Neutrinos from Stored Muons
νSTORM

ν physics with a μ storage ring

Fermilab

The "Collaboration"

P. Kyberd,[1] D.R. Smith,[1] L. Coney,[2] S. Pascoli,[3] C. Ankenbrandt,[4] S.J. Brice,[4] A.D. Brossa,[4] H. Cease,[4] J. Kopp,[4] N. Mokhov,[4] J. Morfin,[4] D. Neufer,[4] M. Popovic,[4] P. Rubinov,[4] S. Striganov,[4] A. Blondel,[5] A. Bravar,[5] E. Noah,[5] R. Bayes,[6] F.J.P. Soler,[6] A. Dobbs,[7] K. Long,[7] J. Pasternak,[7] E. Santos,[7] M.O. Wascko,[7] S.K. Agarwalla,[8] S.A. Bogacz,[9] Y. Mori,[10] J.B. Lagrange,[10] A. de Gouvêa,[11] Y. Kuno,[12] A. Sato,[12] V. Blackmore,[13] J. Cobb,[13] C. D. Tunnell,[13] J.M. Link,[14] P. Huber,[14] and W. Winter[15]

[1]Brunel University, [2]University of California, Riverside,
[3]Institute for Particle Physics Phenomenology, Durham University
[4]Fermi National Accelerator Laboratory, [5]University of Geneva
[6]University of Glasgow, [7]Imperial College London, [8]Instituto de Fisica Corpuscular, CSIC and Universidad de Valencia, [9]Thomas Jefferson National Accelerator Facility, [10]Kyoto University,
[11]Northwestern University, [12]Osaka University, [13]Oxford University, Subdepartment of Particle Physics, [14]Center for Neutrino Physics, Virginia Polytechnic Institute and State University
[15]Institut für theoretische Physik und Astrophysik, Universität Würzburg

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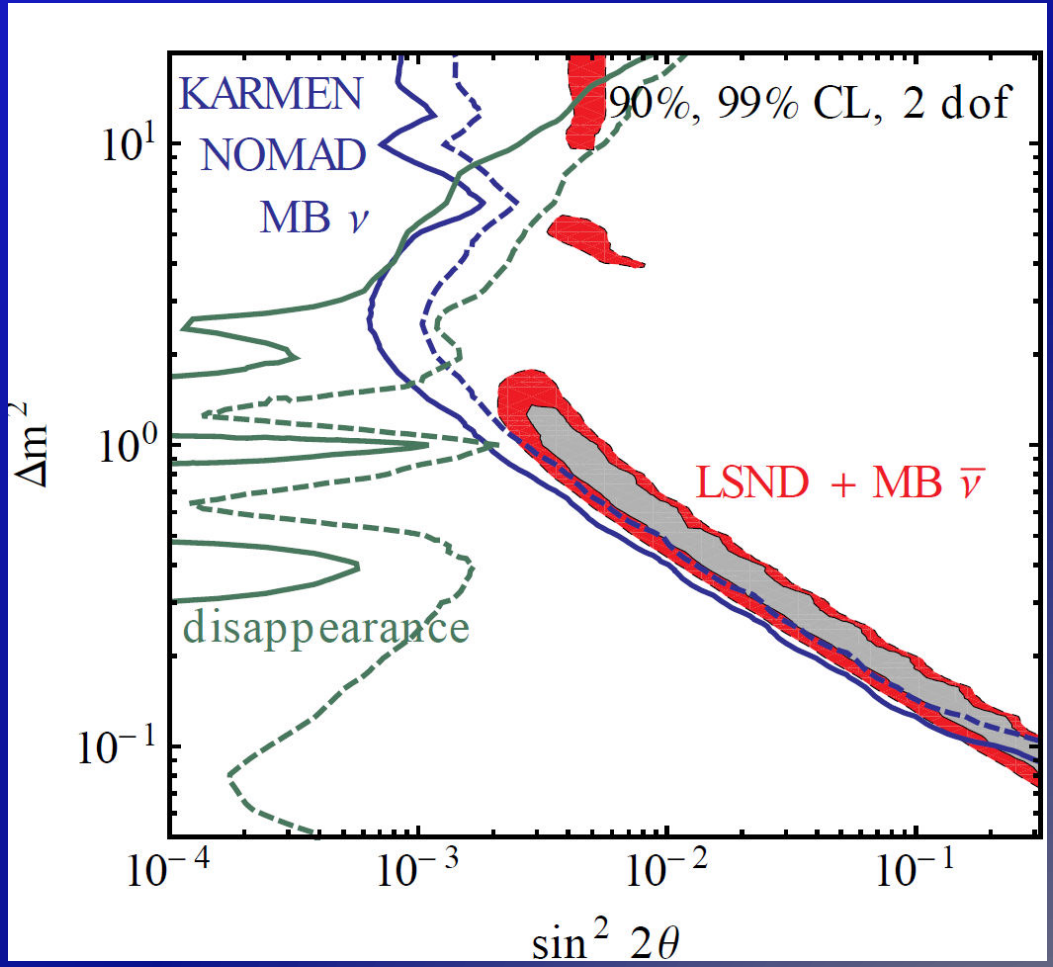
Motivation

- The idea of using a muon storage ring to produce neutrino beams for experiments is not new
  - 50 GeV beam – Koshkarev @ CERN in 1974
  - 1 GeV – Neuffer in 1980
- The facility/program I will describe here can:
  - Address the large Δm^2 oscillation regime and make a major contribution to the study of sterile neutrinos
    - Either allow for precision study if they exist in this regime
    - Or greatly expand the dis-allowed region
  - Make precision ν_e and ν_e-bar cross-section measurements
  - Provide a technology (μ decay ring) test demonstration and μ beam diagnostics test bed
  - Provide a precisely understood ν beam for detector studies

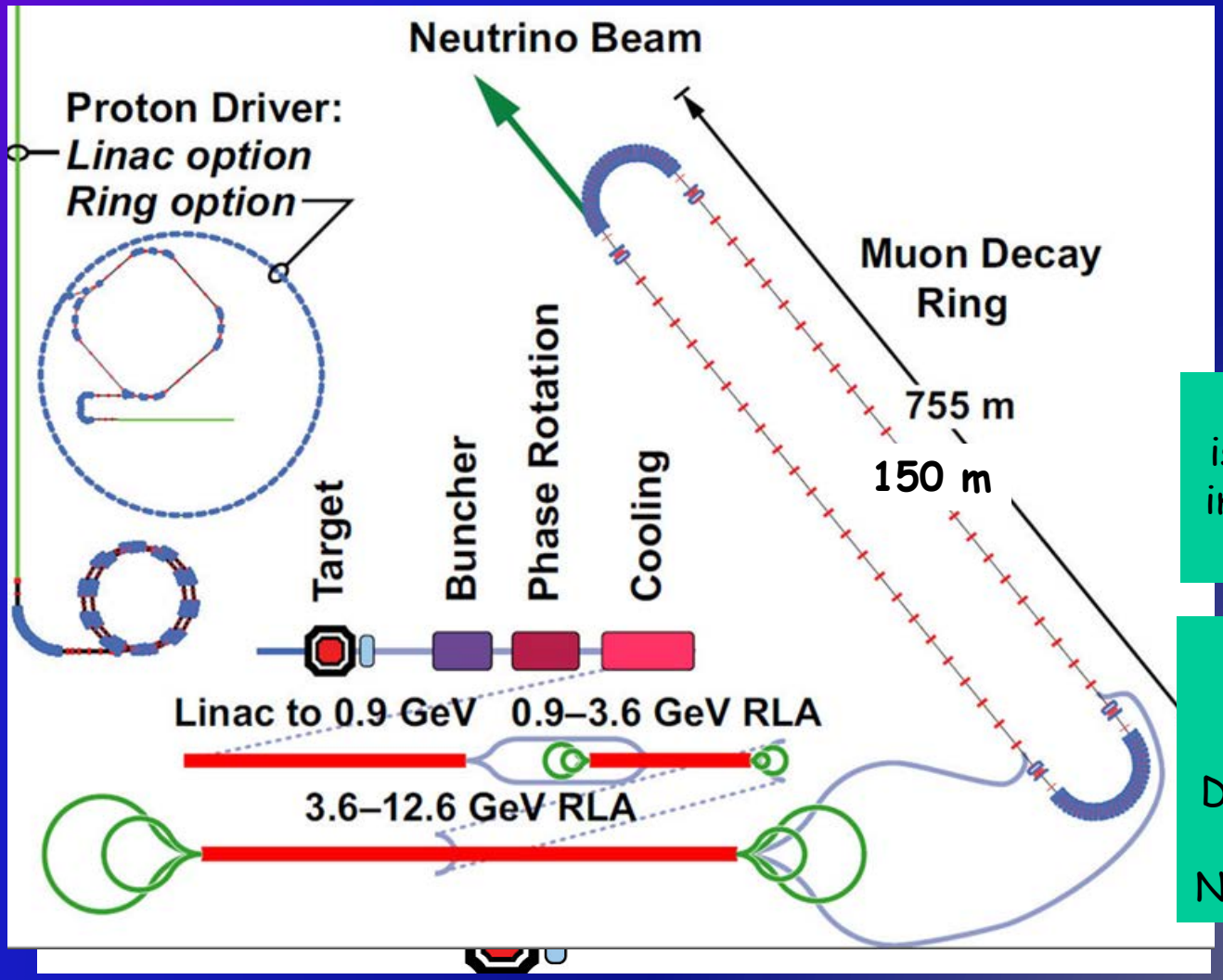
Short-baseline ν oscillation studies

- Sterile neutrinos arise naturally in many extensions of the Standard Model.
  - GUT models
  - Seesaw mechanism for n mass
  - Cosmological models of evolution of early universe
  - "Dark" sector
- Experimental hints
  - LSND
  - MiniBooNE
  - Reactor "anomaly"



