Fermilab

Physics at an Upgraded Fermilab Proton Driver

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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."

Fermilab Proton Driver Upgrade Physics Study

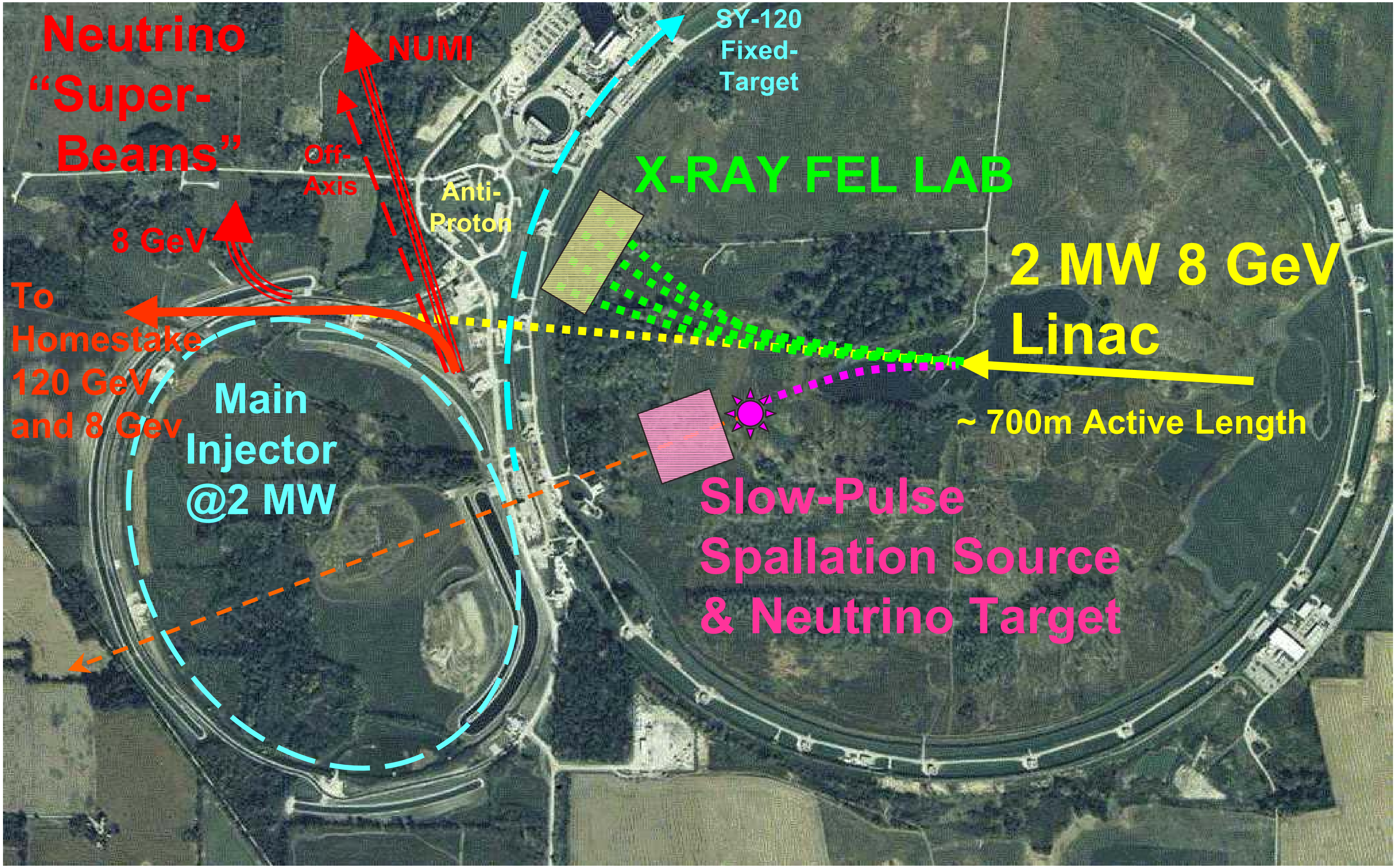
We are in the middle of setting up an organization and planning a workshop to explore the physics case.

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.

