The Very-Low Energy Neutrino Factory (VLENF)

ν physics with a μ storage ring

Muon Accelerator Program

Fermilab

The International Design Study for a Neutrino Factory (IDS-NF)

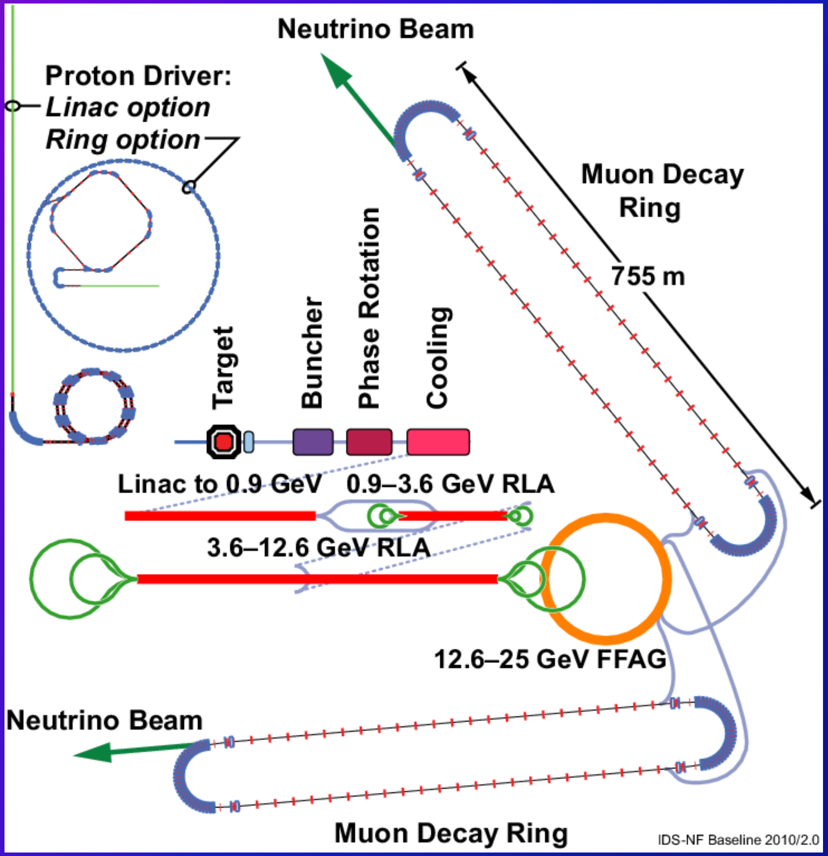


Figure of Merit: ≈ 0.15 μ/pot @ end of cooling channel

- The baseline NF in the IDS-NF Interim Design Report (IDR) is the high-energy (E_μ=25 GeV) machine, two-baseline facility:
  - Proton Driver
    - 4 MW, 2 ns bunch
  - Target, Capture, Drift ($\pi \rightarrow \mu$) & Phase Rotation
    - Hg Jet
    - 200 MHz train
  - Cooling
    - 30 πmm ($\perp$)
    - 150 πmm (L)
  - Acceleration
    - 103 MeV $\rightarrow$ 25 GeV
  - Decay rings
    - 7500 km L
    - 4000 km L

Neil Bliss this afternoon

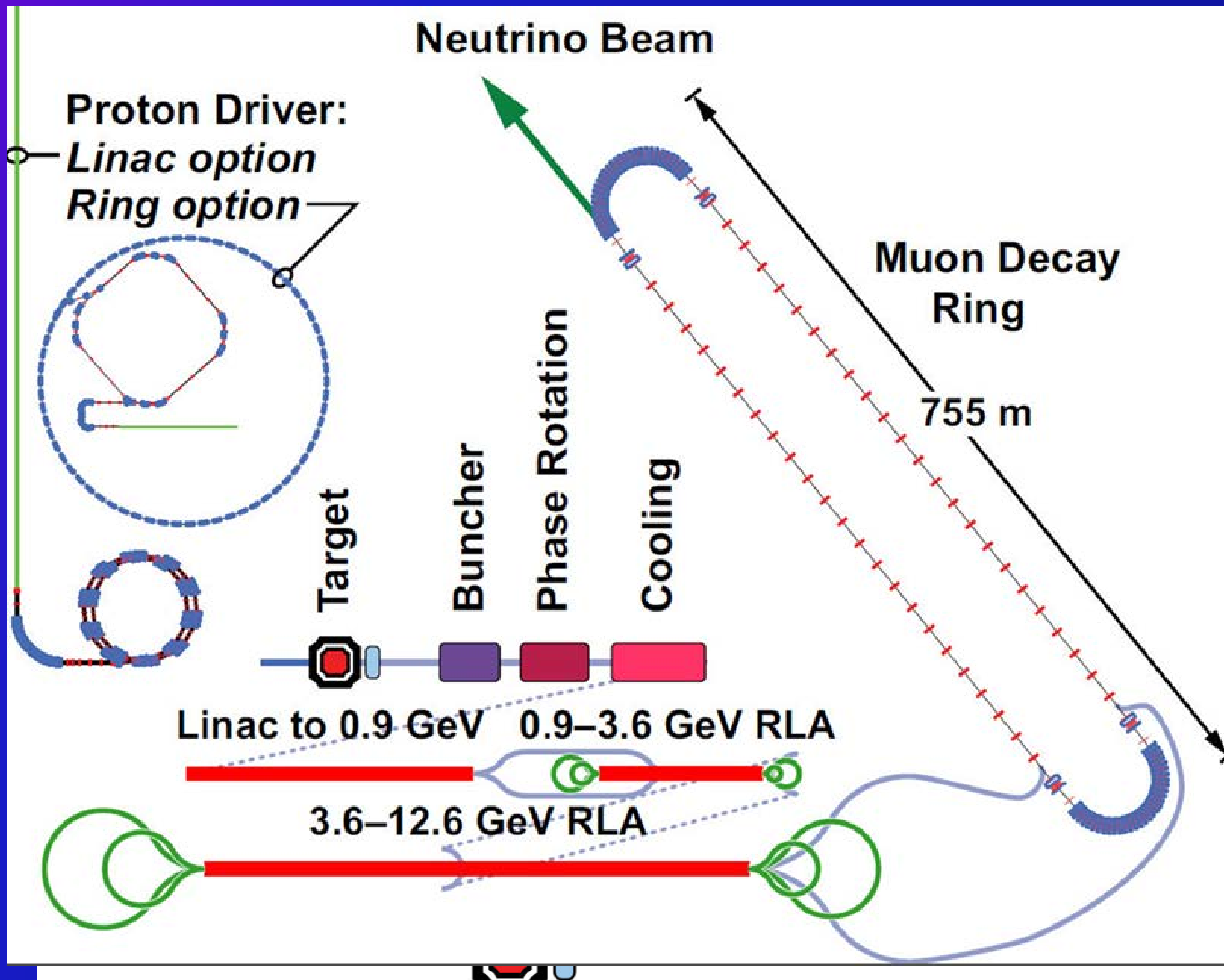
NF: A Staged Approach

- Although the facility described in the IDS-NF RDR gives unprecedented reach in the νSN mixing parameter space (& for non-standard ν physics also) – Can we do good science with something simpler that?:
  - Eliminates the technical risks
  - Does not require a proton driver to start (modest power on target)
    - Utilize existing proton power
  - Yields << Lower Cost Facility

