Fermilab

Physics at a New Fermilab Proton Driver

1. Introduction & Parameters
2. Physics Study
3. Event Rates
4. Neutrino Oscillation Physics Reach
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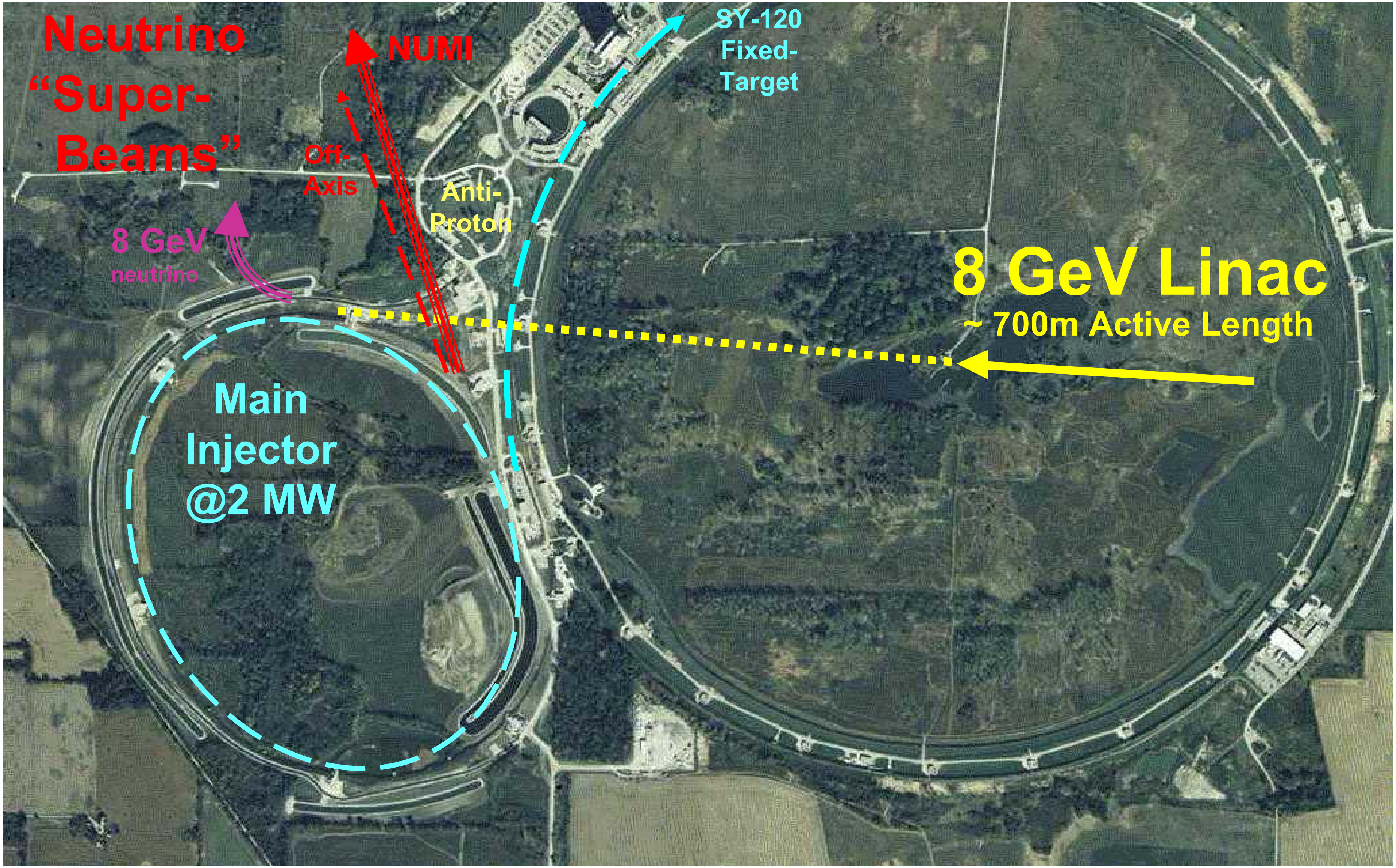
Introduction

The recent (2004) 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."

Neutrino physics provides the primary motivation for upgrading the intensity of the Fermilab Proton Source.

Proposed Fermilab 8 GeV Proton Driver



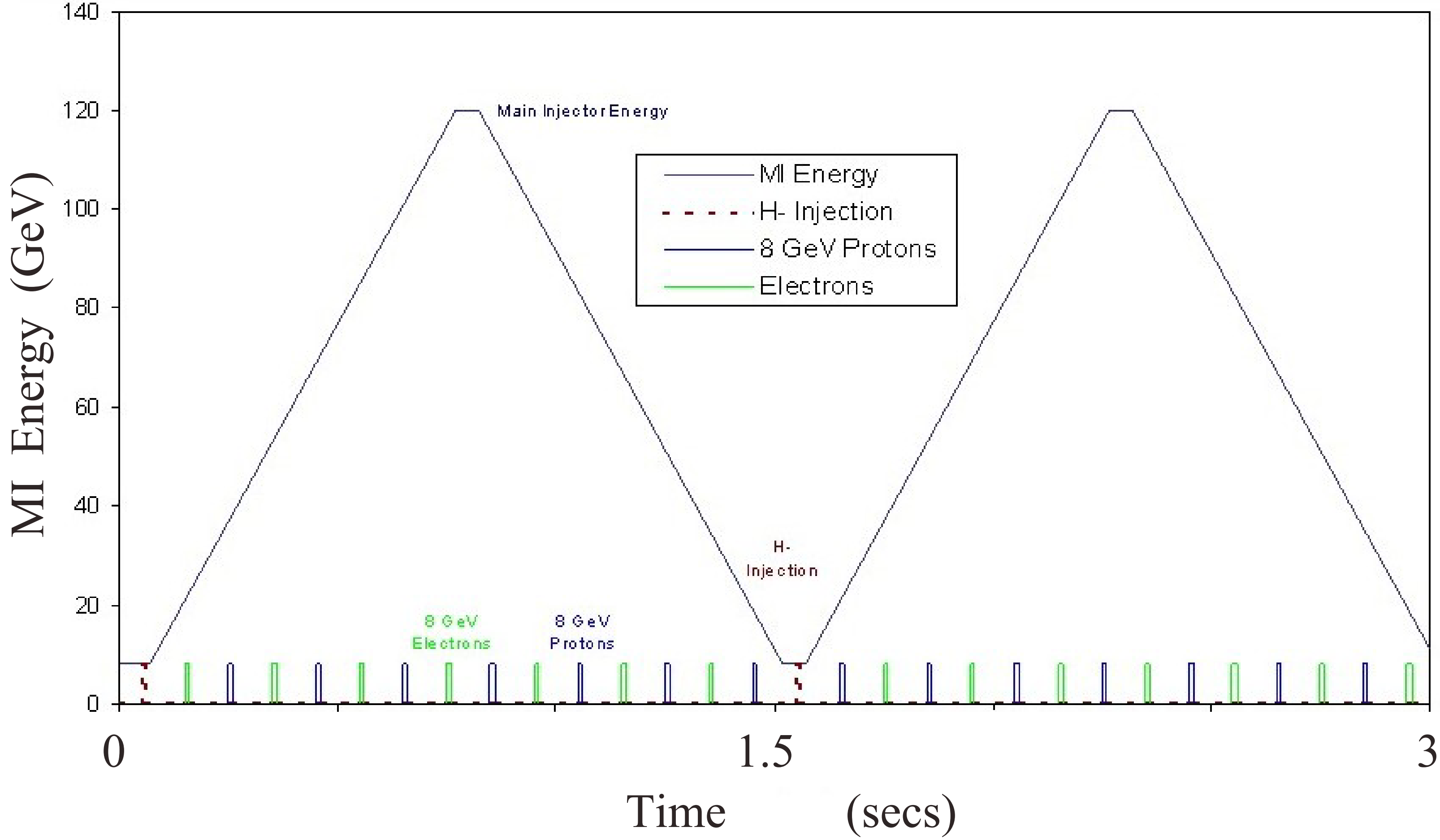
Parameters	*Present*	*Proton Driver*
Linac *(Pulse Freq.)*	*5 Hz*	*10 Hz*
Kinetic Energy	*400 MeV*	*8 GeV*
Peak current	*40 mA*	*28 mA*
Pulse length	*25 μs*	*1 ms*
Booster *(cycles at 15 Hz)*		
Extraction Kinetic Energy	*8 GeV*	
Protons per cycle	5×10^{12}	
Protons per hour	9×10^{16} *(5 Hz)*	
8 GeV Beam Power	*33 KW (5 Hz)*	*2 MW*
Main Injector *(120 GeV)*		
Protons per cycle	3×10^{13}	1.5×10^{14}
Fill time	*0.4 sec*	*0.1 sec*
Ramp time	*1.47 sec*	*1.4 sec*
Cycle time	*1.87 sec*	*1.5 sec*
Protons per hour	5.8×10^{16}	3.5×10^{17}