A New Fermilab Proton Driver would offer Flexibility for the Future Physics Program in General, & the Neutrino Program in Particular



Neutrino Oscillations are Exciting

Stunning experimental results have established that neutrinos have nonzero masses and mixings

The Standard Model cannot 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.

We 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.

Whatever the origin of the observed neutrino masses & mixings is, it will certainly require a profound extension to our picture of the physical world.

Fermilab and Neutrinos

Fermilab is host to the US accelerator-based neutrino program

MiniBooNE: LSND oscillation test
MINOS: Long-baseline, atmospheric neutrino mass scale
MUCOOL: Neutrino Factory R&D
MIPP: (partial motivation): Particle production (ν beam systematics)
Minerva: (neutrino cross-sections)

This suite of experiments provides a cutting-edge World-class experimental program that is a key part of the Global neutrino program.

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} & $\sin \delta$ are non-zero there will be CP Violation in the ν-sector.
Is there CP Violation in the Neutrino Sector ?

A Fermilab Proton Driver Based Program that achieves the Ultimate Sensitivity

Step 1: A 2MW Proton Driver and very massive (off-axis ?) Superbeam experiment that probes $\sin^2 2\theta_{13}$ down to ~0.001-0.002 and if the result is positive, determines the mass hierarchy and begins the search for CP Violation.

Step 2: A second generation Superbeam experiment optimized to complete the first generation physics program OR a Neutrino Factory, as needed.

This will enable the full first order physics program to be completed if $\sin^2 2\theta_{13}$ exceeds $O(10^{-4})$.

Oscillation Physics Reach

Long-Baseline Experiments

Beam Name	Mass (kton)	Power (MW)	$\sin^2 2\theta_{13}$ sens.[a]	δ[b] CPV	Mass Hierarchy
OPERA[a]	1.8	0.15	0.04	-	-
ICARUS[a]	2.4	0.15	0.03	-	-
MINOS[m]	5	$0.25 \rightarrow 0.4$	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[s]	$\lvert\delta\rvert > 20°$	-
Super-NOνA	100	2	~ 0.001[s]	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!

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

[s] Assume 5% systematic uncertainty!

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

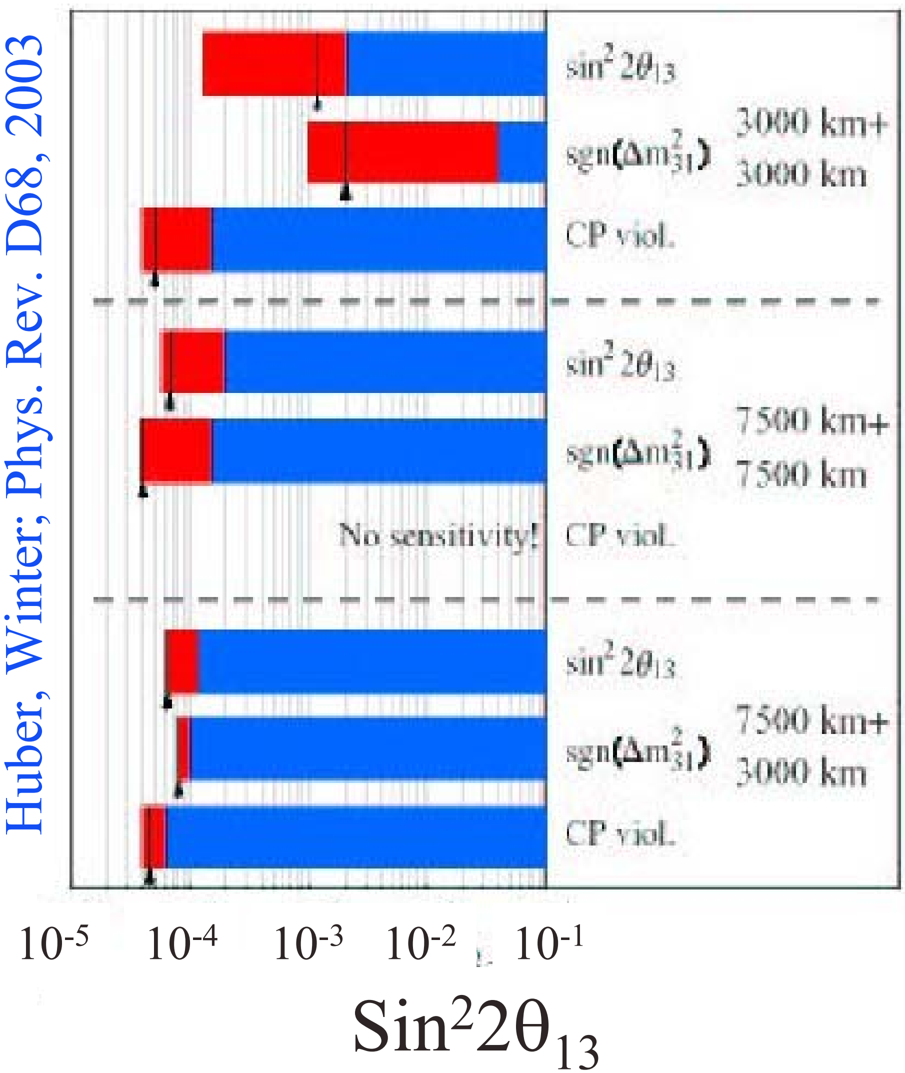
Near-term program: no sensitivity to CPV or mass hierarchy (matter effects)