YES

- A near-term Very-Low-Energy (VLENF) which
  - Addresses the large δm^2 ν oscillation regime
  - Does precision ν cross-section measurements
  - Provides a μ decay ring R&D (instrumentation) & technology demonstration platform

IDS-NF


Neutrino Beam
Proton Driver:
Linac option
Ring option
Muon Decay Ring
755 m
Target
Buncher
Phase Rotation
Cooling
Linac to 0.9 GeV
0.9–3.6 GeV RLA
3.6–12.6 GeV RLA

Experimental Motivation

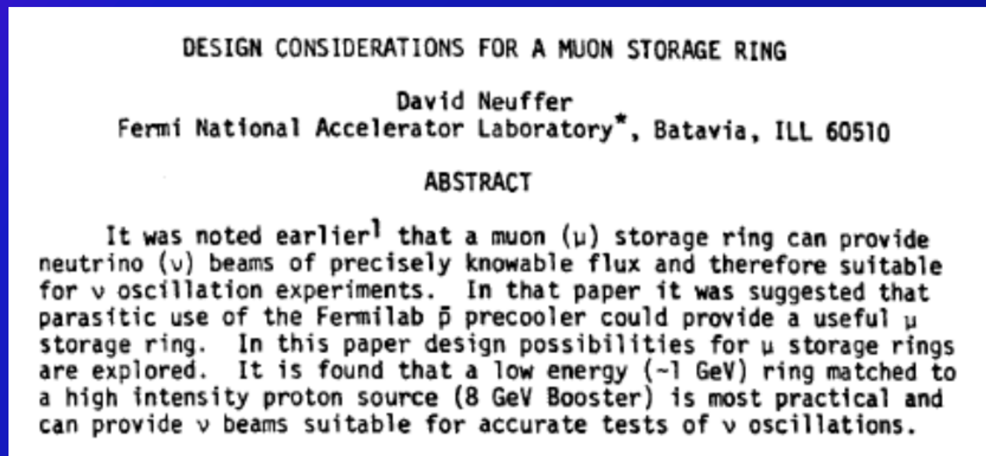
- We have a collection of hints of something…
  - LSND: $\bar{\nu}_\mu \to \bar{\nu}_e$
  - MiniBooNE: $\bar{\nu}_\mu \to \bar{\nu}_e$
  - MiniBooNE: $\nu_\mu \not\to \nu_e$
    - Low E_ν excess
  - Reactor flux anomaly
  - MINOS: ν_μ vs. $\bar{\nu}_\mu$
- Cross-section measurements
  - μ storage ring presents only way to measure ν_μ & ν_e & (ν and $\bar{\nu}$) x-sections in same experiment
    - Supports future long-baseline experiments

Possibilities with a μ storage ring

- Oscillation Physics @ L/E = 1
  - Appearance experiment with low background
    - A different approach to explore the LSND/MiniBooNE result
- ν disappearance experiment with 1% precision (10^4 events)
  - An experiment that uses a ν_e beam from a muon storage ring can go a long way in ruling out sterile νs
  - ν_μ disappearance (@ short baseline) also
- In addition, the beam opens up opportunities for
  - Detailed study of ν interactions
    - Known ν beam flux and flavor composition
    - Only way to get large sample of ν_e interactions

30 Years in the Making

- First proposed in detail by David Neuffer in 1980 at the Telemark WS on neutrino mass



DESIGN CONSIDERATIONS FOR A MUON STORAGE RING

David Neuffer
Fermi National Accelerator Laboratory*, Batavia, ILL 60510

ABSTRACT

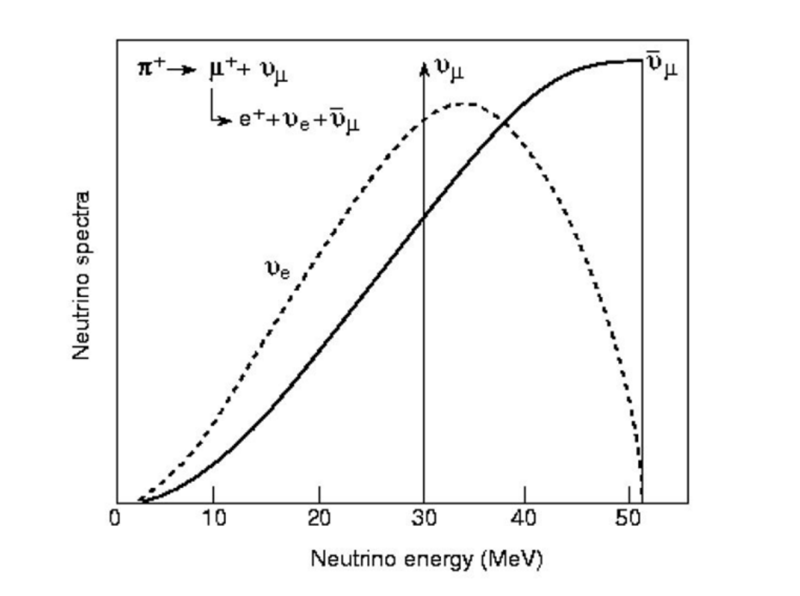
It was noted earlier[1] that a muon (μ) storage ring can provide neutrino (ν) beams of precisely knowable flux and therefore suitable for ν oscillation experiments. In that paper it was suggested that parasitic use of the Fermilab p̄ precooler could provide a useful μ storage ring. In this paper design possibilities for μ storage rings are explored. It is found that a low energy (~1 GeV) ring matched to a high intensity proton source (8 GeV Booster) is most practical and can provide ν beams suitable for accurate tests of ν oscillations.