Global constraints on sterile ν in a 3+1 model

IDS-NF
Neutrinos from STORed Muons
Single baseline, Lower E



This is the simplest implementation of the NF

And DOES NOT Require the Development of ANY New Technology

μ-based ν beams

Well-understood neutrino source:

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

μ Decay Ring: $$\mu^- \rightarrow e^- \nu_\mu \bar{\nu}_e$$

- Flavor content fully known
- "*Near Absolute*" Flux Determination is possible in a storage ring
  - Beam current, polarization, beam divergence monitor, μ_p spectrometer
- Overall, there is tremendous control of systematic uncertainties with a well designed system

Oscillation channels

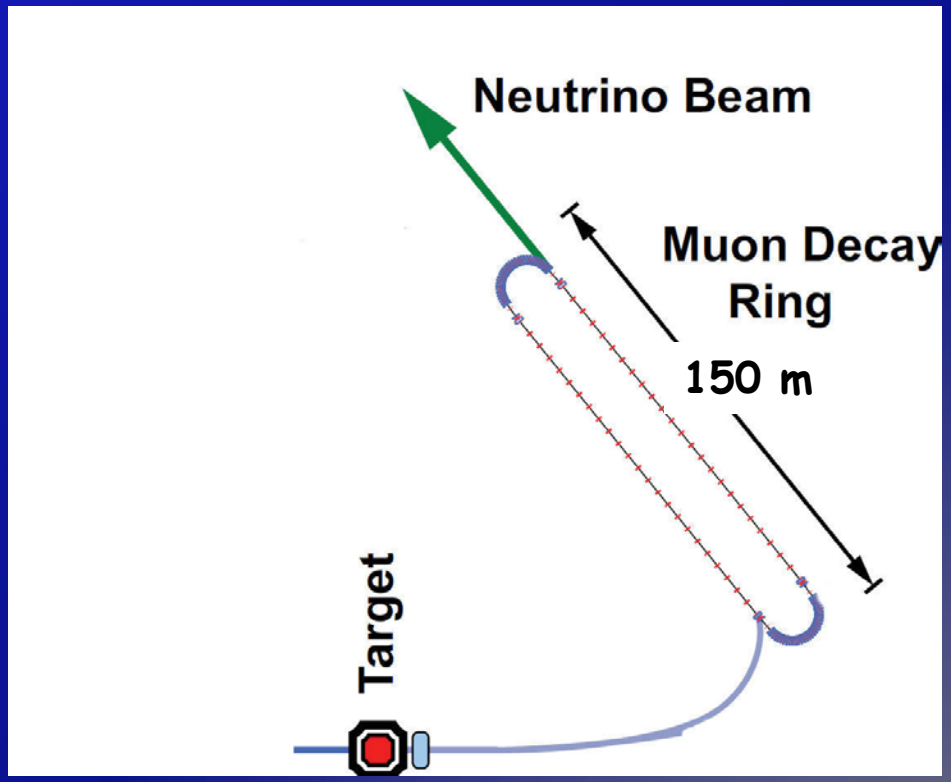
$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging)
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	appearance: "silver" channel

8 out of 12 channels potentially accessible

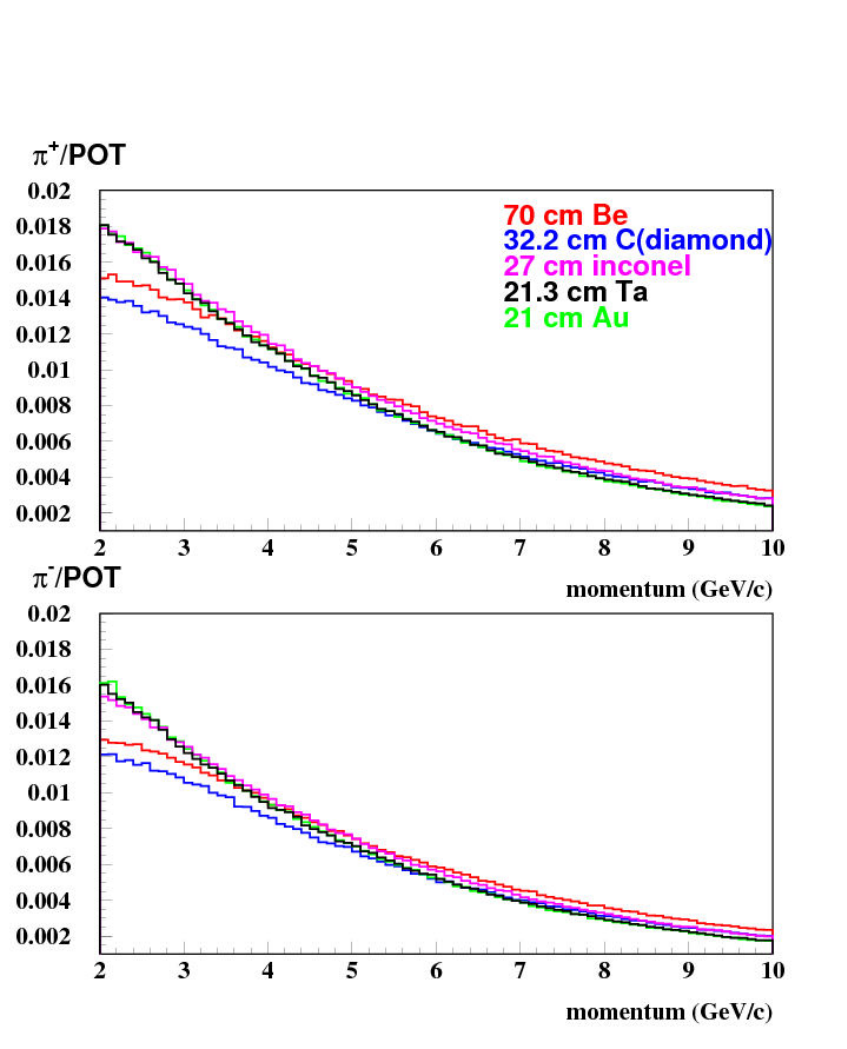
The Facility

Baseline(s)

- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Be target
    - Optimization on-going
  - Li Lens or horn collection after target
- Collection/transport channel
  - Two options
    - Stochastic injection of π
    - Kicker with $\pi \rightarrow \mu$ decay channel
    - At present NOT considering simultaneous collection of both signs
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter



π production

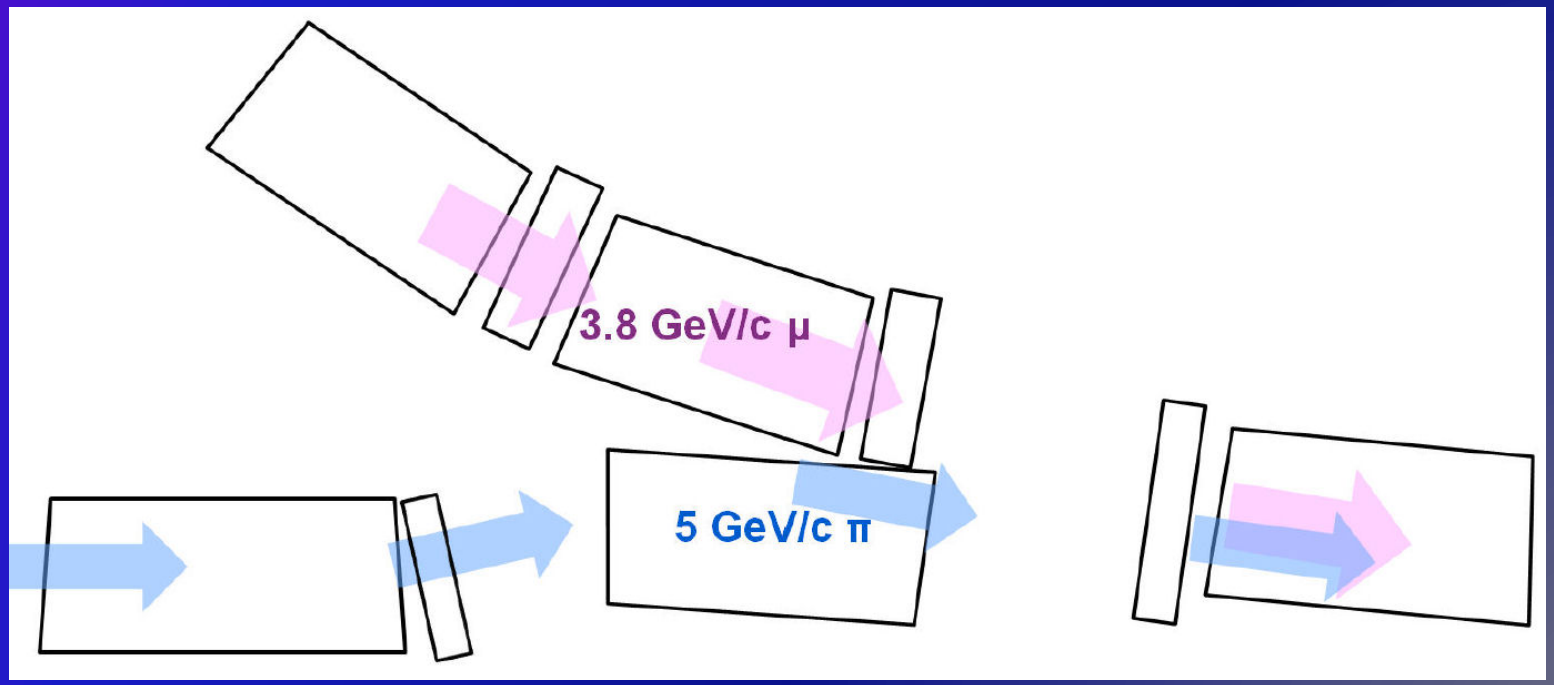


In momentum range
4.5 < 5.0 < 5.5
Obtain
≈ 0.11 $\pi^{\pm}$/pot
with 60 GeV p

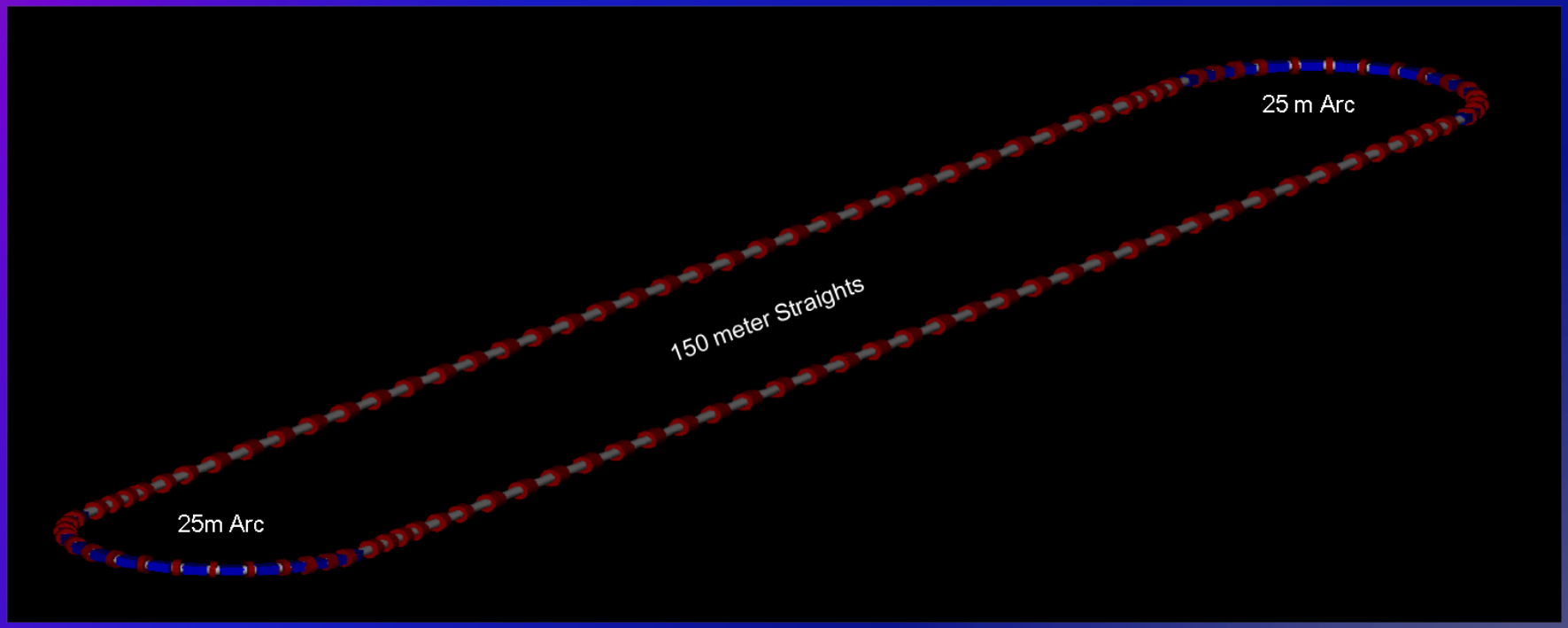
Target/capture optimization ongoing

Injection Concept

- π's are in injection orbit
  - separated by chicane
- μ's are in ring circulating orbit
  - lower energy - ~3.8 GeV/c
- ~30cm separation between
- Concept works for FODO lattice
- Work in progress for RFFAG