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

A MW-Scale Proton Driver provides a path to the Ultimate Neutrino Oscillation Physics Reach at a Neutrino Factory

Huber, Winter; Phys. Rev. D68, 2003



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 !

The Broader Neutrino Program

The Booster-Based ν Program is limited by proton economics and this will get worse when the NuMI program begins.

An upgraded proton driver will provide flexibility to exploit big surprises (for example, a positive MiniBooNE result) ….

… and opportunities for new "small" neutrino experiments.
Examples: low energy neutrino cross-section measurements, neutrino magnetic moment and exotic interaction searches.

The neutrino program that could be supported by a 2MW proton driver is likely to consist of a multi-phase program with at least a handful of experiments that provide world class cutting edge physics for a period of a couple of decades or longer.

Low Energy Neutrino Event Rates

1. MiniBooNE-type beam: 25KW → ~2MW

2. Decays at Rest:

Brice, Geer, Paul & Tayloe

	FNAL 2 MW at 8 GeV	SNS 1.4 MW at 1.3 GeV
P/yr	1.6×10^{22}	6.7×10^{22}
DAR (ν/p)	1.5	0.13
DAR (ν/yr)	2.3×10^{22}	0.92×10^{22}
ν_e Events/yr	$8900\ \varepsilon_{REC}$	$3500\ \varepsilon_{REC}$
ν_μ Events/yr	$1500\ \varepsilon_{REC}$	$600\ \varepsilon_{REC}$
ν_μ Events/yr	$3200\ \varepsilon_{REC}$	$1200\ \varepsilon_{REC}$

Neutrino production from Decays At Rest

Event rates for a MiniBooNE-like detector at L = 60 m *(scaled from G. Van Dalen nucl-ex/0309014)*

Neutrino Superbeam Flexibility: An Example

Doug Michael, Chris Smith, Mark Messier

→ A new neutrino beamline using the same 120 GeV extraction line as the current NuMI beam but then redirecting towards Homestake.

→ In addition, a beamline to deliver 8 GeV protons from the new proton driver.

→ Dual targeting/focussing stations

→ Decay region ~200 m in length, 4 m tall and 8 m wide. (Roughly the same scale as NuMI construction.)

→ Tunable Off Axis beams for 120 GeV protons. On axis beam for 8 GeV protons.

→ 2 MW of proton power at both 120 GeV and 8 GeV.