Proton Source Parameters

Present MI Beam Power = 0.3 MW

With Proton Driver MI Beam Power → 2 MW

New Fermilab Proton Driver



Cycle Time

Since the MI injection time << cycle time, most of the 2 MW 8 GeV (initially 0.5 MW) Linac beam available for an additional program.

Proton Driver Physics Study

In Spring 2004 the Fermilab Directorate initiated a study to explore the physics potential of a new Fermilab Proton Driver.

What (particle) physics can be done with 2 MW Main Injector proton beam ?
What (particle) physics could be done with a 0.5 – 2 MW 8 GeV proton beam ?

The study included a workshop at Fermilab in October 2004, and produced a written report in 2005.

Web Page: http://protondriver.fnal.gov/

Proton Driver Physics Study
Working Groups and Conveners

WG1: Neutrino Oscillations
D. Harris (FNAL), S. Brice (FNAL), W. Winter (Princeton)

WG2: Neutrino Interactions
J. Morfin (FNAL), R. Ransome (Rutgers), R. Tayloe (Indiana)

WG3: Muons
R. Ray (FNAL), R. Roberts (BU)

WG4: Kaons and Pions
H. Nguyen (FNAL), T. Yamanaka (Osaka U.)

WG5: Antiprotons
D. Christian (FNAL), M. Mandelkern (UCI)

WG6: Tevatron Collider
H. Cheung (FNAL), Penny Kasper (FNAL), P. Ratoff (Lancaster U.)

WG7 Neutrons
T. Bowles (LANL), G. Greene (ORNL)

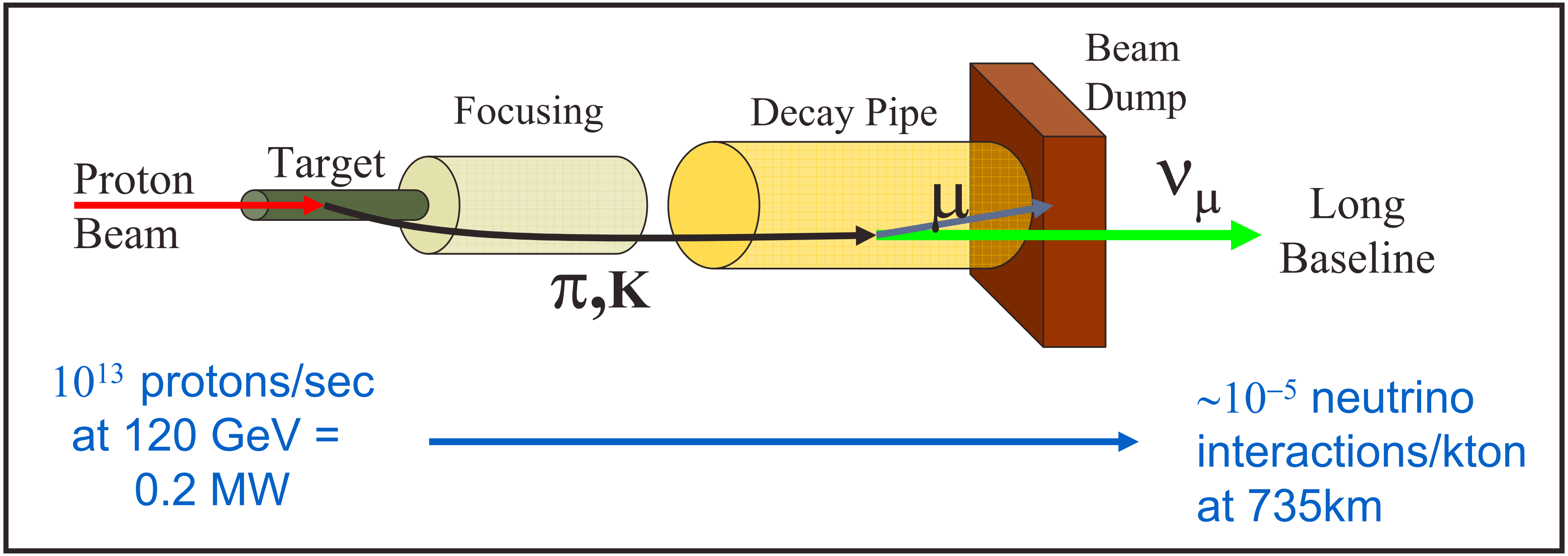
Proton Driver Scientific Advisory Committee

Peter Meyers (Chair)	Princeton
Ed Blucher	Chicago
Gerhard Buchalla	Munich
John Dainton	UK
Yves Declais	Lyon
Lance Dixon	SLAC
Umberto Dosselli	INFN
Don Geesaman	ANL
Geoff Greene	ORNL
Taka Kondo	KEK
Marvin Marshak	Minnesota
Bill Molzon	UCI
Hitoshi Murayama	UC Berkley
James Siegrist	LBNL
Anthony Thomas	JLab
Taku Yamanaka	Osaka

1. Give emerging physics case a critical review

2. Help us to reach out to a broad community as we develop a constituency excited by the Proton Driver Physics Program

Why Do We Need Higher 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
& DETECTORS of a FEW TIMES 10kt

Determining all of the Parameters will be Challenging

Expand in $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ and $\sin^2 2\theta_{13}$ and keep first order terms

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \;\approx\;& \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
&\pm \sin\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
&+ \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
&+ \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

ν / $\bar{\nu}$ → ±

NOTE:

$\Delta = \Delta m^2_{31}\, L/E$

Matter parameter $A = 2\sqrt{2} G_F n_e \; E/\Delta m^2_{31}$

For $\nu \to$ anti-ν, $A \to -A$, AND the sign of A depends on the sign of Δm_{32}^2

$\nu_\mu \rightarrow \nu_e$ Event Rates: 5 Years Running

Calculations of W. Winter

Normal Hierarchy, $\delta = 0$

	$\sin^2 2\theta_{13} = 0.1$		$\sin^2 2\theta_{13} = 0.01$	
Expt	*Signal*	*Backgr*	*Signal*	*Backgr*
MINOS	*49.1*	*108*	*6.7*	*109*
ICARUS	*31.8*	*69.1*	*4.5*	*70.3*
OPERA	*11.2*	*28.3*	*1.6*	*28.6*
T2K	*132*	*22.7*	*16.9*	*23.5*
NOvA	*186*	*19.7*	*23.0*	*20.7*
NOvA+FPD	*716*	*75.6*	*88.6*	*79.5*
NuFact nu	*29752*	*44.9*	*4071*	*44.9*
NuFact nubar	*7737*	*82.0*	*1116*	*82.0*