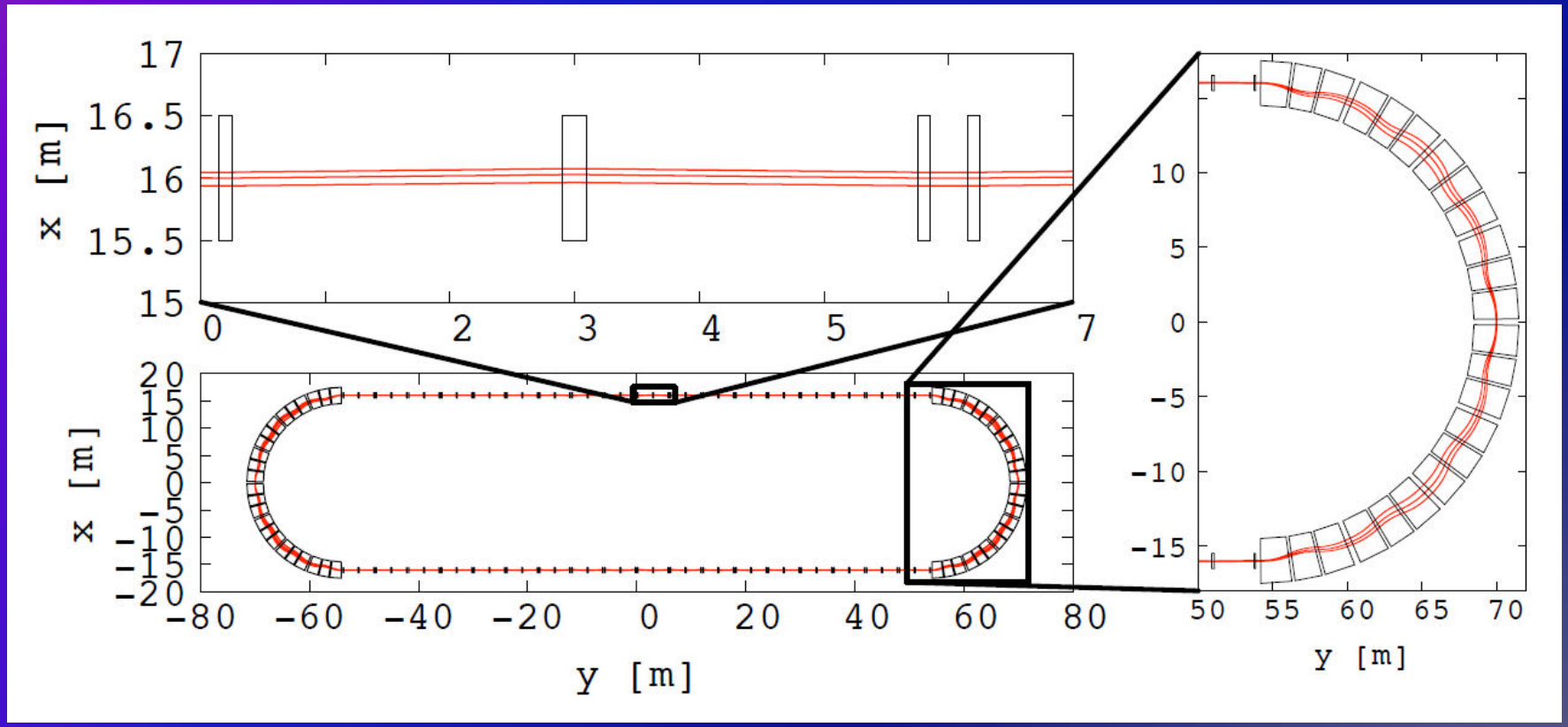


FODO Decay ring



3.8 GeV/c ± 10% momentum acceptance, circumference = 350 m

FFAG Racetrack

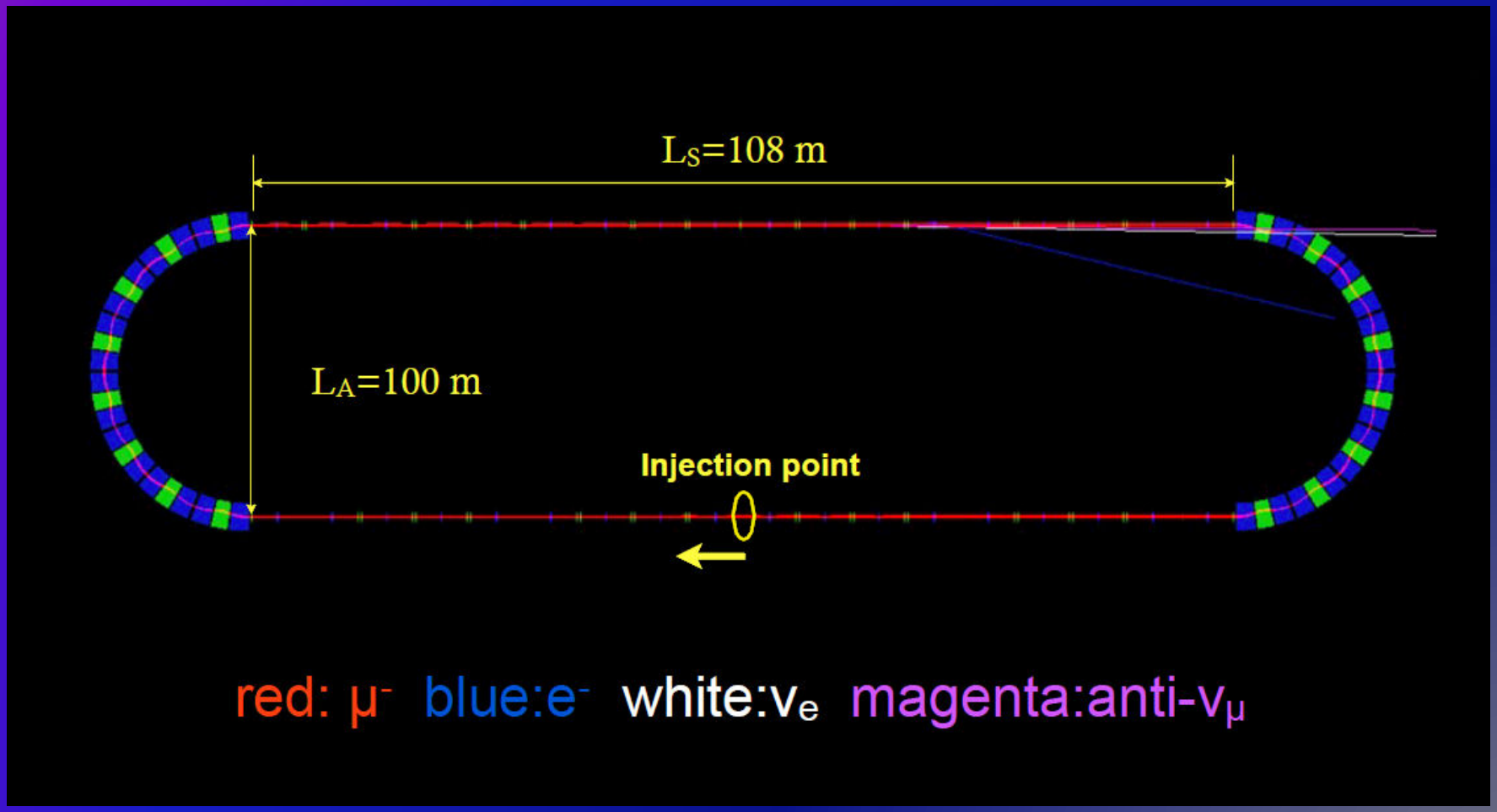


$\delta p/p \approx 15\%$

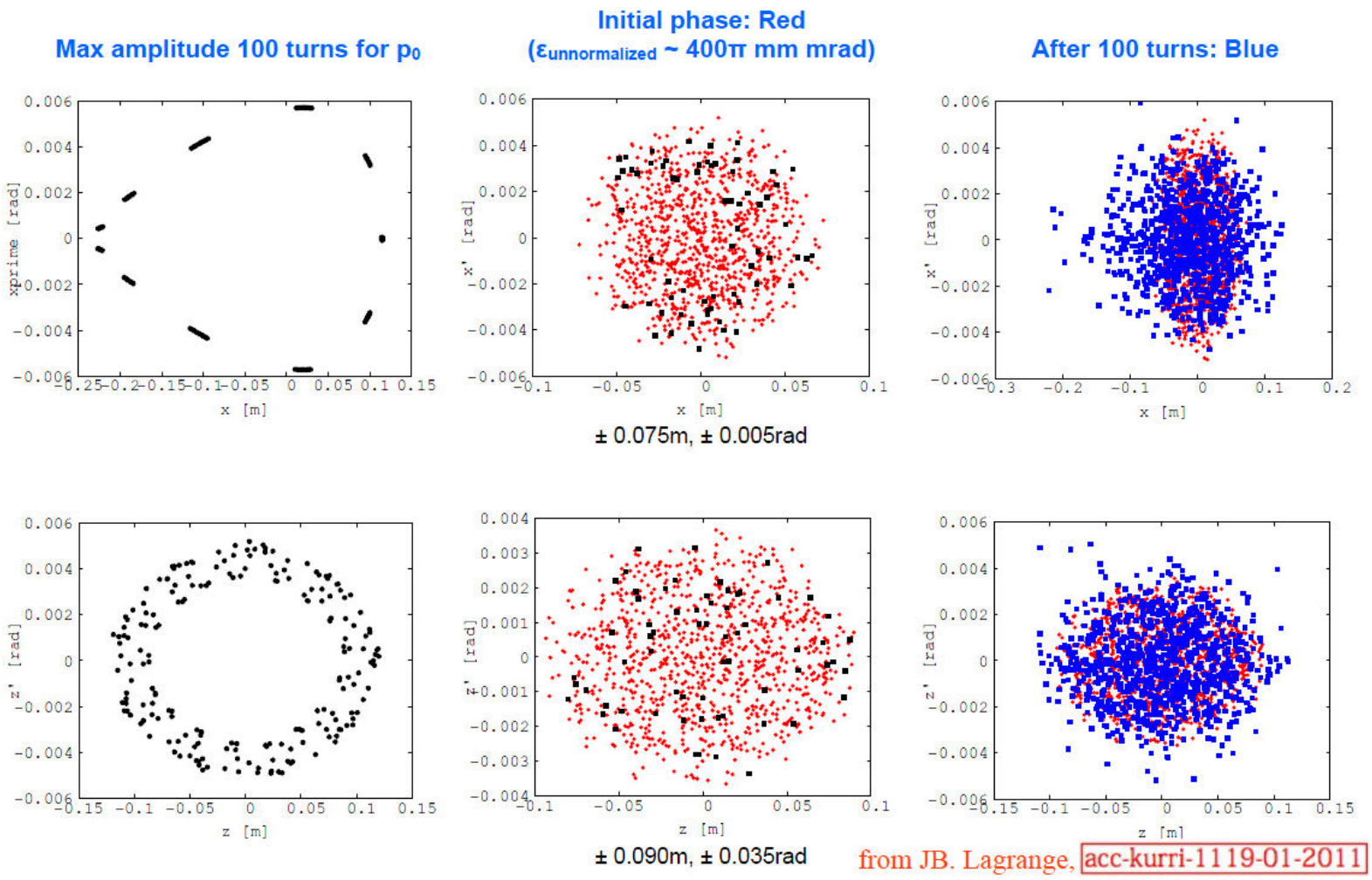
Low dispersion in straight

3.8 GeV/c

RFFAG Tracking Studies



FFAG Tracking



from JB. Lagrange, acc-kurri-1119-01-2011

>90% dynamic aperture

FODO vs. RFFAG

Table II. Relative μ yield for FODO vs. RFFAG rings

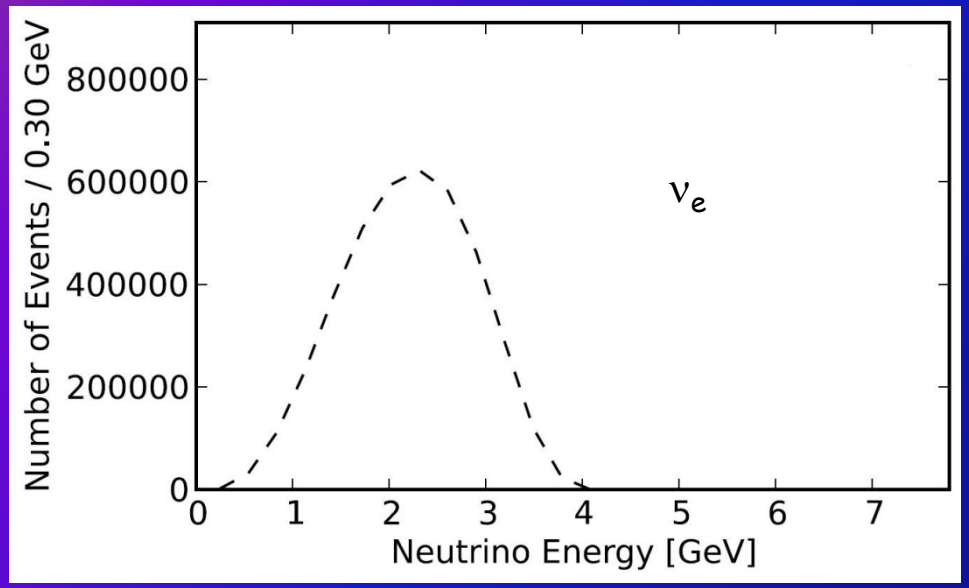
Parameter	FODO	RFFAG
$L_{straight}$ (m)	150	240
Circumference (m)	350	606
Dynamic aperture A_{dyn}	0.7	0.95
Momentum acceptance	$\pm$ 10%	$\pm$ 16%
π/POT within momentum acceptance	0.112	0.171
Fraction of π decaying in straight (F_s)	0.41	0.57
Ratio of $L_{straight}$ to ring circumference (Ω)	.43	.40
Relative factor ($A_{dyn} \times \pi/\mathrm{POT} \times F_s \times \Omega$)	0.014	0.037

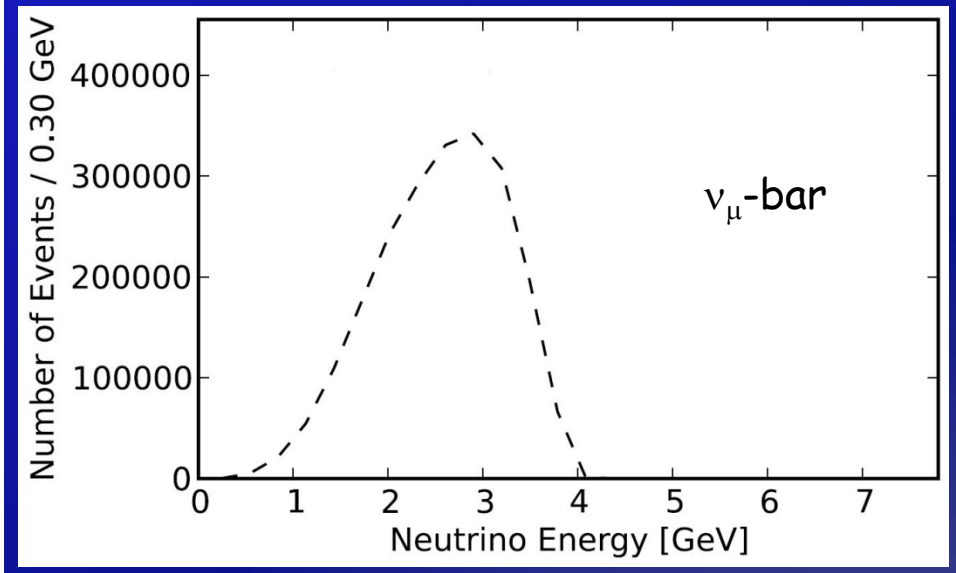
The Physics Reach

Assumptions

- N_μ = (POT) X (π/POT) X $\varepsilon_{collection}$ X ε_{inj} X (μ/π) X $A_{dynamic}$ X Ω
  - 10^{21} POT in 5 years of running @ 60 GeV in Fermilab PIP era
  - 0.1 π/POT
  - $\varepsilon_{collection}$ = 0.8
  - ε_{inj} = 0.8
  - μ/π = 0.08 (γct X μ capture in $\pi \rightarrow \mu$ decay) [π decay in straight]
    - Might do better with a $\pi \rightarrow \mu$ decay channel
  - $A_{dynamic}$ = 0.75 (from G4Beamline simulation)
  - Ω = Straight/circumference ratio (0.43)
- This yields $\approx$ 1.7 X 10^{18} useful μ decays