νs from μ decay

- Running with μ^-

$$\mu^- \rightarrow e^- + \nu_\mu + \bar{\nu}_e$$

- Well defined flavor composition & energy



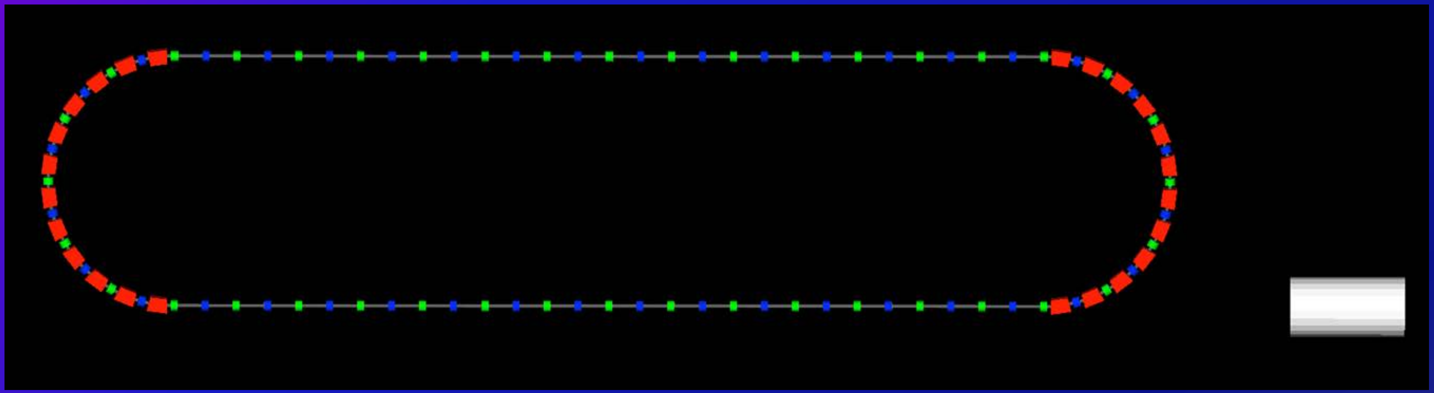
Accelerator Science

- A technology proving ground and a test bed for μ storage ring instrumentation (Goal of flux normalization to 1% or better)
  - BCT
  - Momentum spectrometer in arc(s)
  - Polarimeter
  - Beam divergence monitor
- Demonstration of new lattice design (Racetrack FFAG – see following)

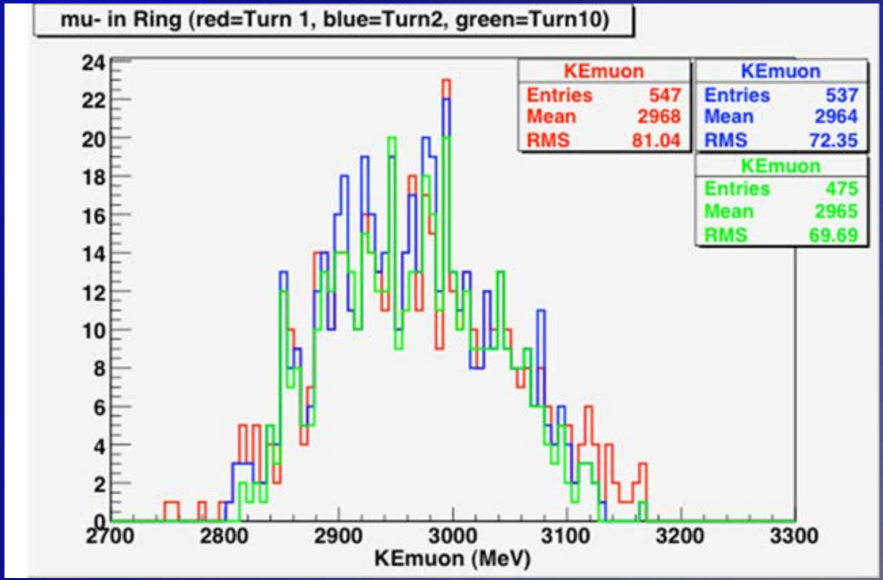
The Facility

Tom Roberts
Muons Inc.

Initial concept
G4Beamline Simulation



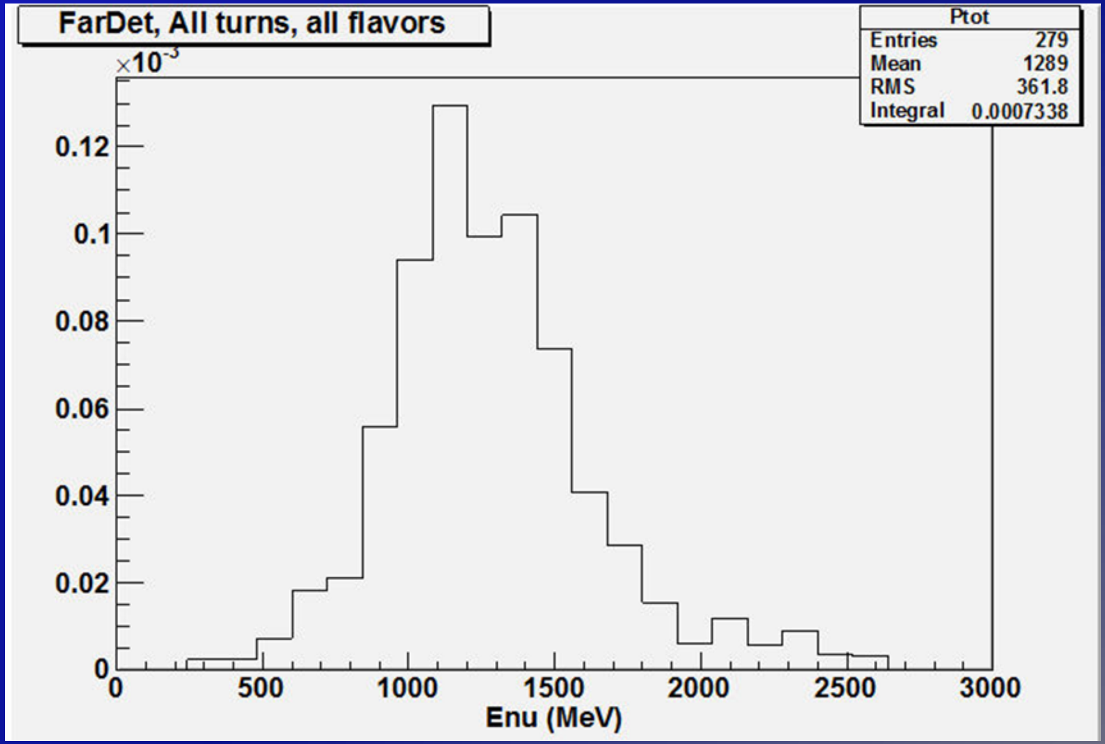
- 8 GeV protons on 2 λ_I Be target
- 3 GeV Racetrack ring (M. Popovic)
  - For now, injection is perfect
    - Not defined
- Tuned for μ^- with KE = 3.000 GeV
  - 3 GeV chosen primarily for x-section meas.
  - $\delta p/p \approx 2\%$
- Detectors (scintillator)
  - Near: 20 m
  - Far: 800T @ 600 - 1000 m



