP Violation) can be accomplished provided $\mathrm{Sin}^2 2\theta_{13} > O(10^{-4})$!

PLUS additional tests of the 3−flavor framework through $\nu_e \rightarrow \nu_\tau$ measurements.

If $\theta_{13} = 0$, will still discover ν_e appearance !

Proton Driver Technology Choice

- Charge headed by Bill Foster at Fermilab

- Two Main Options to Replace the Current Fermilab Booster:

  8 GeV Conventional Proton Synchroton

  8 GeV Super Conducting Proton Linac based on
  SC technology developed for RIA, SNS, and Tesla

- Getting from 0.3 MW to 2 MW:

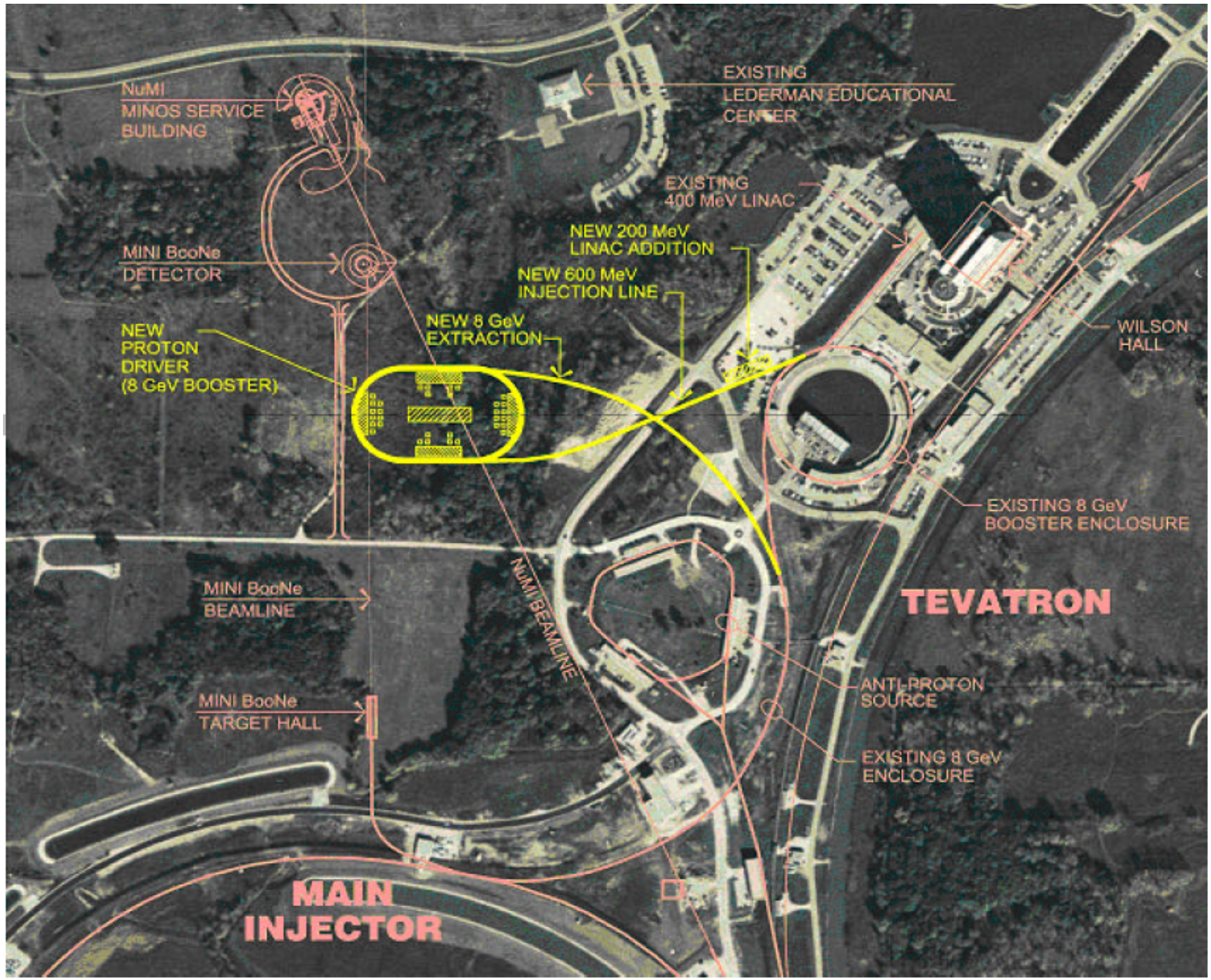
  More protons per pulse

  Increase repetition rate

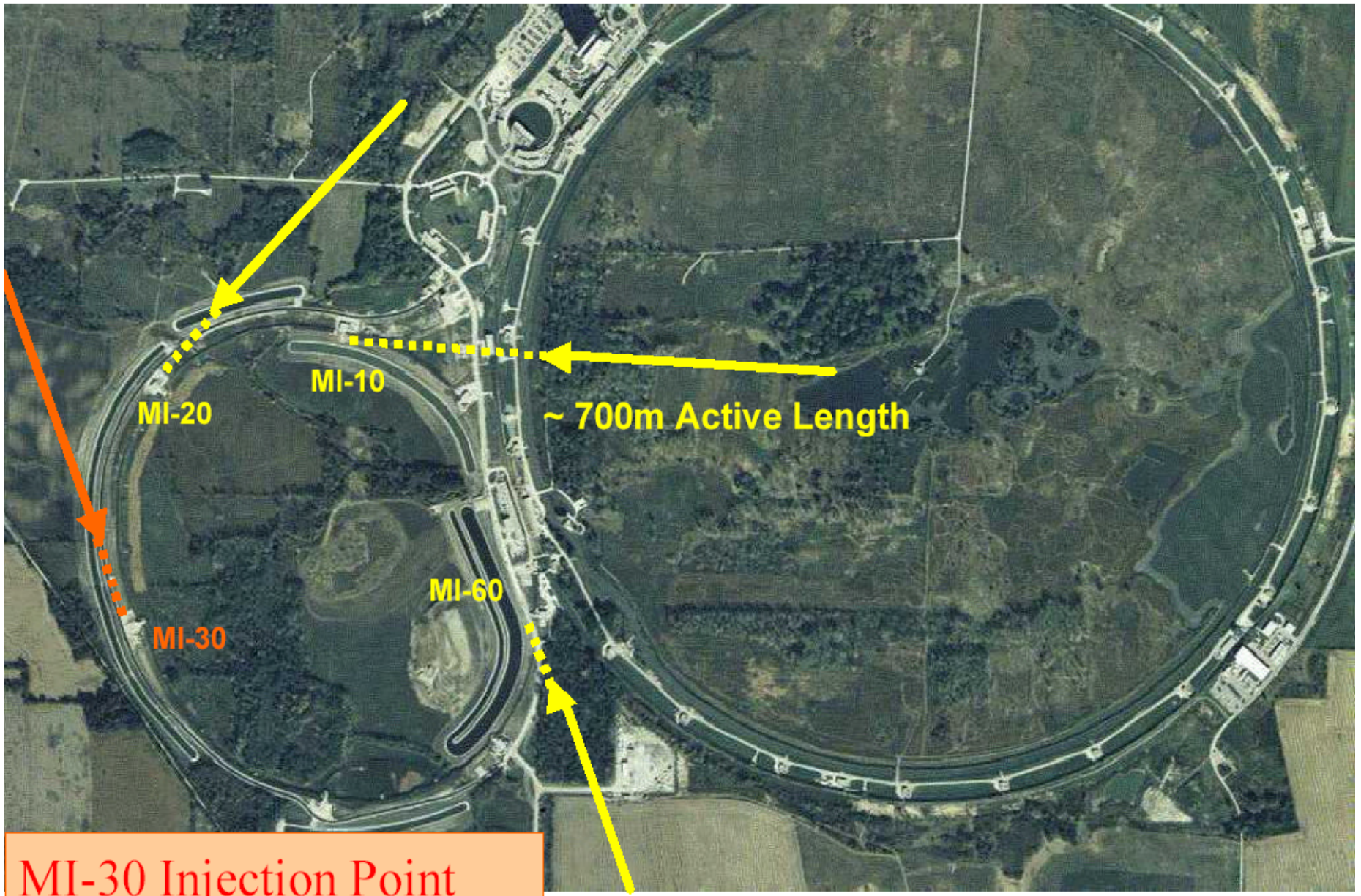
  Increase machine aperture to take advantage of large
  aperture of Main Injector