E_ν spectra (μ^+ stored)



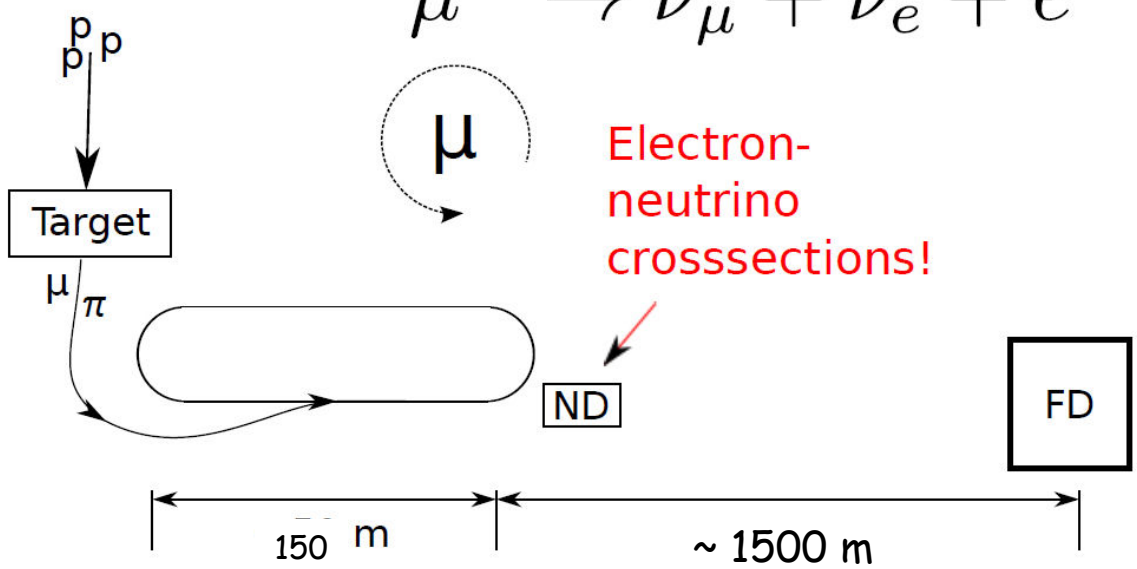


Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421

Event rates/100T
at ND hall 50m from straight

Experimental Layout

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



Appearance-only (though disappearance good too!)

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

Appearance Channel:

$\nu_e \rightarrow \nu_\mu$

Golden Channel

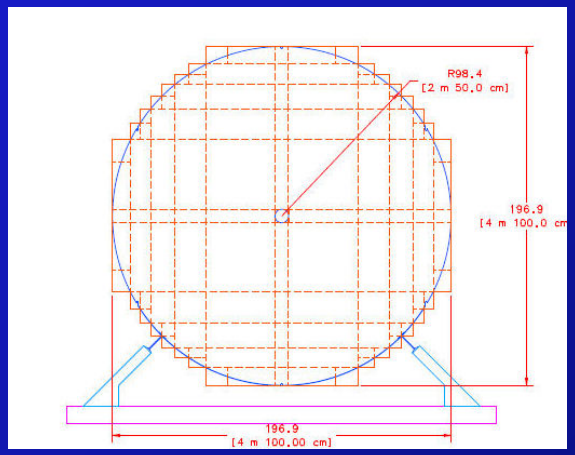
Must reject the "wrong" sign μ with great efficiency

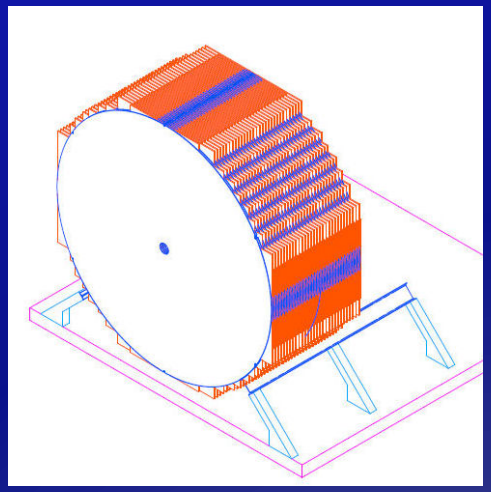
Why $\nu_\mu \rightarrow \nu_e$ Appearance Ch. not possible

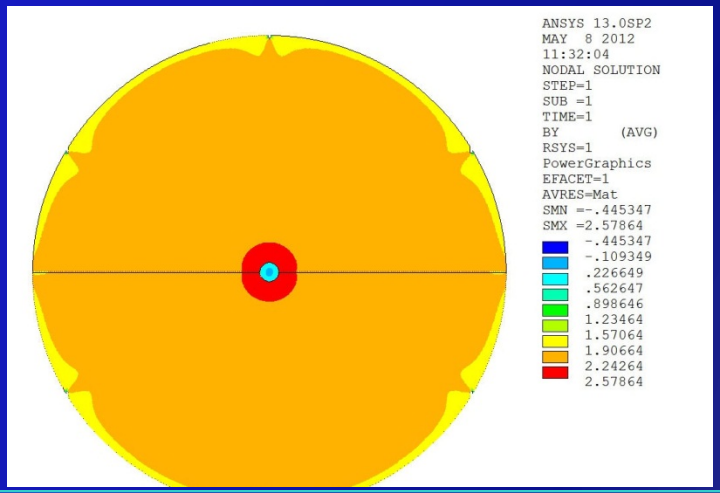
Baseline Detector

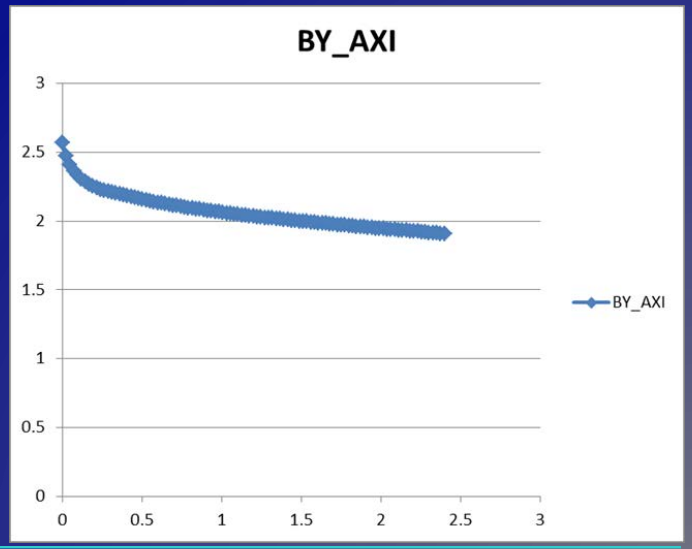
Super B Iron Neutrino Detector: SuperBIND

- Magnetized Iron
  - 1.3 kT fiducial volume
    - Following MINOS ND ME design
    - 1 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM



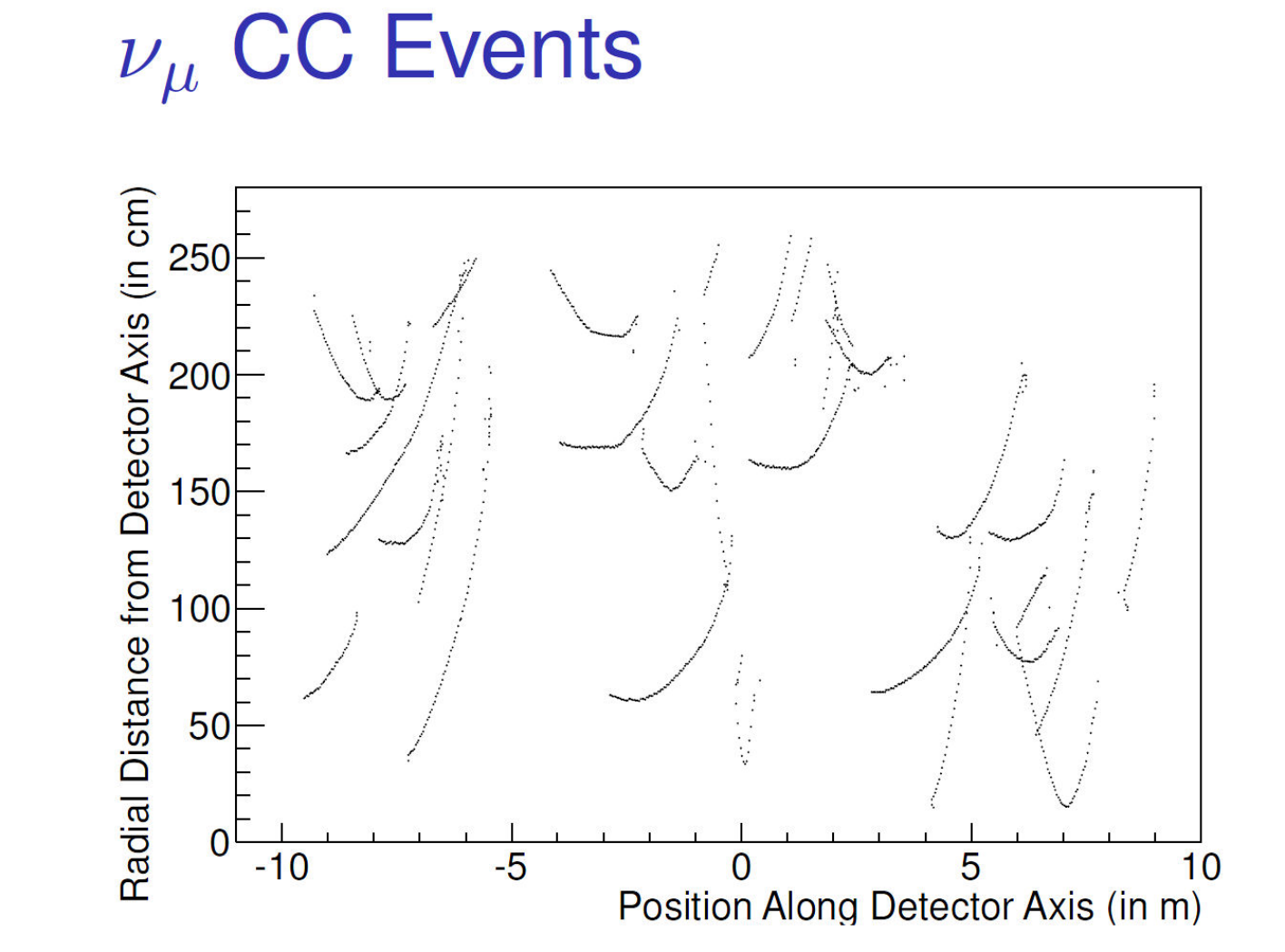






20 cm hole
For 3 turns
of STL

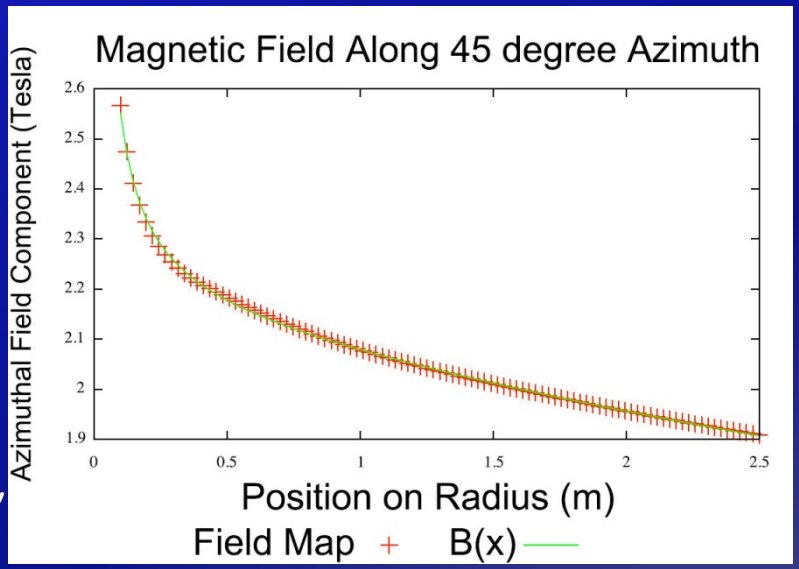
Event Candidates in SuperBIND



Hits
R vs. Z

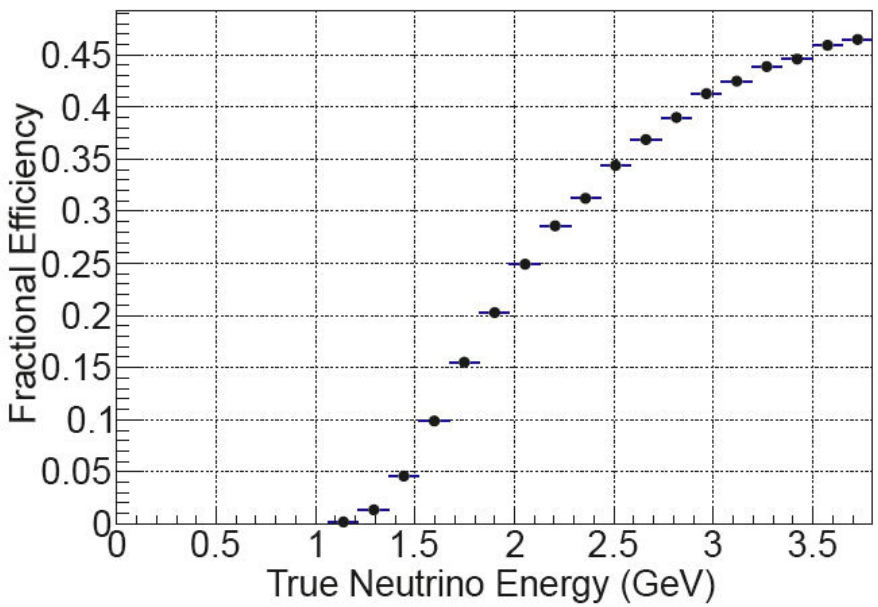
Simulation

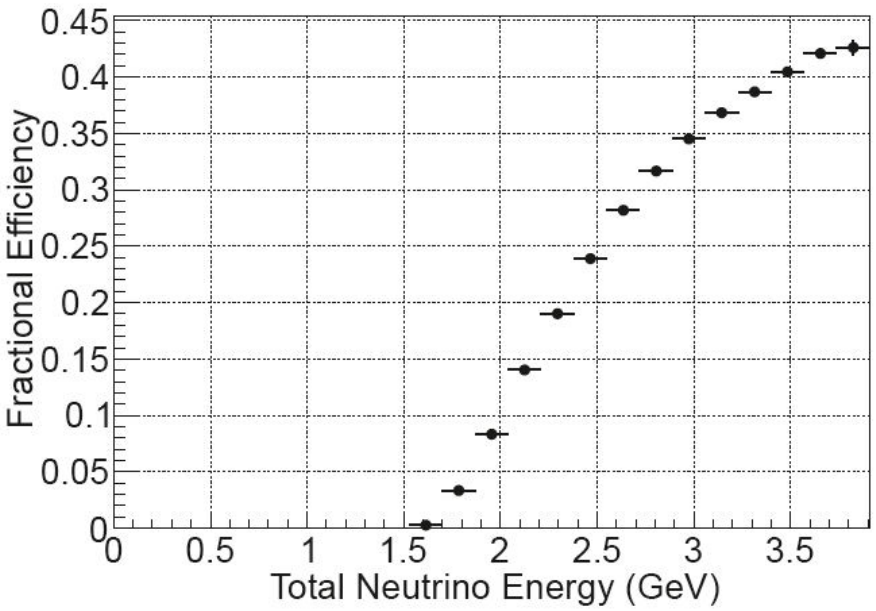
- Full GEANT4 Simulation
  - Extrapolation from ISS and IDS-NF studies for the MIND detector
  - Uses GENIE to generate the neutrino interactions.
  - Involves a flexible geometry that allows the dimensions of the detector to be altered easily (for optimization purposes, for example).
  - Does not yet have the detailed B field, but parameterized fit is very good
  - Event selection/cuts
    - Cuts-based analysis
    - Multivariate to come later



Event Cut	Description
Successful Reconstruction	Failed Kalman reconstruction of event removed
Fiducial	First hit of event is more than 1 m from end of detector
Maximum Momentum	Muon momentum less than $1.6 \times E_\nu$
Fitted Proportion	60% of track nodes used in final fit.
Track Quality	$\log(P(\sigma_{q/p}/(q/p)\|CC)/P(\sigma_{q/p}/(q/p)\|NC)) > -0.5$
NC Rejection (1 cm plates)	$\log(P(N_{hit}\|CC)/P(N_{hit}\|NC)) > 6.5$