Estimated event rates

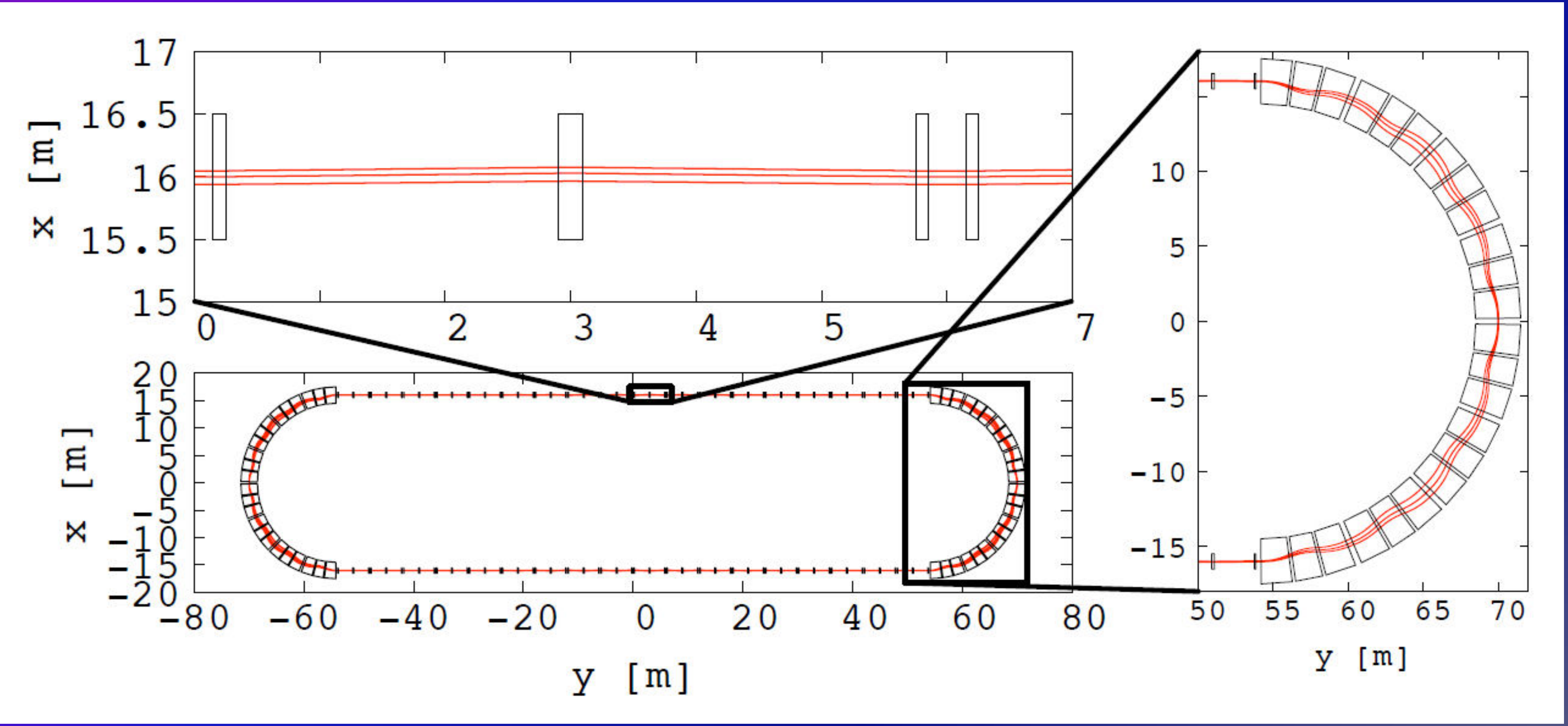
- ν_μ Events per 10^{21} POT (turns 10 & up)
  - Near: 1.3×10^5 (200T)
  - Far: 0.7×10^4 (800T)