		Present	Synchrotron	Linac
Linac				
Kinetic Energy		400	600	**8000**
Peak Current		40	50	25
Pulse Length		90	90	1000
Protons/pulse		2.3E+13	2.8E+13	1.6E+14
Repetition Rate		15	15	10
Average Beam Power		0.02	0.04	**2.00**
Booster				
Kinetic Energy (Out)		8	8	
Protons per Pulse		5.0E+12	2.5E+13	
Repetition Rate		7.5	15	
Protons/hour		1.4E+17	1.4E+18	
Average Beam Power		0.05	**0.5**	
Main Injector				
Kinetic Energy (Out)		120	**120**	**120**
Protons per Pulse		3.0E+13	1.5E+14	1.6E+14
Repetition Rate		0.54	0.65	0.67
Protons/hour		5.8E+16	3.5E+17	3.8E+17
Average Beam Power		0.3	**1.9**	**2.0**

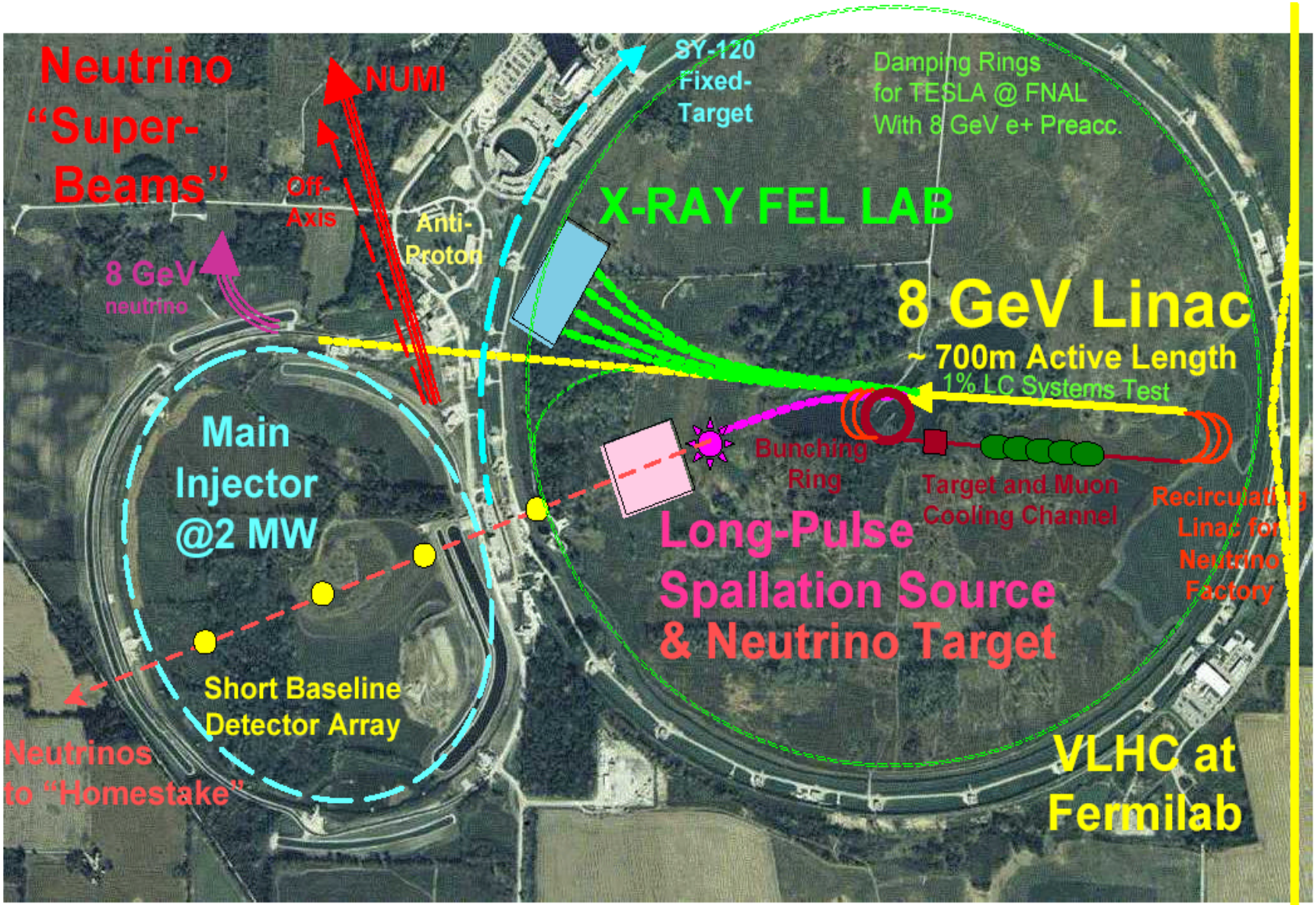
Proton Driver Option: Conventional 8 GeV Proton Synchroton