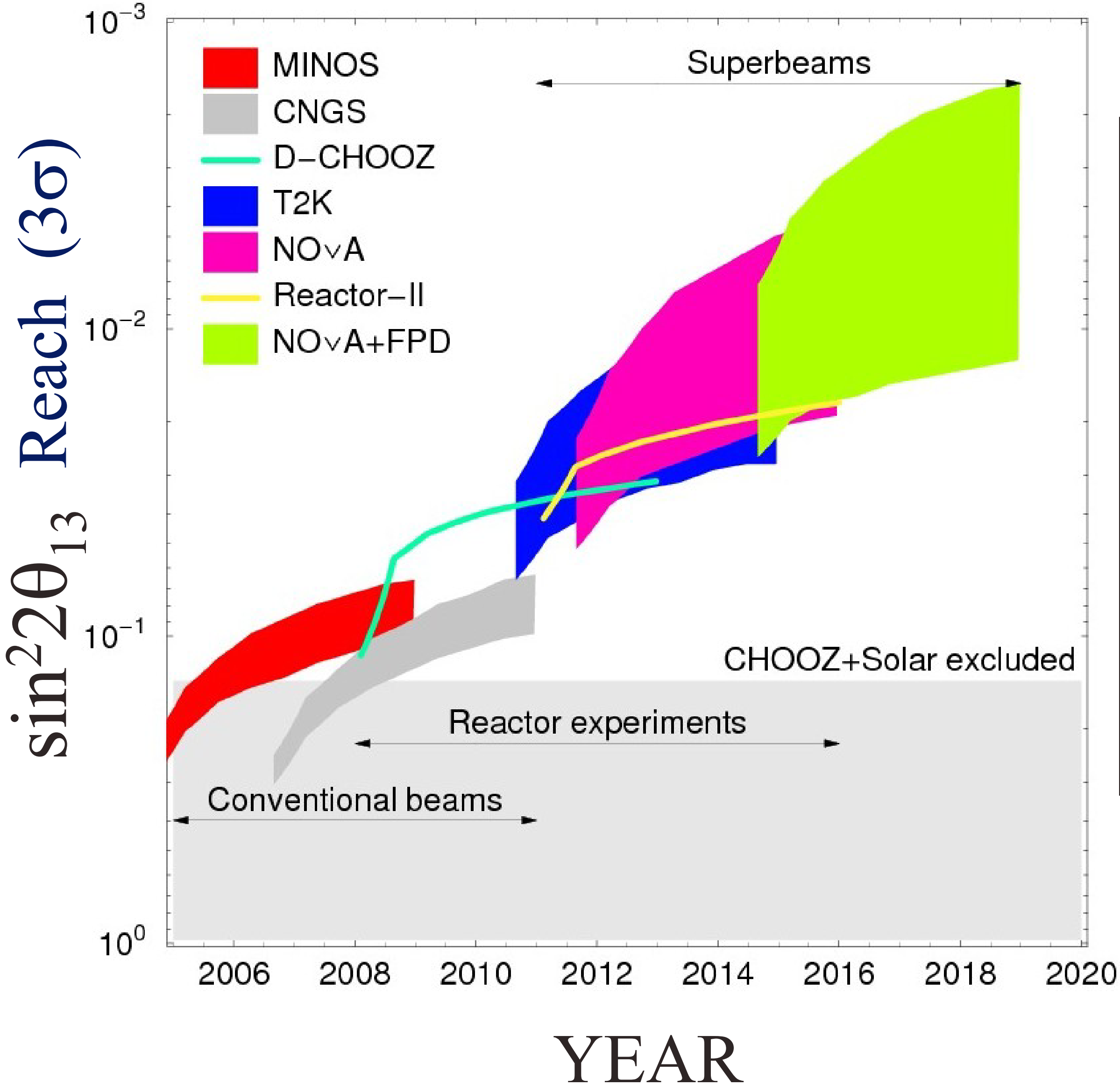
$\nu_\mu \rightarrow \nu_e$ Event Rates: 5 Years Running

$\sin^2 2\theta_{13} = 0.1$

Calculations of W. Winter

	Normal		Inverted		
Expt	$\delta = 0$	$\delta = \pi/2$	$\delta = 0$	$\delta = \pi/2$	*Backgr*
T2K	*132*	*96*	*102*	*83*	*24*
NOvA	*186*	*138*	*111*	*85*	*21*
NOvA+FPD	*716*	*531*	*430*	*326*	*80*
NuFact nu	*29752*	*27449*	*13060*	*17562*	*45*
NuFact nubar	*7737*	*5942*	*9336*	*10251*	*82*

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



Calculations include statistical & systematic uncertainties, & correlations.