Note:
Figure of Merit: $\approx 10^{-4}$ μ/pot



J.B. Lagrange
Yoshi Mori
Kyoto

FFAG Racetrack



$\delta p/p \approx 20\%$

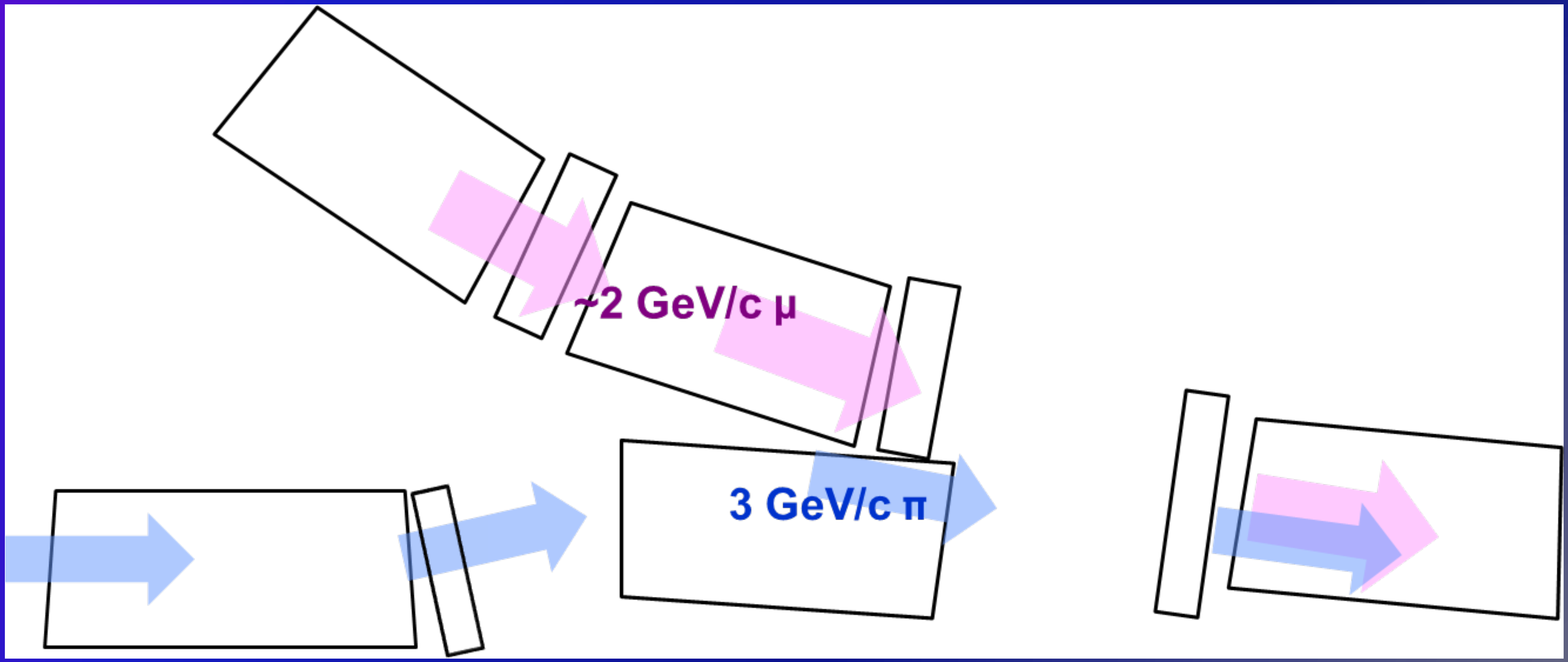
acc-kurri – 1119-01-2011

2 GeV/c

David Neuffer
circa 2011

Injection Concept

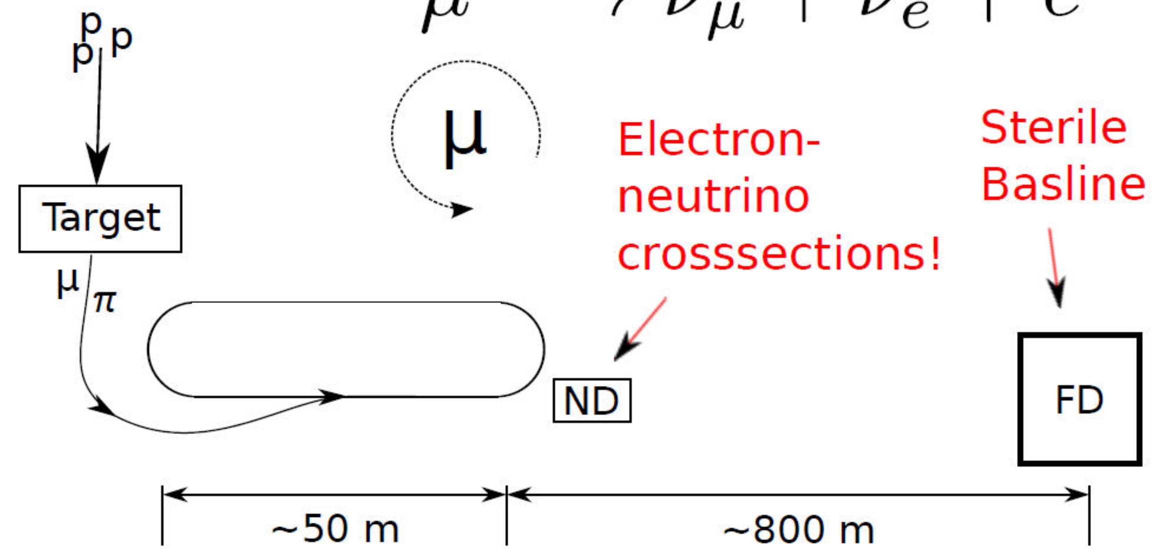
- π's are in injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower energy - ~2GeV/c
- ~30cm separation between



The Physics Reach

Experimental Layout

$$\mu^+ \rightarrow \bar{\nu}_\mu + \nu_e + e^+$$



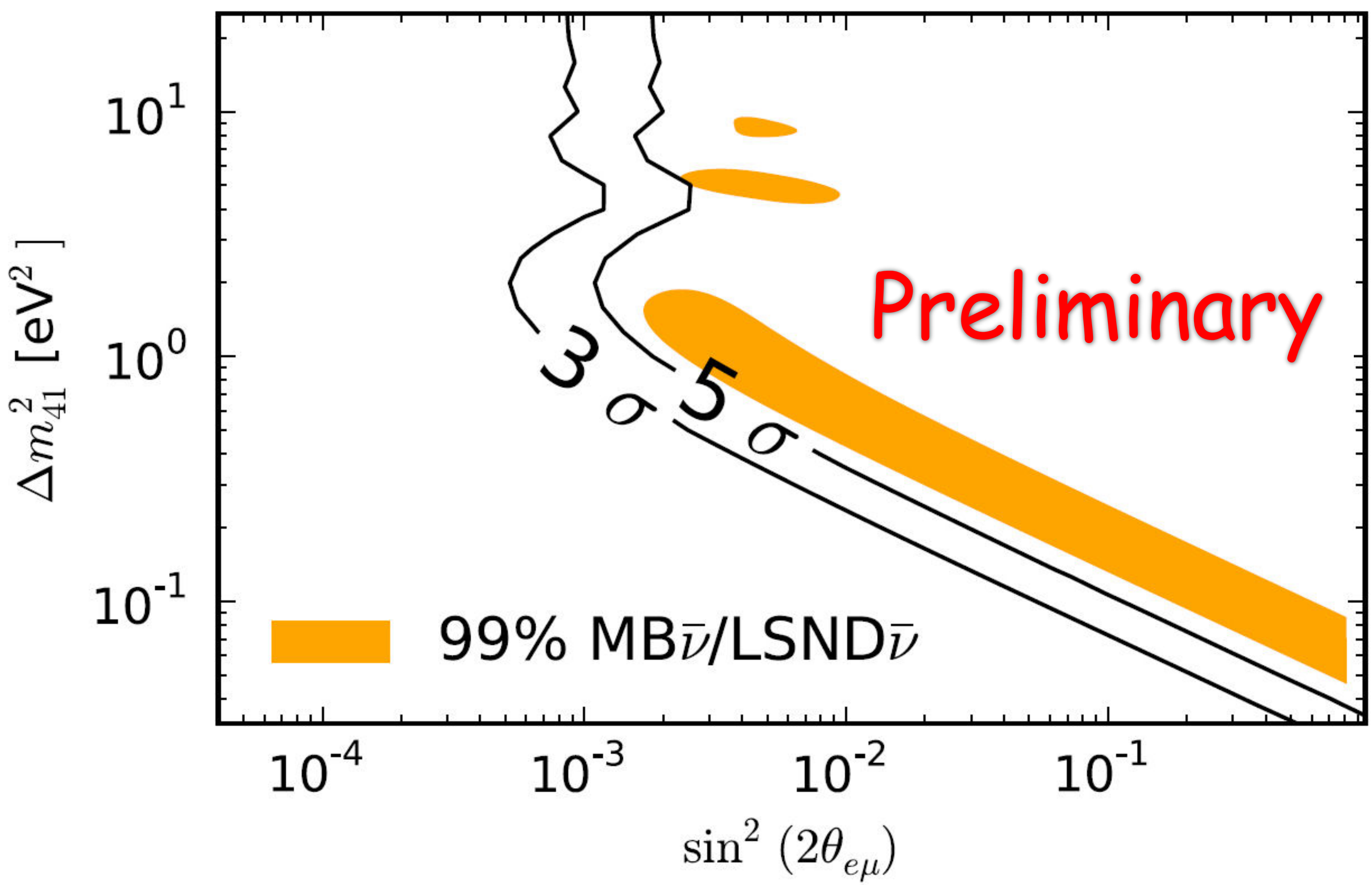
Must reject the "wrong" sign μ with great efficiency

Appearance-only (though disappearance good too!)

$$Pr[e \rightarrow \mu] = 4|U_{e4}|^2|U_{\mu 4}|^2 \sin^2(\frac{\Delta m_{41}^2 L}{4E})$$