Proton Driver Option: 8 GeV Super Conducting Linac



A Path to the Very Long Term Future With an 8 GeV Linac as Envisioned by Bill Foster



The Broader Physics Program

Neutrino physics arguably provides a compelling case for a 2 MW proton driver, but diversity is also important.

We believe that it also can support a host of other world−class experiments with discovery potential.

Initial Set of Working Groups

1. **Accelerator−Based Neutrino Oscillation Physics**
2. **Neutrino Interaction Physics (includes exploring using electrons from the Linac)**
3. **Low Energy & Stopped Muon Program**
4. **Kaons and Pions**
5. **Antiprotons**
6. **Neutrons**
7. **Accelerator−Based Particle Astrophysics**
8. **Tevatron Collider (including B and C physics)**

Some examples from previous proton driver physics study in 2001

Probes of Lepton Flavor Violation: $\mu \rightarrow e\gamma$, $\mu \rightarrow e\gamma\gamma$, $\mu \rightarrow$ e conversion

Precision tests & measurements of the CKM Matrix: Testing the SM description of CP in both B and K systems

We need to reevaluate in the context of New Physics implied by Neutrino Masses and Mixing.

Potential Connection Between the Muon Properties and Neutrino Masses and Mixing

- Explored by Ellis, Raidal, Hisano, Nomura, Strumia, and **many many** others
- Extension of the seesaw phenomology to include supersymmetry
  - Lepton Flavor Violation in Muon Decays:

    BR($\mu \rightarrow e\,\gamma$) could be as large as 10^{-11}

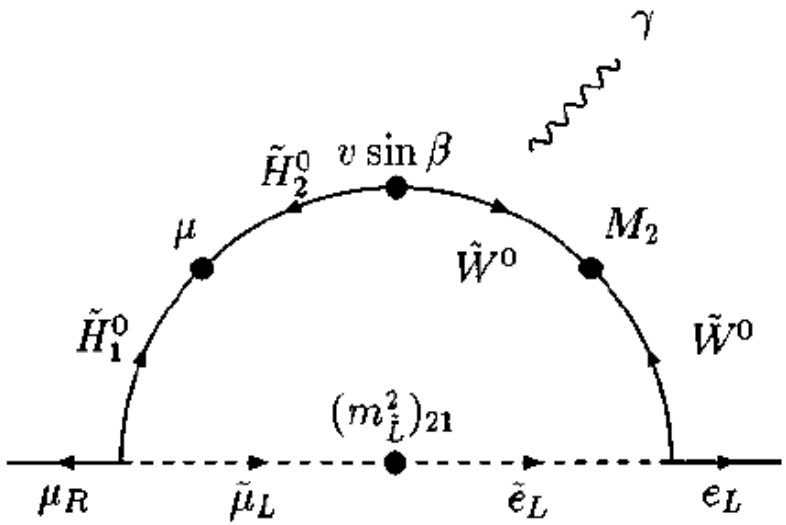
  - Muon Electric Dipole Moment:

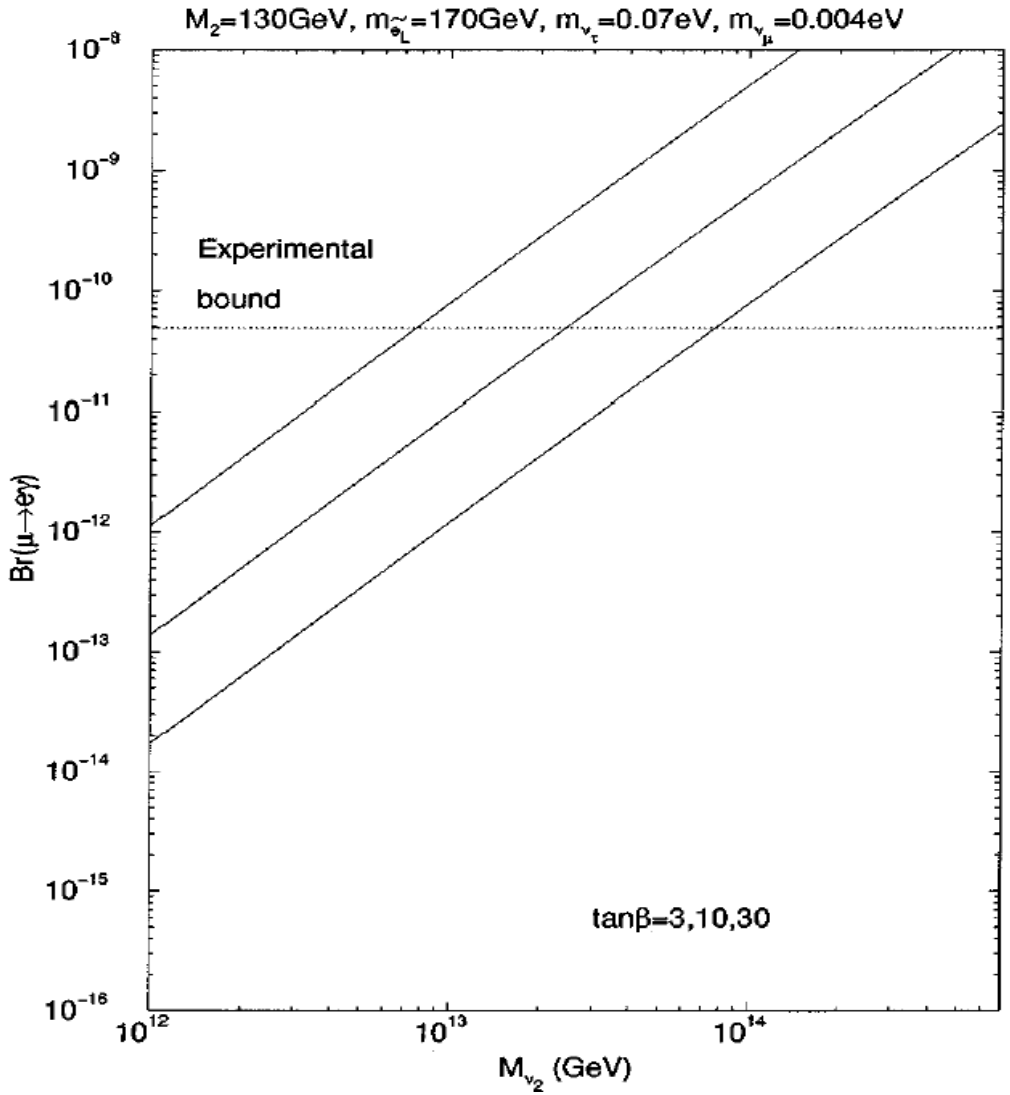
    Could be as large as 10^{-25} ecm (Ellis + Raidal hep−ph/0206174)