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

FPD = Fermilab Prot. Driver

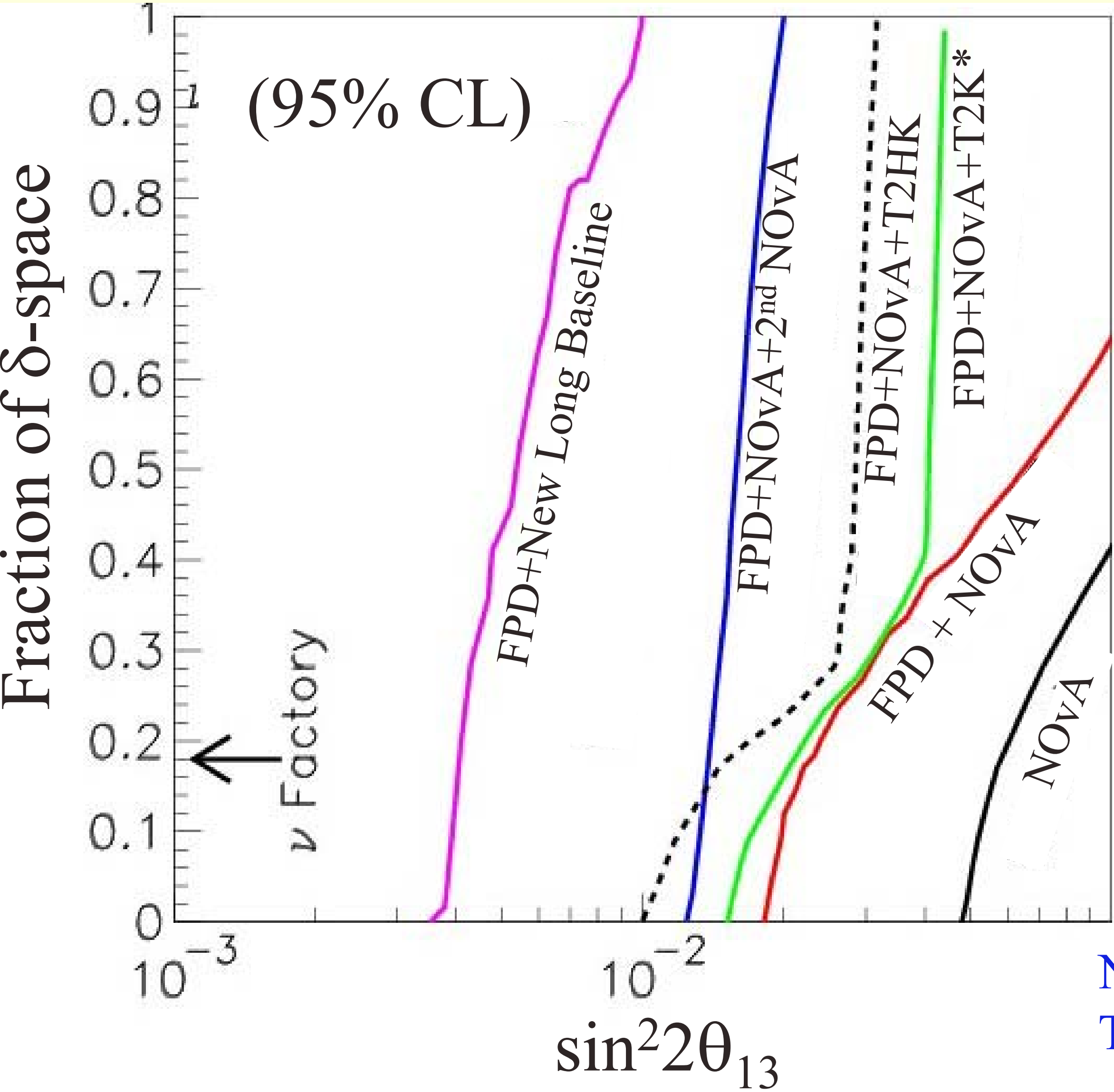
From Searches to Measurements

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.

Determining the Mass Hierarchy

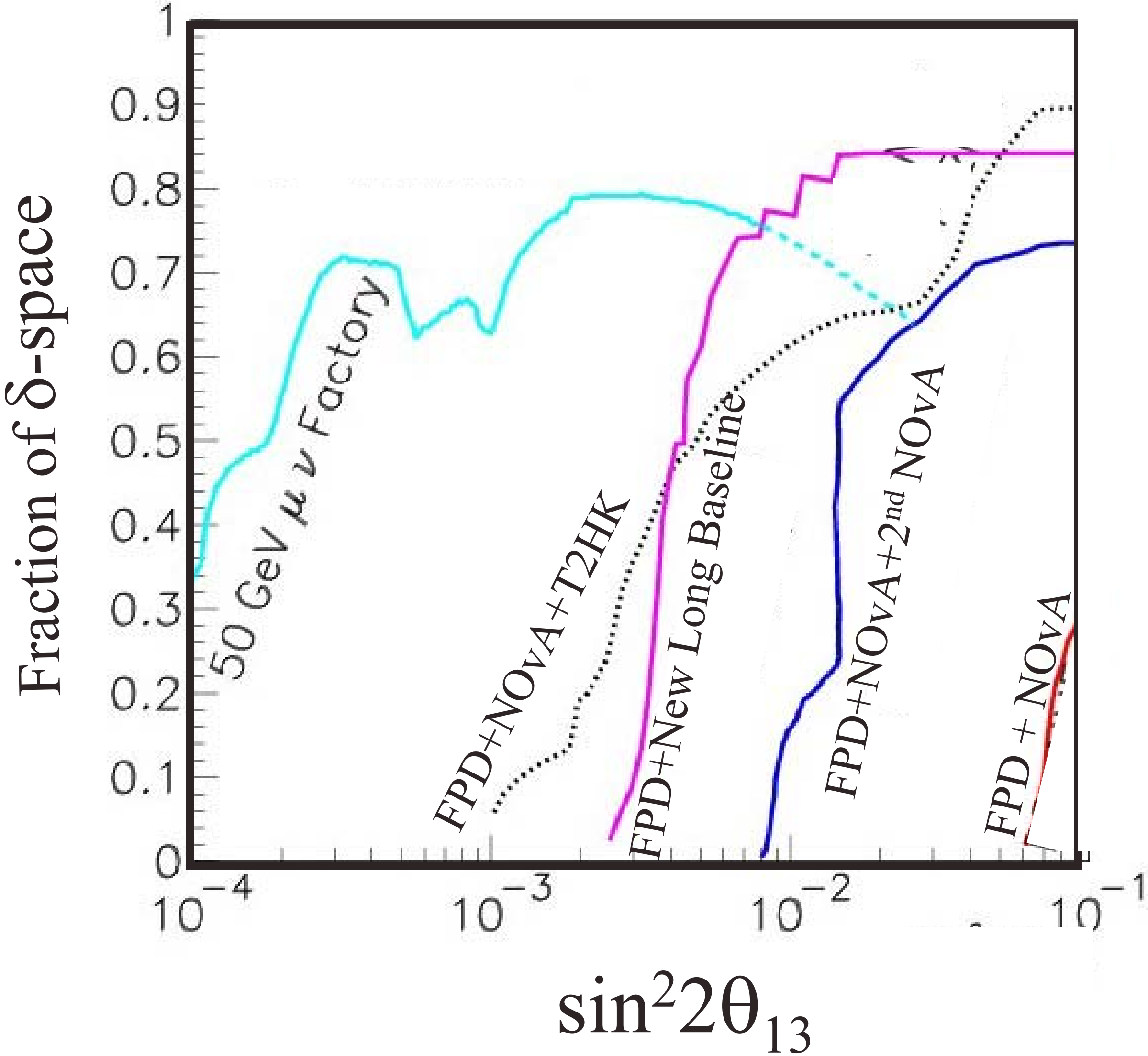


The long NuMI baseline → disentangle mass hierarchy from CP violation.

The FPD together with either an UPGRADED T2K or| a second NOvA detector would enable the mass hierarchy to be determined for all δ provided θ_{13} is "large".

Note: FPD = Fermilab Proton Drive
T2K* = T2K + 4MW beam

Searching for CP Violation



FPD would enable NOvA to begin the search for CP Violation

Multi-Stage program

Further Studies

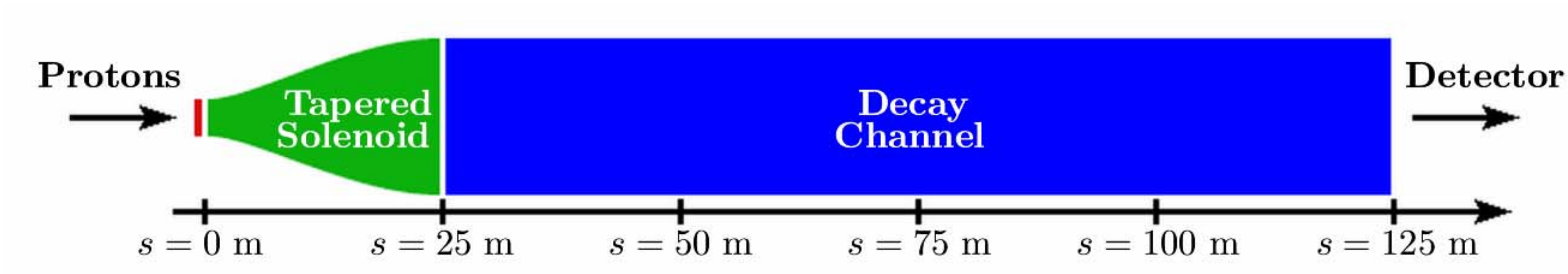
The 2nd generation Fermilab Proton Driver long baseline neutrino Experiments (beyond NOvA) studied to date are "representative", not optimized.

A follow-on study is now beginning to look in more detail at the Superbeam experiment possibilities at Fermilab beyond NOvA.

Meeting at Fermilab March 6-7

Longer Term Possibilities – a Neutrino Factory

The 8 GeV Linac could eventually be used to drive a Neutrino Factory.