Chris Tunnell
Oxford

L/E ≈ 1 Oscillation reach
Exclusion contours

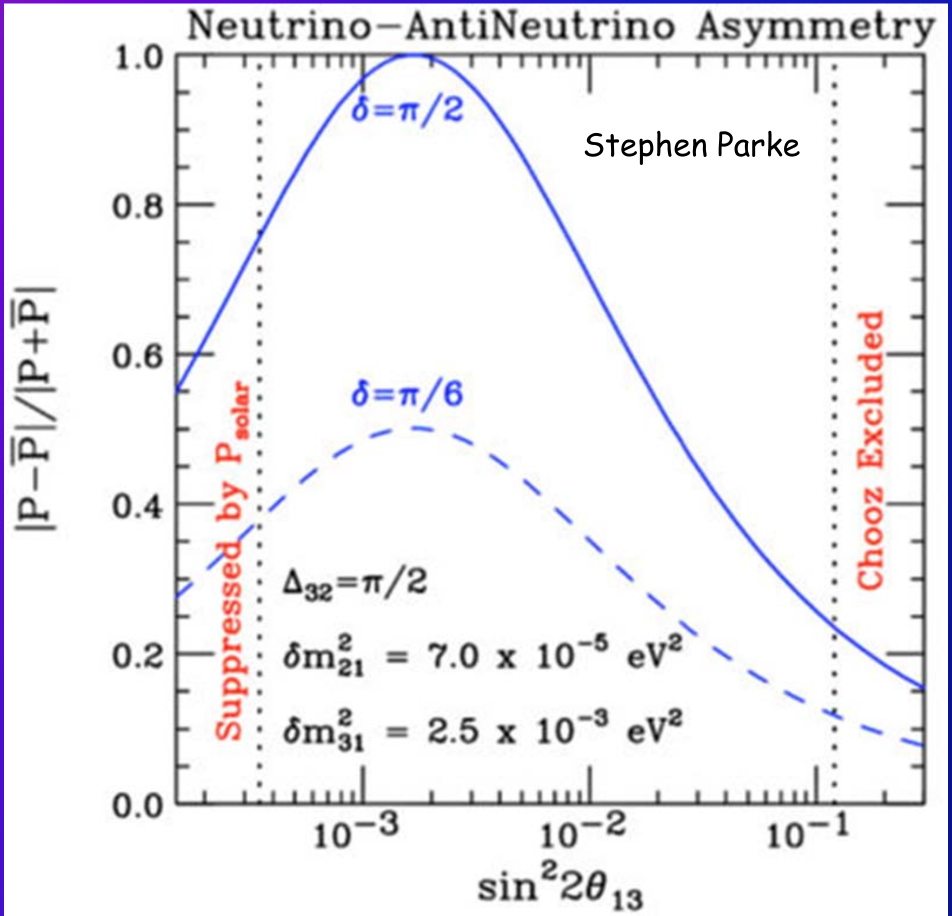


http://arxiv.org/abs/1111.6550v1

Cross-section Measurements

- The next generation of LB experiments face some significant challenges
  - CP asymmetry decreases with increasing $\sin^2 2\theta_{13}$
  - Flux and cross-sections must be known to much better than 5%
  - Hadro production experiments (such as NA61@CERN) + near detectors will only expect to reach a precision of <≈ 5%
- Gaining a better understanding of x-sections Will Be crucial to these future experiments
  - The energy range of interest is roughly 1-3 GeV
- μ storage rings provide the only way to get large sample of ν_e and ν_μ interactions (neutrino and anti-neutrino) in a single experiment and:
  - With μ decay ring instrumentation we anticipate getting the flux uncertainty below 1% and
  - With a well designed suite of near detectors x-section uncertainties to the few % level or less.
    - Great deal of ND work for LBNE & IDS-NF
  - Nuclear effects are important (Short-range correlations, Final-state interactions).
    - Important implications for near detector(s)
  - Reach an overall systematic uncertainly that is very difficult for SB

Cross-section measurements II
ν_e & CP̸



$$\frac{P(\nu_\mu \to \nu_e) - P(\bar{\nu}_\mu \to \bar{\nu}_e)}{P(\nu_\mu \to \nu_e) + P(\bar{\nu}_\mu \to \bar{\nu}_e)}$$

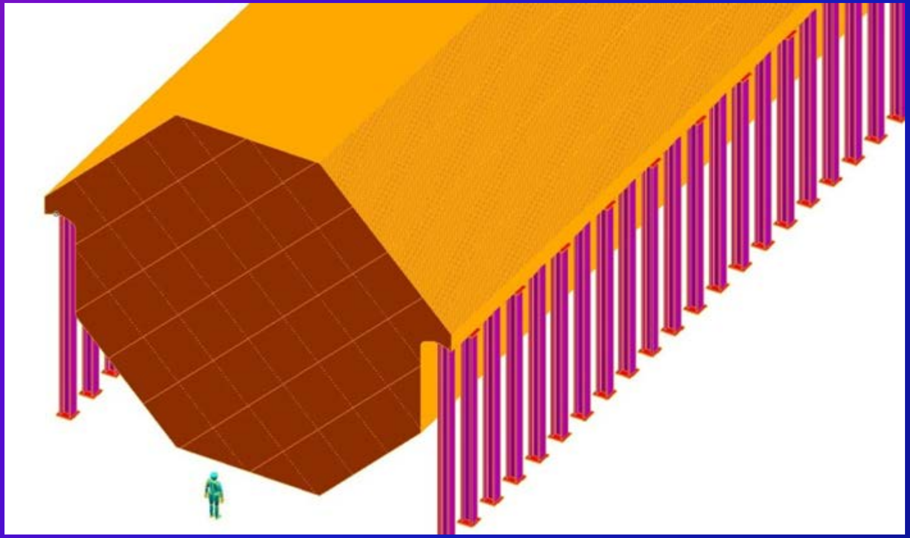
- Important to note that if θ_{13} is large, the asymmetry you're trying to measure is small, so:
  - Need to know underlying ν/vbar flux & σ more precisely
  - Bkg content & uncertainties start to become more important

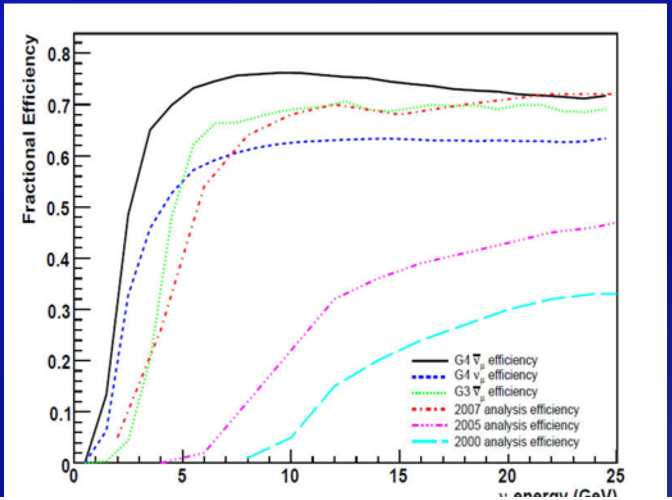
Better data on ν_e and $\bar{\nu}_e$ important for CP̸, δ_{CP} measurements