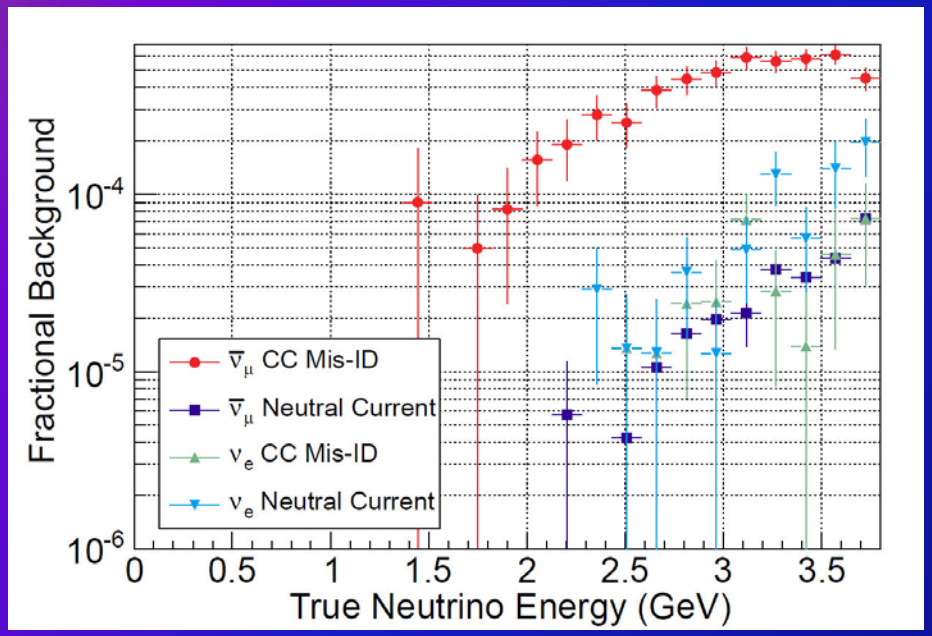
Event reconstruction efficiency

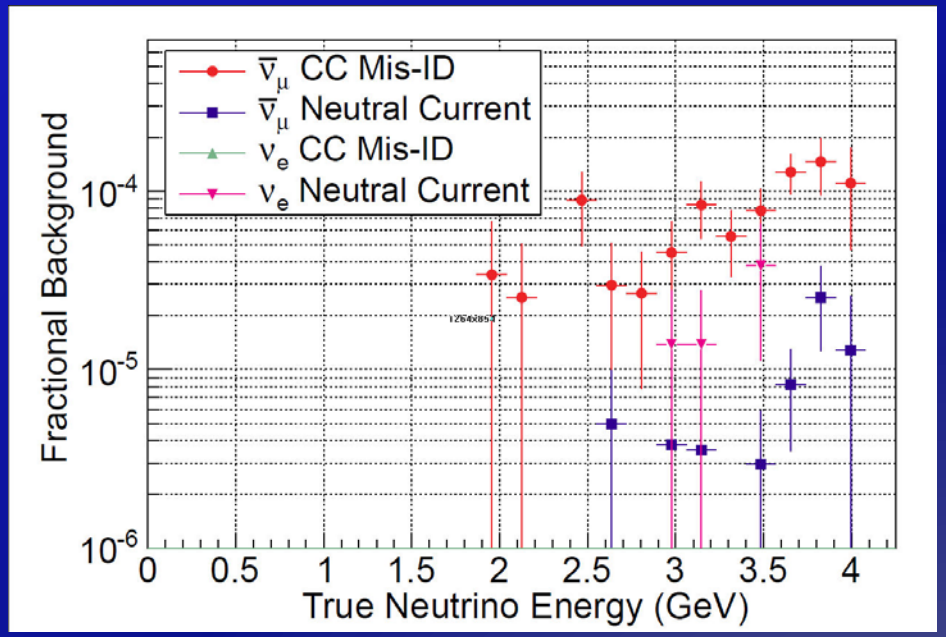




Left: 1 cm plates, Right: 2 cm plates

Backgrounds





Left: 1 cm plates

Right: 2 cm plates

Raw Event Rates

Neutrino mode with stored μ^+.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\nu_e \to \nu_\mu$ CC	332	0	∞	∞
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-4.8%	-10.7
$\nu_e \to \nu_e$ NC	73941	78805	-6.2%	-17.3
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-4.8%	-17.1
$\nu_e \to \nu_e$ CC	216657	230766	-6.1%	-29.4

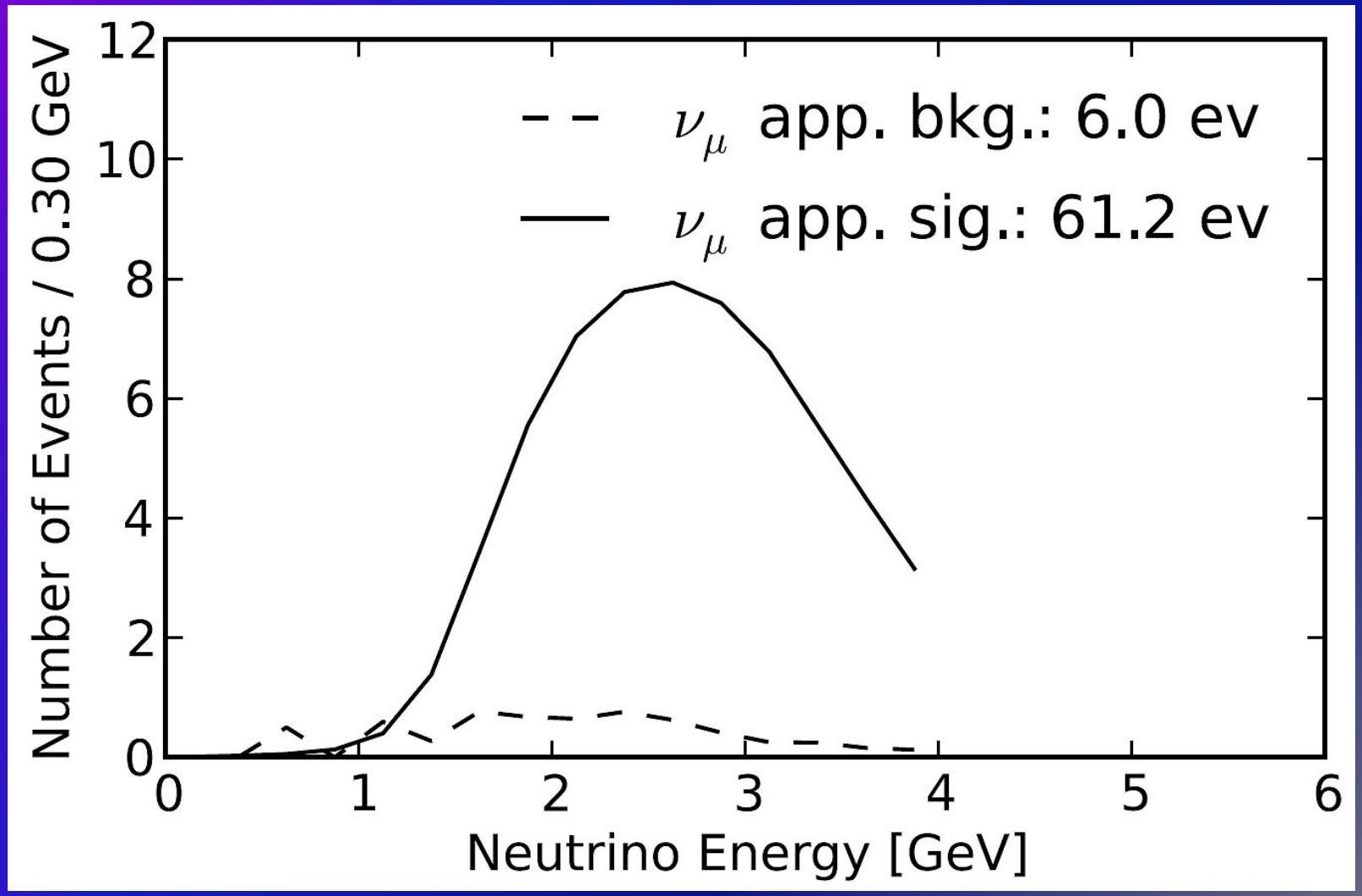
Anti-neutrino mode with stored μ^-.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$ CC	197284	207274	-4.8%	-21.9