One example: Hisano + Nomura PRD 59 116005

BR($\mu \rightarrow e\gamma$) $\sim 10^{-54}$ if
light−neutrino mixing were
the only source of LFV

Enhanced $\mu \rightarrow e\gamma$
due to large θ_{12} contribution to
slepton mixing





Is There a Potential Connection Between Quark Flavor and Neutrino Masses and Mixing ?

- Explored by Perez (1999), and very recently by Grossman, Isidori, and Murayama (2003) for the ultra−rare decay mode $K \to \pi\nu\bar{\nu}$

- seesaw phenomenology + supersymmetry + non−universal interactions can induce effects in $K_L \to \pi^0\nu\bar{\nu}$

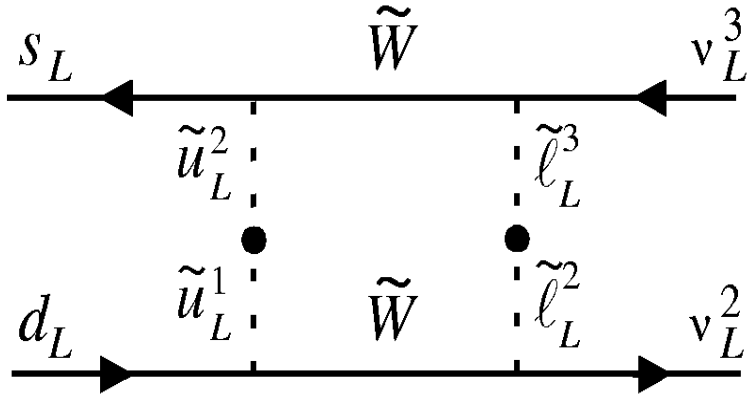


Figure 1: Wino-Wino box diagram.

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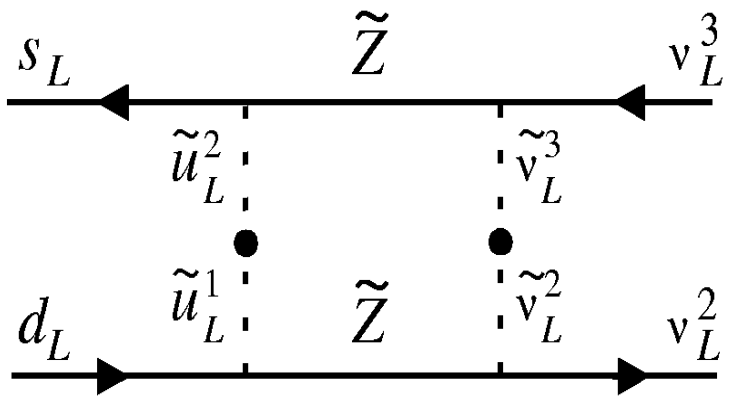

Figure 2: Zino-Zino box diagram.

Physics Study

A previous Fermilab proton driver study in 2001 included a physics study that produced a 134 page report → good starting point.

We need to update and extend the study, look more at how the expected physics capabilities change with proton driver performance, and produce the documentation needed for the next step.

We are in the middle of putting together an organization to accomplish this, with working groups to cover the various physics sub-topics, and a workshop in the Fall.

Summary

A 2MW proton driver at Fermilab would provide, for decades to come, an exciting World Class physics program for its user community.

Neutrino oscillation physics would provide the main thrust for the program, but the proton driver can also support a more diverse program of world class experiments.

The details need further exploration and the case needs to be well documented to enable us to proceed to the next step … this is the purpose of the physics study

→ **Workshop will be at Fermilab October 6–9th.**