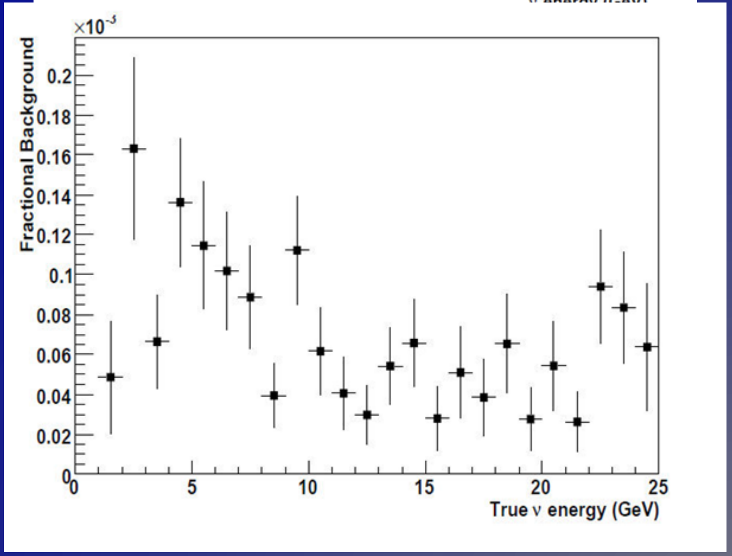
The Detector (FAR)

Magnetized Iron Neutrino Detector (MIND)

Re-Optimize for lower energy?





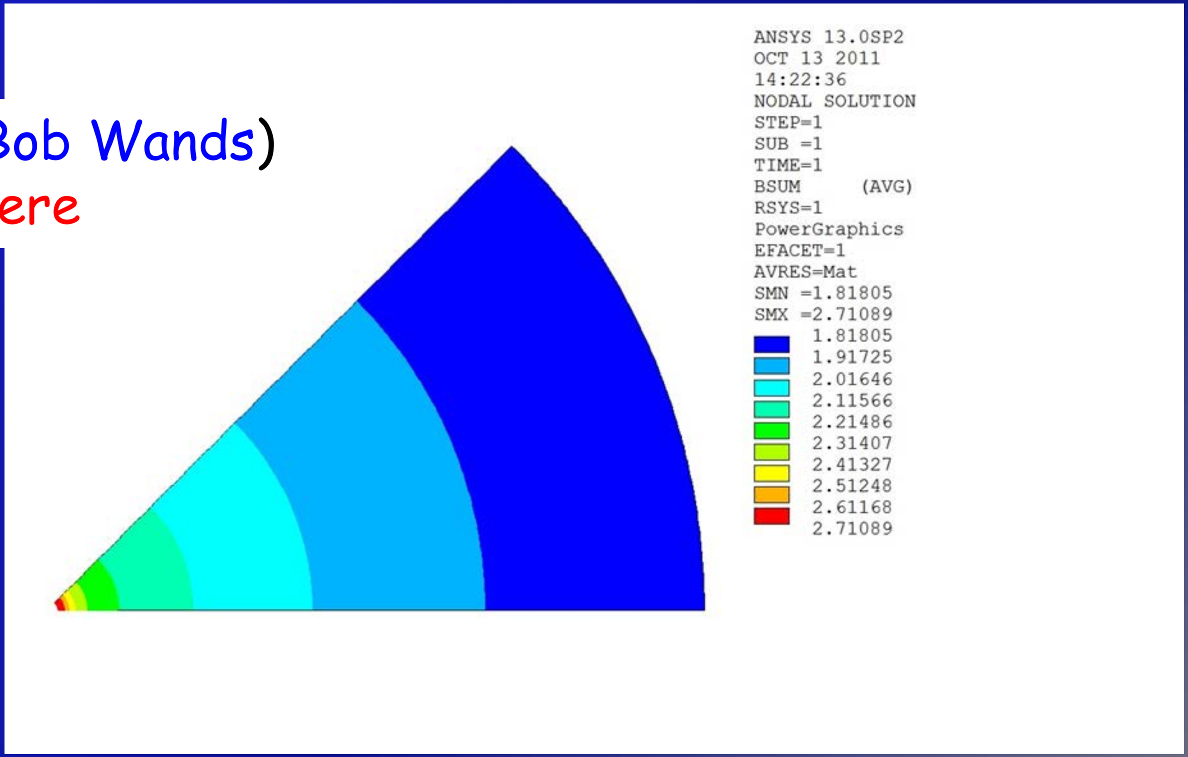


- MIND was optimized for the "Golden" channel at the NF (25 GeV μ storage ring)
- Optimization for FD for $L/E \approx 1$
  - Essentially Minos ND with upgrades
    - Reduce plate thickness
    - 100-300kA-turn excitation (SCTL)
    - XY readout between planes

Super B Iron Neutrino Detector
SuperBIND

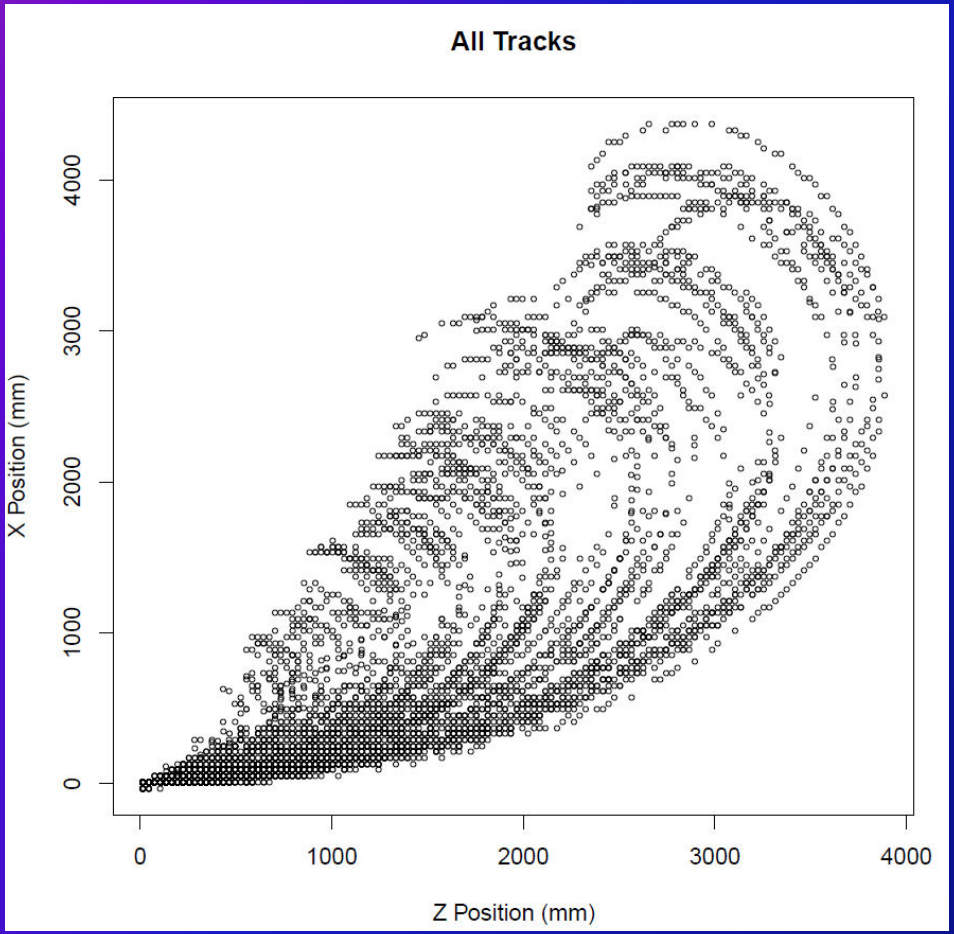
- Reduce Plate thickness to 1cm
- Increase excitation to 270kA-turn
- XY scintillator strip readout between each plate as in MIND