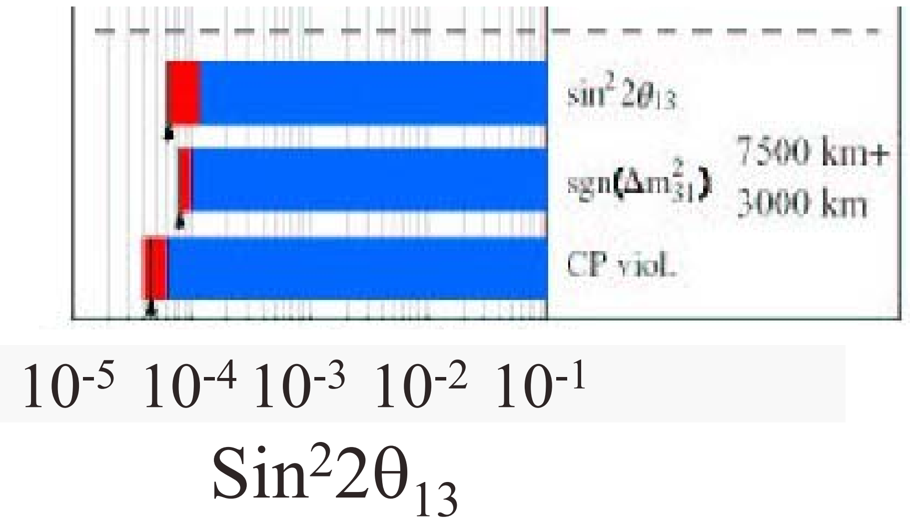
MARS simulations yield 0.2 muons/p …momenta O(100 MeV/c), occupying large transverse phase space

→ 3×10^{21} muons per year (10^7 secs)

Neutrino Factory Reach

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

Huber, Winter; Phys. Rev. D68, 2003



Note: As $\theta_{13} \rightarrow 0$, $P(\nu_e \rightarrow \nu_\mu) \rightarrow 0$. If $Sin^2 2\theta_{13} < O(10^{-4})$ a Neutrino Factory will make the first observation of $\nu_e \leftrightarrow \nu_\mu$ appearance & provide a very important test of three-flavor mixing.

Other Topics - Neutrino Scattering

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 at the Proton Driver

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 $\pi+/\ \pi$ - 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.

Intermediate Possibilities – a Muon Program

•Lepton Flavor Violation (LFV) has been established in the neutrino sector, suggesting new LFV processes at high mass scales. This physics might result in observable effects in the muon sector (?)

•Examples:

muon g-2

muon Electric Dipole Moment ($\rightarrow$ new CP violation)

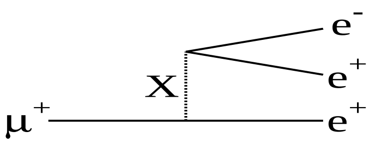
$\mu^- \rightarrow e^-$ conversion

$\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$

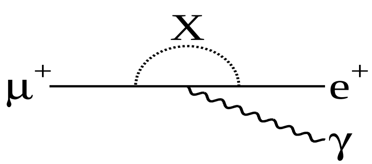
•Beam rebunching at the present and future Fermilab proton source is being studied by those of us interested in possible $\mu \rightarrow e$ experiments in the near-term and at the Proton Driver.

Muon Physics - 1

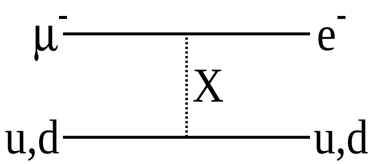
Rare muon processes probe high mass scales:



$B(\mu^+ \rightarrow eee) < 1 \times 10^{-12}$ — 86 TeV/c²



$B(\mu^+ \rightarrow e^+\gamma) < 1.2 \times 10^{-11}$ — 21 TeV/c²

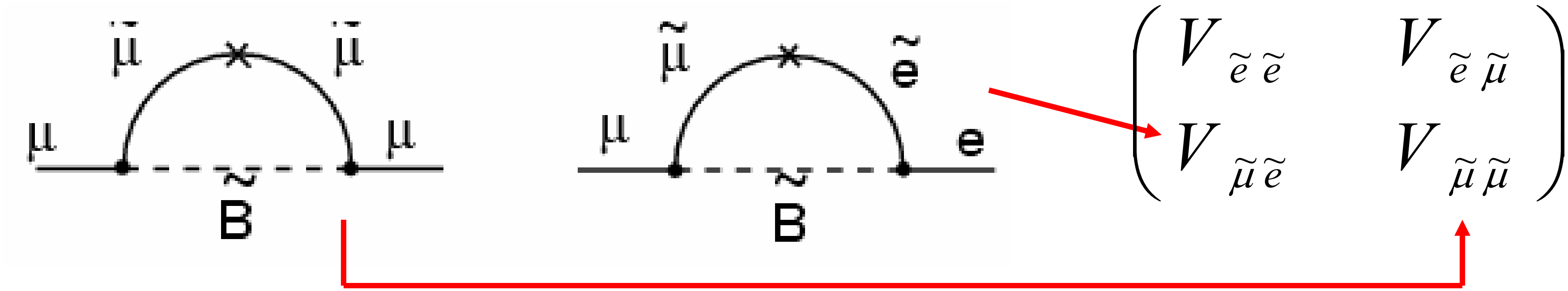


Normalized Rate $< 6.1 \times 10^{-13}$ — 365 TeV/c²

Muon Physics - 2

In addition, precision muon experiments are sensitive to new physics at the TeV scale … complementary to the LHC experiments. Examples: muon (g-2), Electric Dipole Moment, and LFV muon decays.

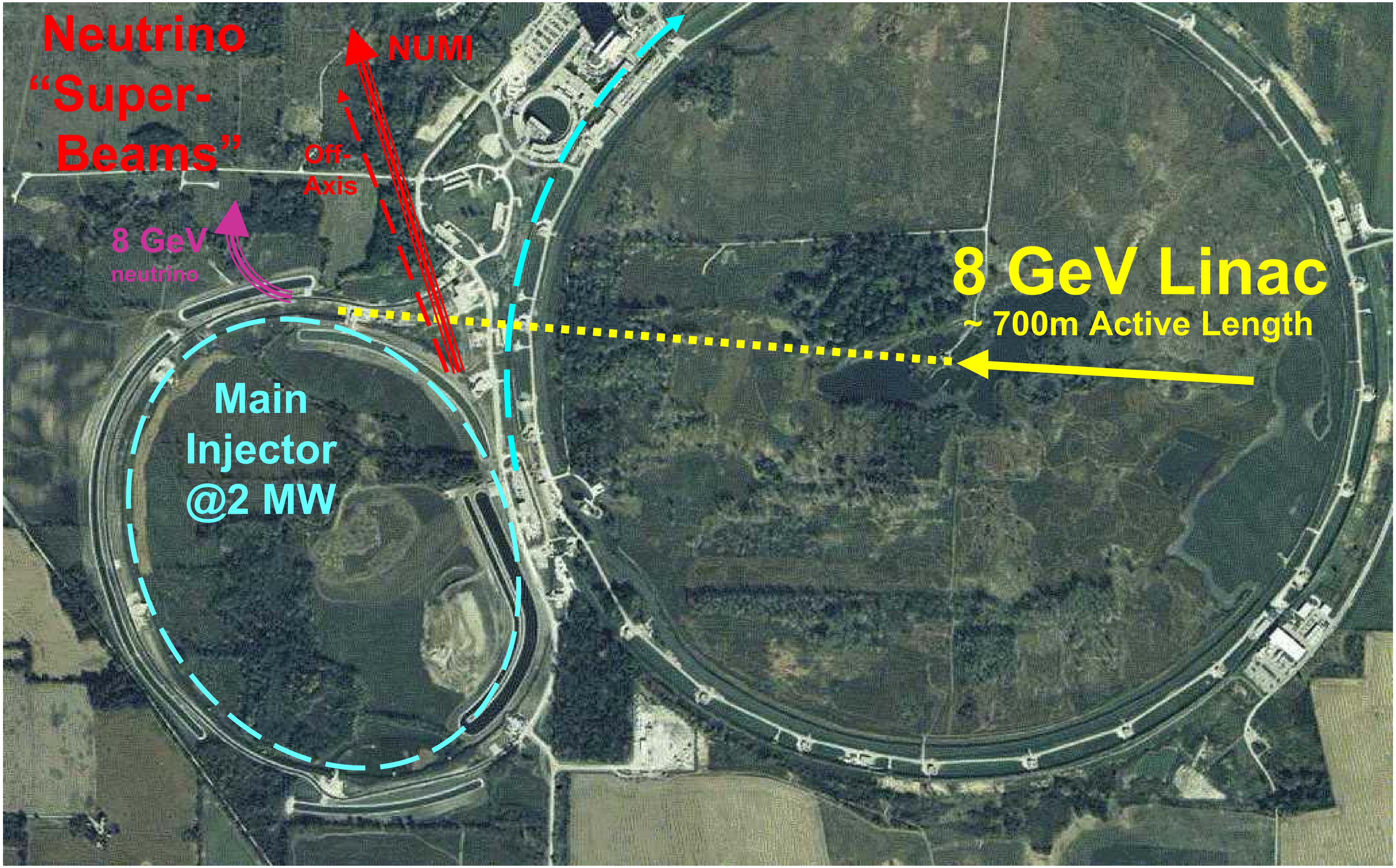
Within the framework of Supersymmetry:



Muon (g-2) and EDM

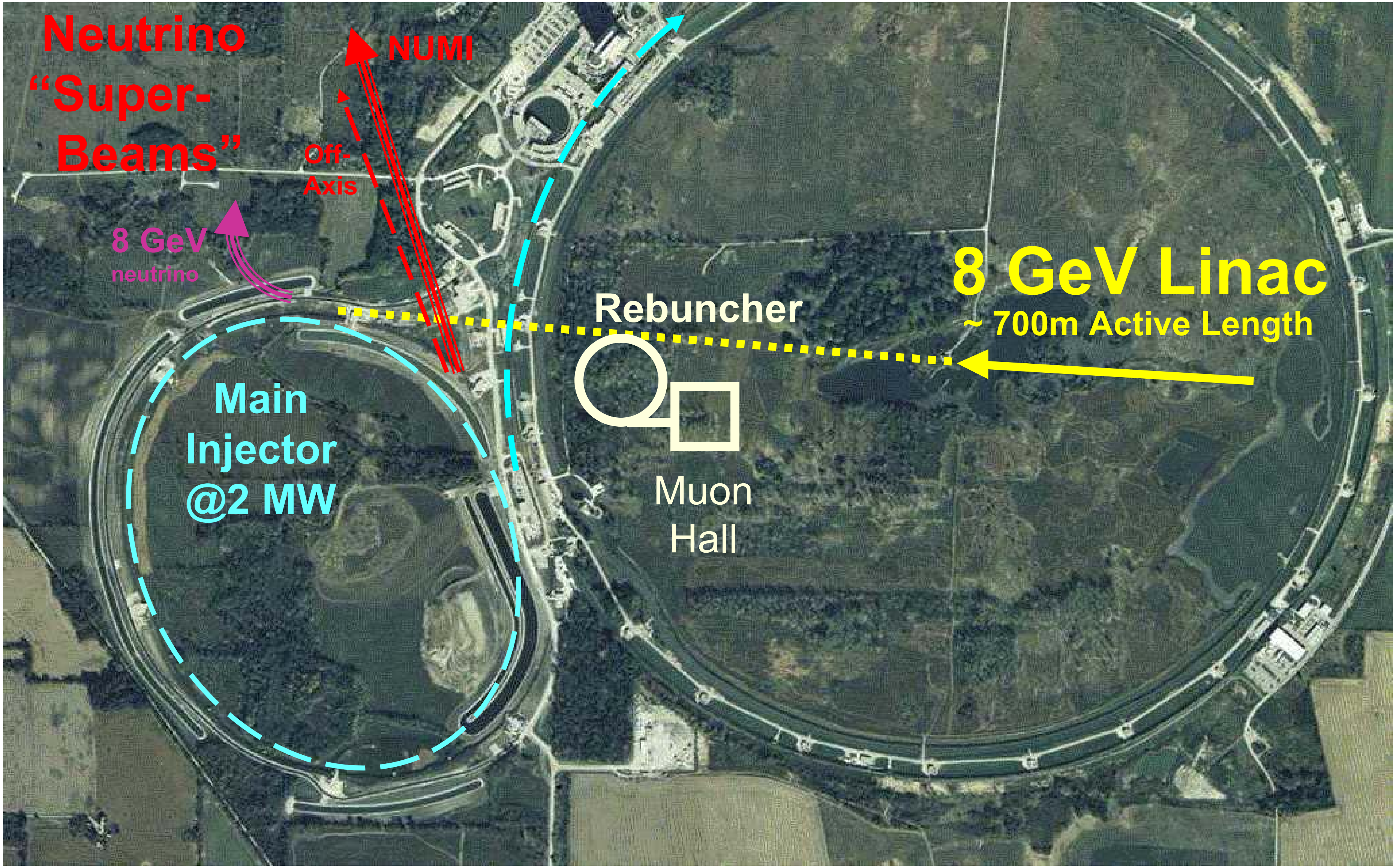
LFV Decays

One Dream …

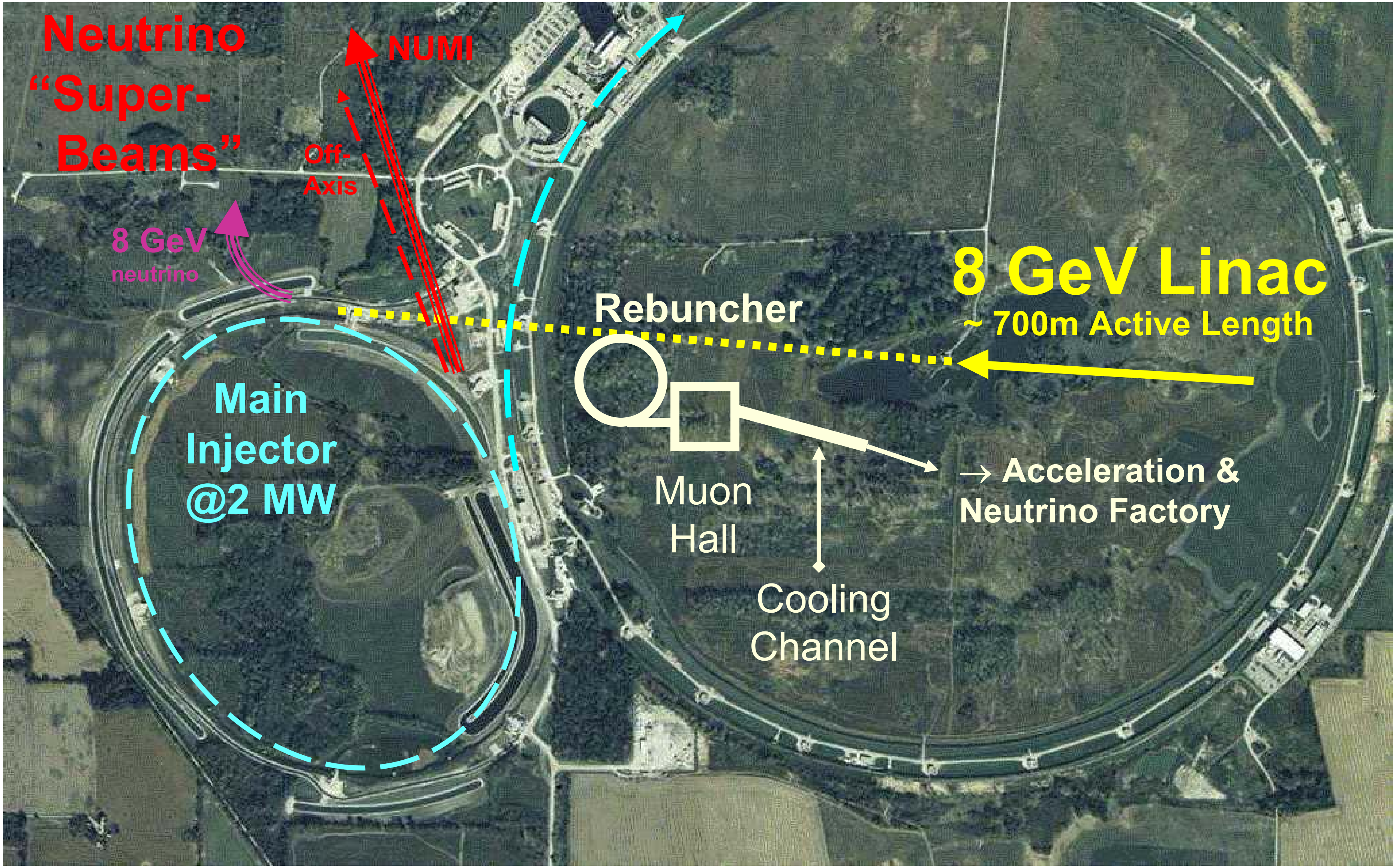


Neutrino
"Super-
Beams"
NUMI
Off-
Axis
8 GeV
neutrino
8 GeV Linac
~ 700m Active Length
Main
Injector
@2 MW

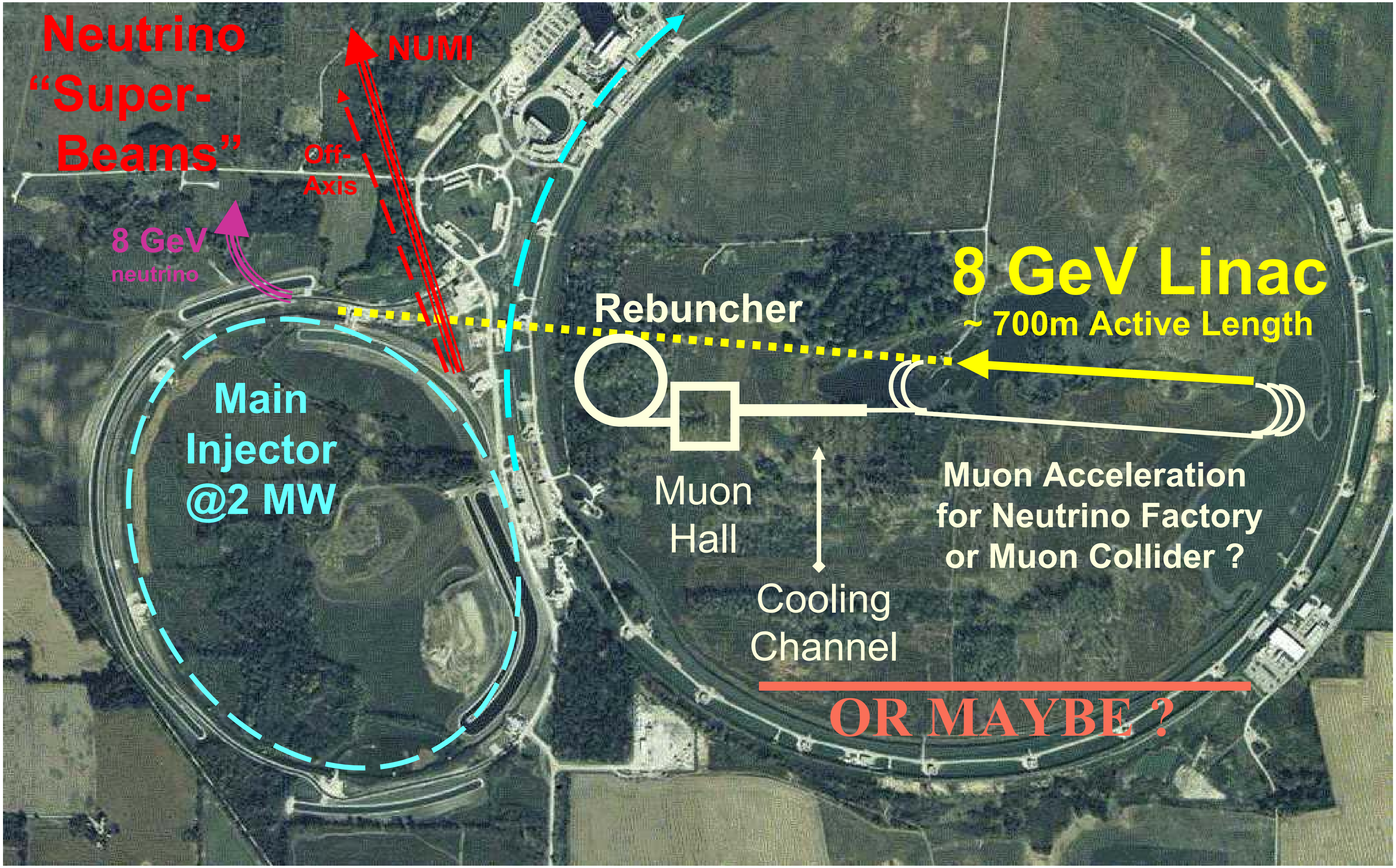
One Dream … to explore LFV



One Dream … to explore LFV



One Dream … to explore LFV



SUMMARY

A Proton Driver yielding 0.5MW (2MW) at MI energies would complement and facilitate critical contributions to the Global long-baseline neutrino program.

The NuMI beam is the longest-baseline beam in the World with the right energy range for significant matter effects!

Fermilab long-baseline neutrino vision: MINOS → NOvA → NOvA+FPD → 2nd generation superbeam experiment (or Neutrino Factory).

The proton Driver could support a more diverse program, including Neutrino scattering measurements and a program of muon experiments.