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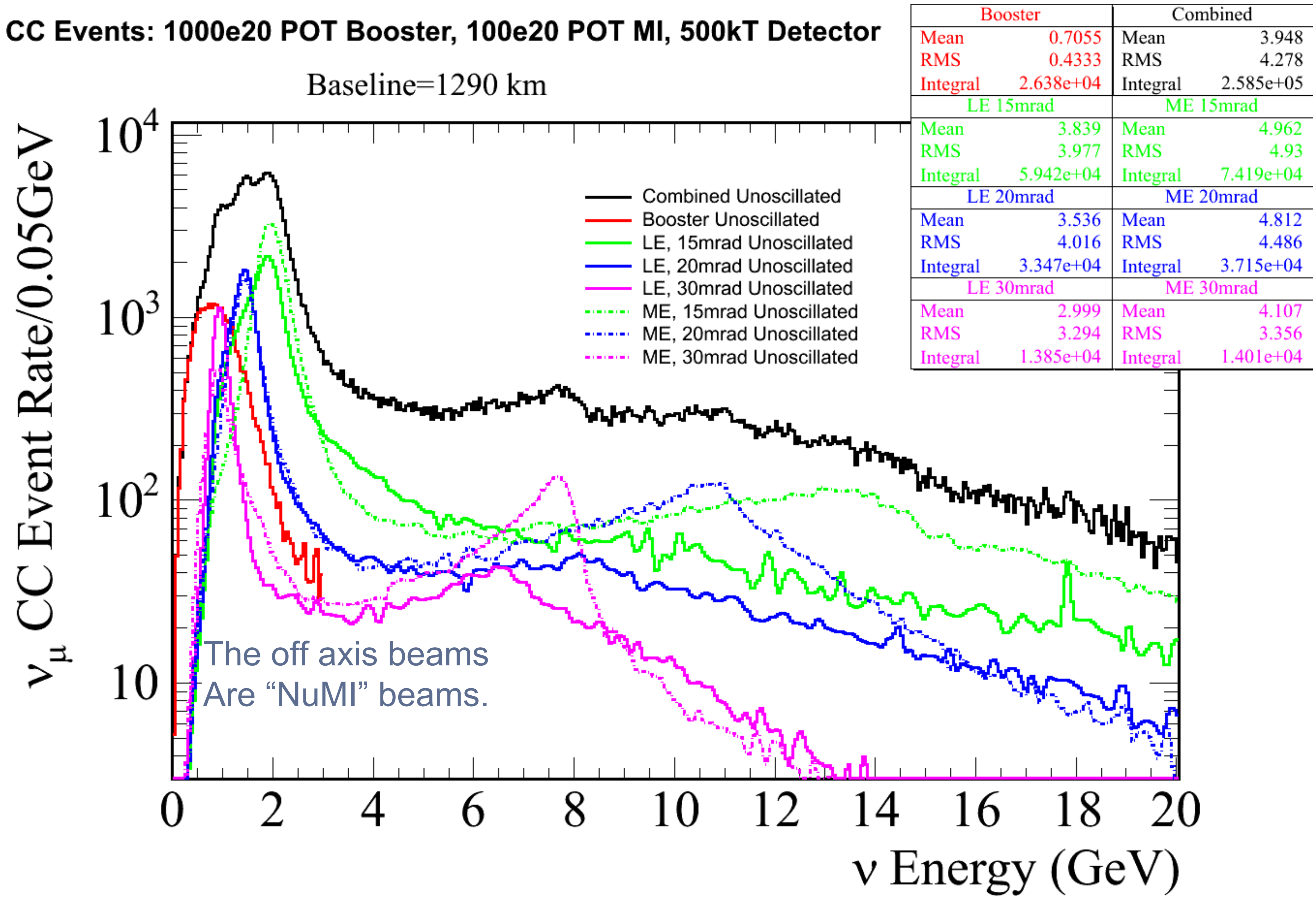

A Broader Proton Driver Program

Neutrino physics (I believe) provides a compelling case for a 2MW proton driver, but diversity is also important. With an intensity frontier machine there are other potentially big discovery type experiments, and important measurements, to chose from:

Some Examples from previous physics study in 2001

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

Precision tests & measurements of the CKM Matrix: Comparison of B-physics measurements and rare kaon decay measurements, and the search for CP-Violation in the hyperon system.

Interface between particle & nuclear physics: Flavor-dependent and polarized nucleon structure functions, search for exotic hadrons, nuclear shadowing, pion structure function.

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.

Workshop will be at Fermilab October 6-9th.

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)**

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Summary

A 2MW proton driver at Fermilab would provide, for decades to come, an exciting World Class physics program for the laboratory and 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

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