Quick first pass at B (Bob Wands)
B>1.8T everywhere



Malcolm Ellis
HIENPH

SuperBIND



For p_{μ} > 250 MeV/c there is "no" confusion with respect to bending up or down

But the devil is in the details
This is uniform 1.8T dipole field
Not realistic
Work in progress

Outlook

The VLENF presents an approachable ($$) first step towards a NF and/or Muon Collider. The physics and accelerator technology cases are compelling.

More work needs to be done, however, but provides the framework for US-UK cooperative *Scientific Innovation*

- Facility
  - Targeting, capture/transport & Injection
    - Need detailed design and simulation
  - Decay Ring optimization
    - Continued study of conventional and FFAG decay rings
  - Decay Ring Instrumentation
    - Define and simulate performance of BCT, polarimeter, Bspectrometer, etc.
  - Produce full G4Beamline simulation of all of the above to define ν flux
    - And the precision to which it can be known
- Detector simulation
  - For oscillation studies much more detailed MC study of backgrounds & systematics
  - For cross-section measurements need detector baseline design
    - Learn much from detector work for NF & LBNE
    - Near Detector hall could be envisioned as ν detector test facility

VLENF: Conclusions

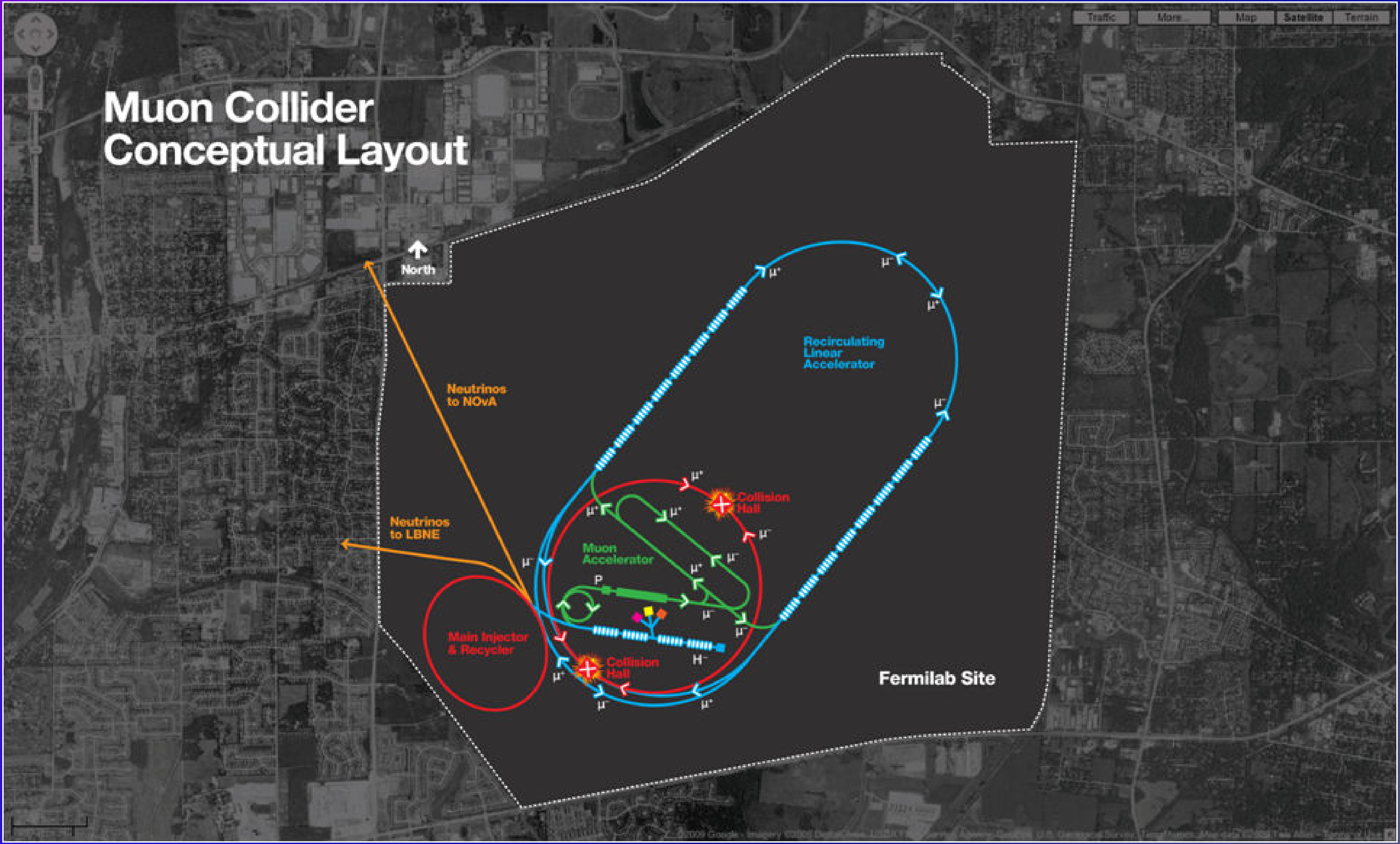
The Physics case:

- Initial simulation work indicates that a L/E ≈ 1 oscillation experiment using a muon storage ring can "easily" reach a 5σ+ benchmark, *it is just the "Golden Channel" after all*
- ν_e and ν_μ disappearance experiments delivering at the 1% level look to be doable
  - Systematics need careful analysis
- Cross section measurements with near detector(s) offer a unique opportunity

The Facility:

- Presents manageable extrapolations from existing technology
  - But can explore new ideas regarding beam optics and instrumentation
- Offers opportunities for extensions
  - Add RF for bunching/acceleration/phase space manipulation
    - Provide μ source for 6D cooling experiment with intense pulsed beam

"The start of a long journey?"



Thank You