BACKUP SLIDES

$\nu_\mu \rightarrow \nu_e$ Event Rates: 5 Years Running

	$\sin^2 2\theta_{13} = 0.1$		$\sin^2 2\theta_{13} = 0.01$	
Expt	*Signal*	*Backgr*	*Signal*	*Backgr*
MINOS	*31.3*	*108*	*2.3*	*109*
ICARUS	*21.6*	*71.3*	*1.37*	*72.6*
OPERA	*7.60*	*28.7*	*0.48*	*29.0*
T2K	*102*	*22.8*	*10.5*	*23.4*
NOvA	*111*	*19.9*	*12.4*	*20.6*
NOvA+FPD	*430*	*76.7*	*47.6*	*79.2*
NuFact nu	*13060*	*44.7*	*773*	*44.7*
NuFact nubar	*9336*	*81.6*	*652*	*81.6*

Calculations of W. Winter

Inverted Hierarchy, $\delta = 0$

$\nu_\mu \rightarrow \nu_e$ Event Rates: 5 Years Running

Calculations of W. Winter

	$\sin^2 2\theta_{13} = 0.1$		$\sin^2 2\theta_{13} = 0.01$	
Expt	*Signal*	*Backgr*	*Signal*	*Backgr*
MINOS	*7.4*	*108*	*2.9*	*109*
ICARUS	*25.7*	*69.1*	*2.5*	*70.3*
OPERA	*9.0*	*28.3*	*0.9*	*28.6*
T2K	*96.3*	*22.7*	*5.4*	*23.5*
NOvA	*138*	*19.7*	*7.5*	*20.7*
NOvA+FPD	*531*	*75.6*	*28.9*	*79.5*
NuFact nu	*27449*	*44.9*	*3324*	*44.9*
NuFact nubar	*5942*	*82.0*	*549*	*82.0*

Normal Hierarchy, $\delta = \pi/2$

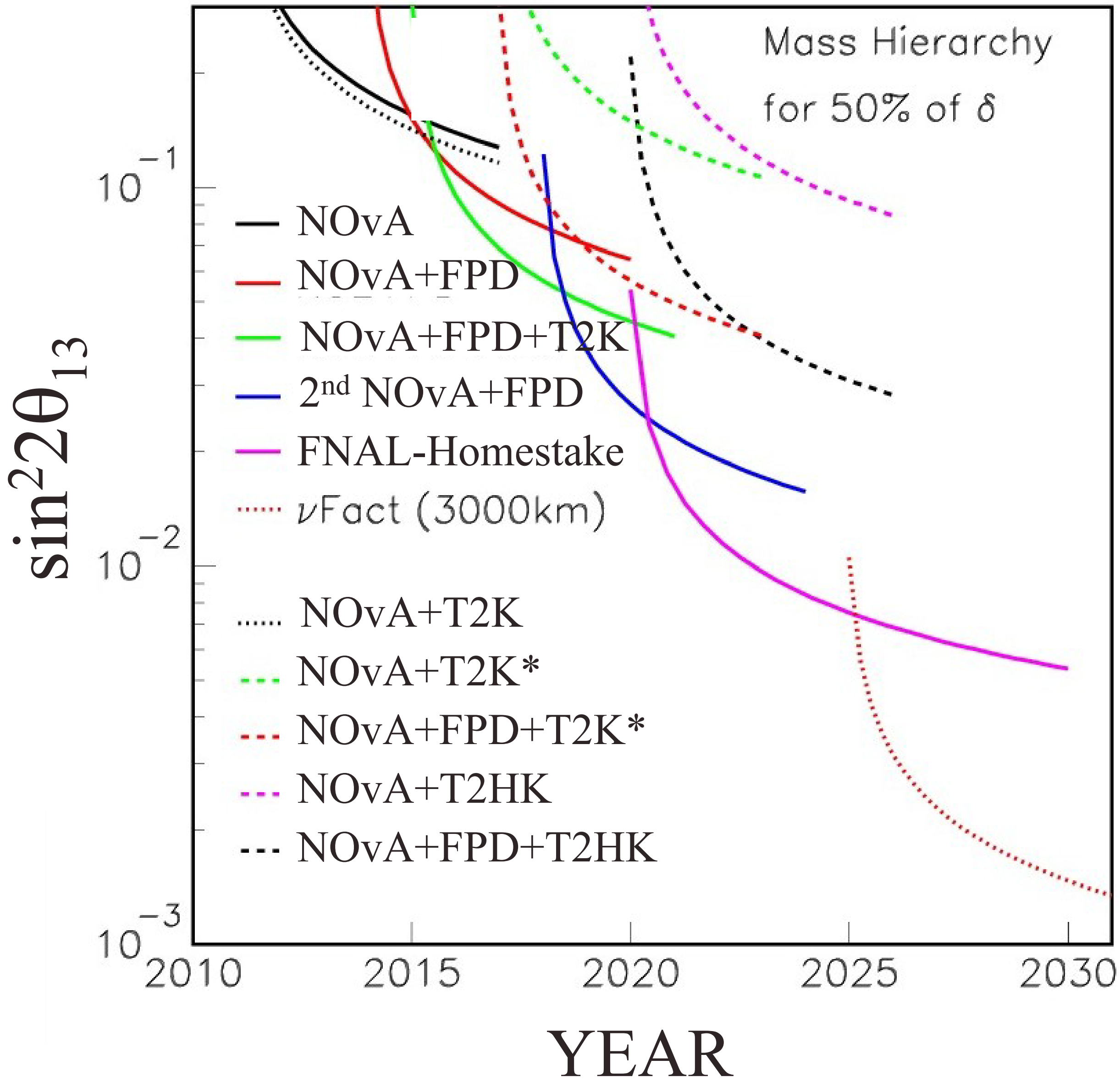
$\nu_\mu \rightarrow \nu_e$ Event Rates: 5 Years Running

Calculations of W. Winter

Inverted Hierarchy, $\delta = \pi/2$

	$\sin^2 2\theta_{13} = 0.1$		$\sin^2 2\theta_{13} = 0.01$	
Expt	*Signal*	*Backgr*	*Signal*	*Backgr*
MINOS	*31.3*	*108*	*2.3*	*109*
ICARUS	*24.9*	*71.3*	*2.4*	*72.6*
OPERA	*8.7*	*28.6*	*0.85*	*29.0*
T2K	*82.9*	*22.8*	*4.3*	*23.4*
NOvA	*84.6*	*19.9*	*3.7*	*20.6*
NOvA+FPD	*326*	*76.6*	*14.4*	*79.2*
NuFact nu	*17562*	*44.7*	*2196*	*44.7*
NuFact nubar	*10251*	*81.6*	*949*	*81.5*

Mass Hierarchy Evolution



FPD = Fermilab Proton Driver

T2K* = 4MW T2K

υFact = Neutrino Factory driven by the Fermilab Proton Driver

Muon Experiments: Examples 1

g-2

The present BNL g-2 result shows a 2.7σ effect

Some minimal SUSY models → large contributions to a_μ from loops with a chargino & muon sneutrino and loops with a neutralino & smuon.

If SUSY discovered at LHC new a_μ measurements → tan β & SUSY mixing.

EDM

Non-zero EDM would indicate new CP violation beyond the Standard Model.

Present limit $d_\mu < 3.7 \times 10^{-19}$ e-cm constrains SUSY.

If SUSY discovered at the LHC, d_μ & a_μ measurements → information about the new CP-violating phases difficult to obtain any other way.

JPARC proposal → 10^{-24} e-cm. To go further need better beam structure → many short pulses, each separated by >500ms. Fermilab Proton Driver experiment might be designed to have a sensitivity ~ 10^{-26} e-cm

Muon Experiments: Examples 2

$\mu \rightarrow e\gamma$

In SUSY Seesaw models LFV depends on SUSY breaking.

If SUSY observed at the LHC, LFV measurements $\rightarrow$ information about SUSY breaking.

Present limit BR $< 1.2 \times 10^{-11}$. MEG experiment expected $\rightarrow \sim 10^{-14}$

Further progress requires improved muon source & better detector technology giving better background rejection (i.e. resolutions) & enabling higher rates.

Improvement to $10^{-15} - 10^{-16}$ seems plausible.

$\mu \rightarrow e$ conversion

MECO at BNL $\rightarrow$ BR $\sim 10^{-17}$.

JPARC proposal (PRISM/PRIME) $\rightarrow$ BR $\sim 10^{-19}$.

PRISM/PRIME could be located at the Fermilab Proton Driver if it does not find a home at JPARC.