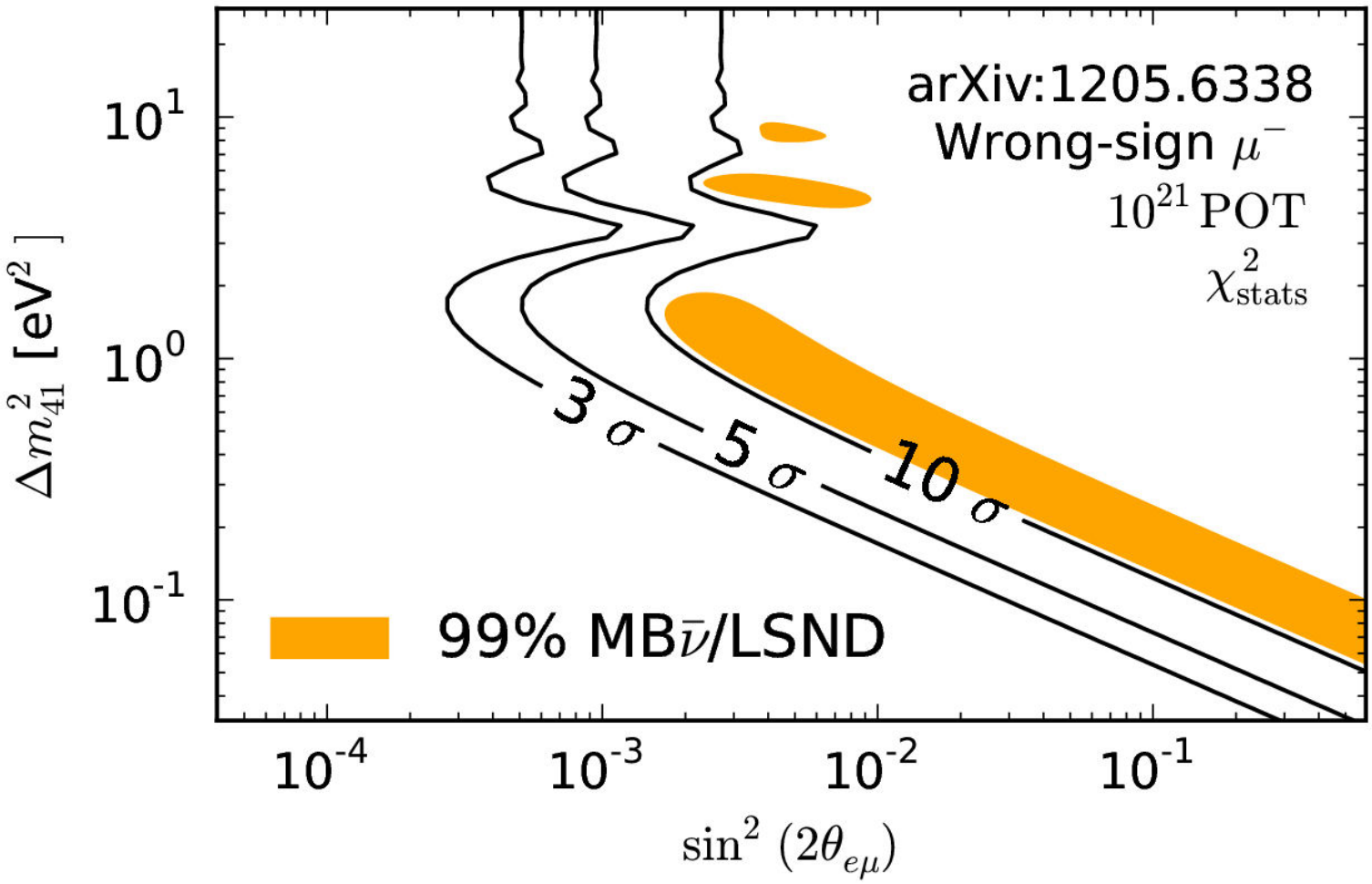
3+1
Assumption

Appearance channels

$\nu_e \rightarrow \nu_\mu$ appearance
CPT invariant channel to MiniBooNE

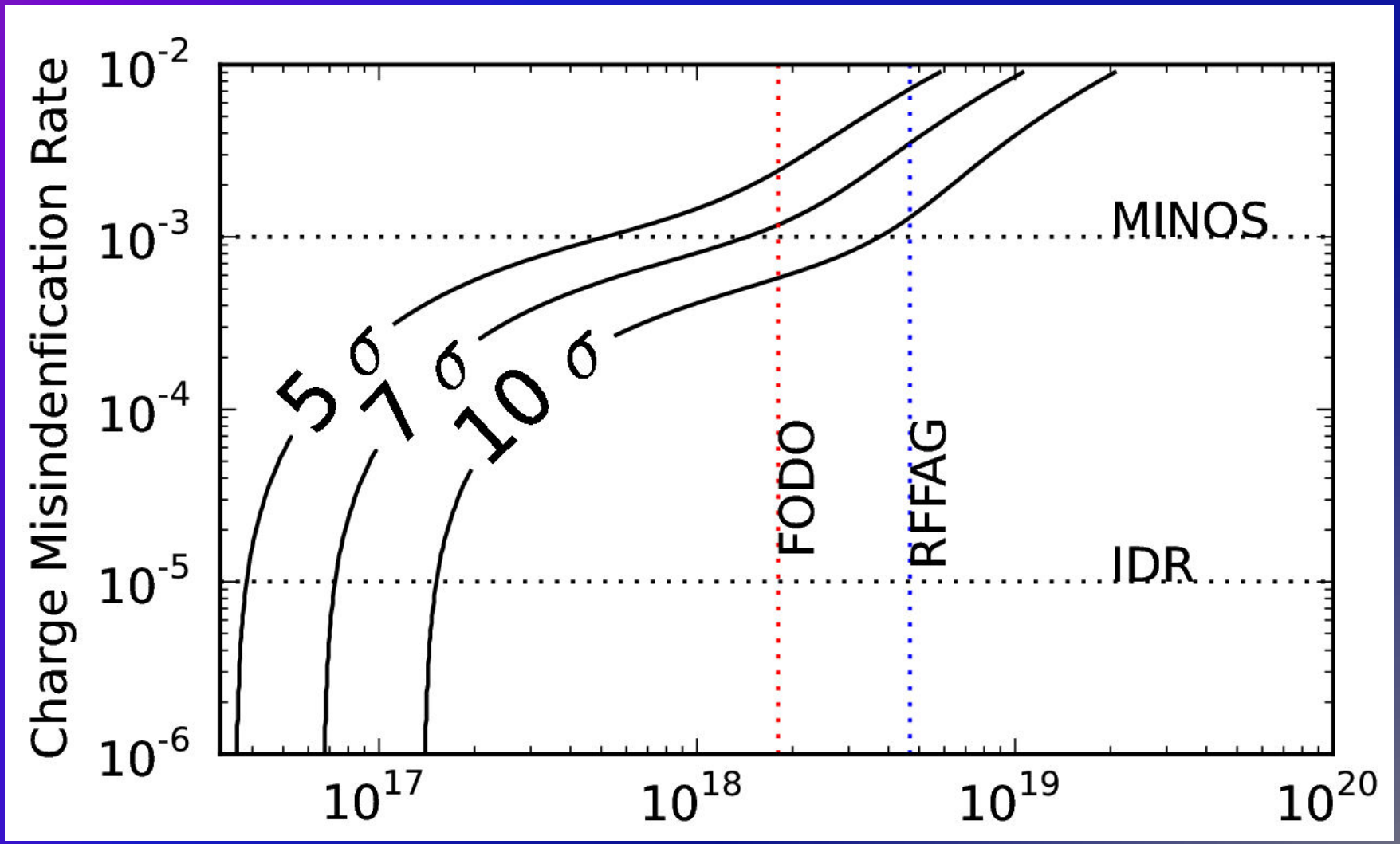


$\nu_e \rightarrow \nu_\mu$ appearance
CPT invariant channel to MiniBooNE



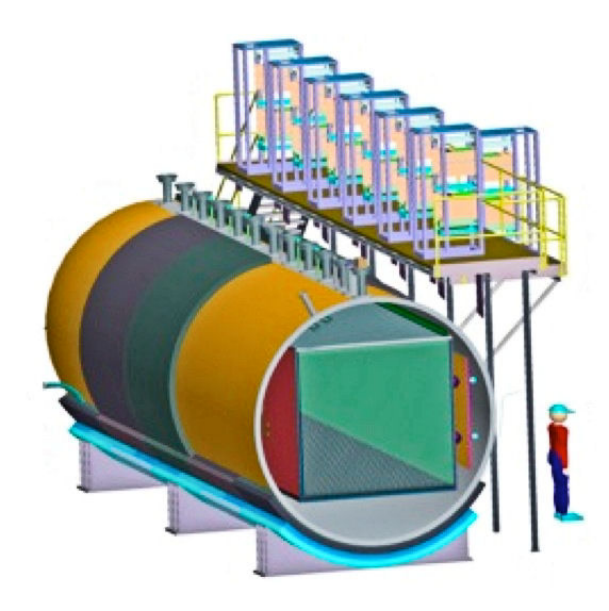
3+1 Assumption

Required μ charge mis-ID rate needed for given sensitivity



Detector Considerations

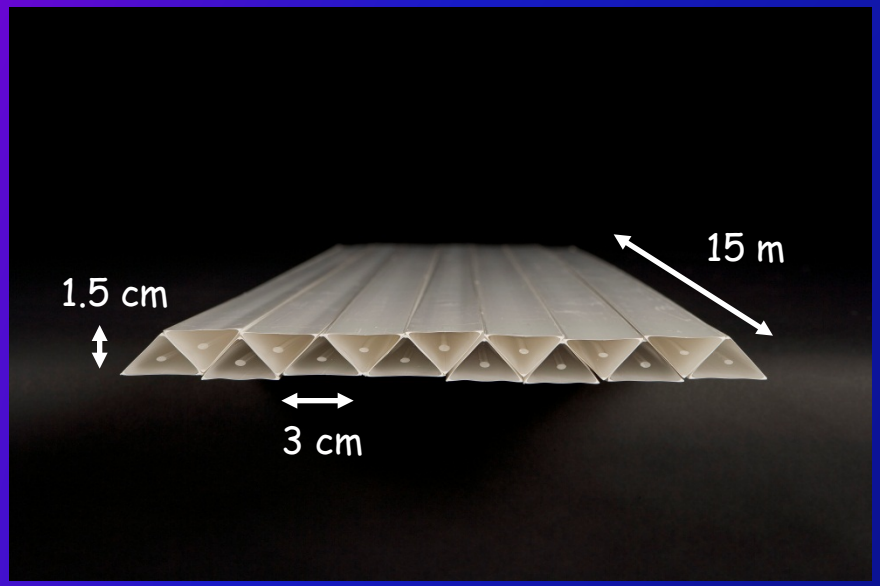
- Other options
  - Totally Active Scintillator - TASD
  - LAr
  - Present opportunity to measure ν_e appearance?
- Must be Magnetized, however
  - A hybrid approach (external μ spectrometer) is a possibility

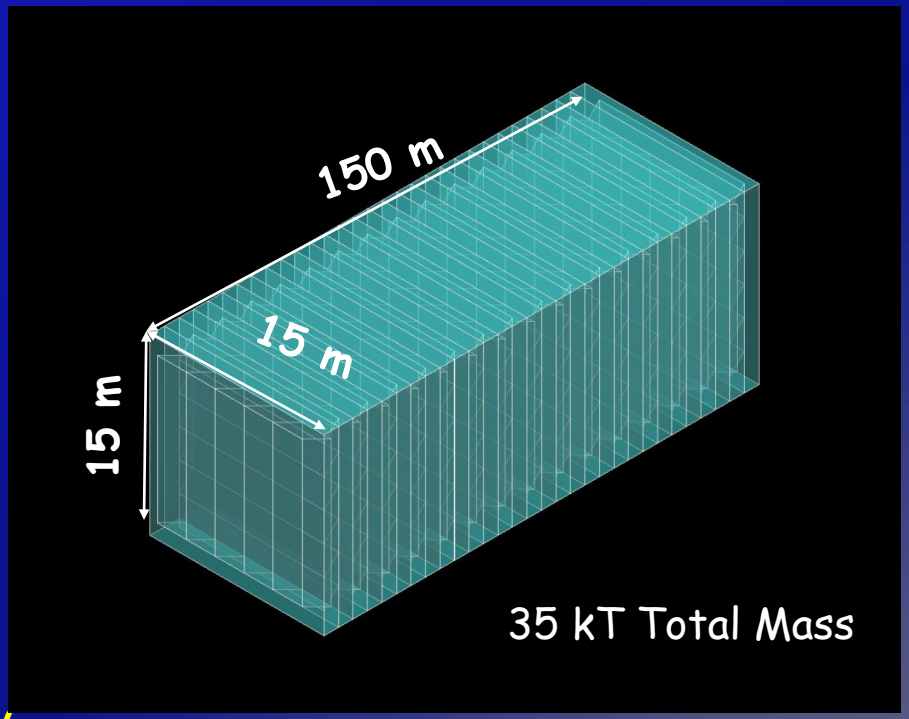


Fine-Resolution Totally Active Segmented Detector (IDS-NF)

Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels



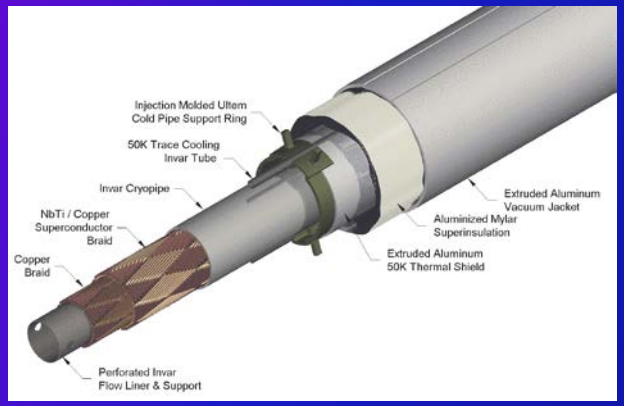


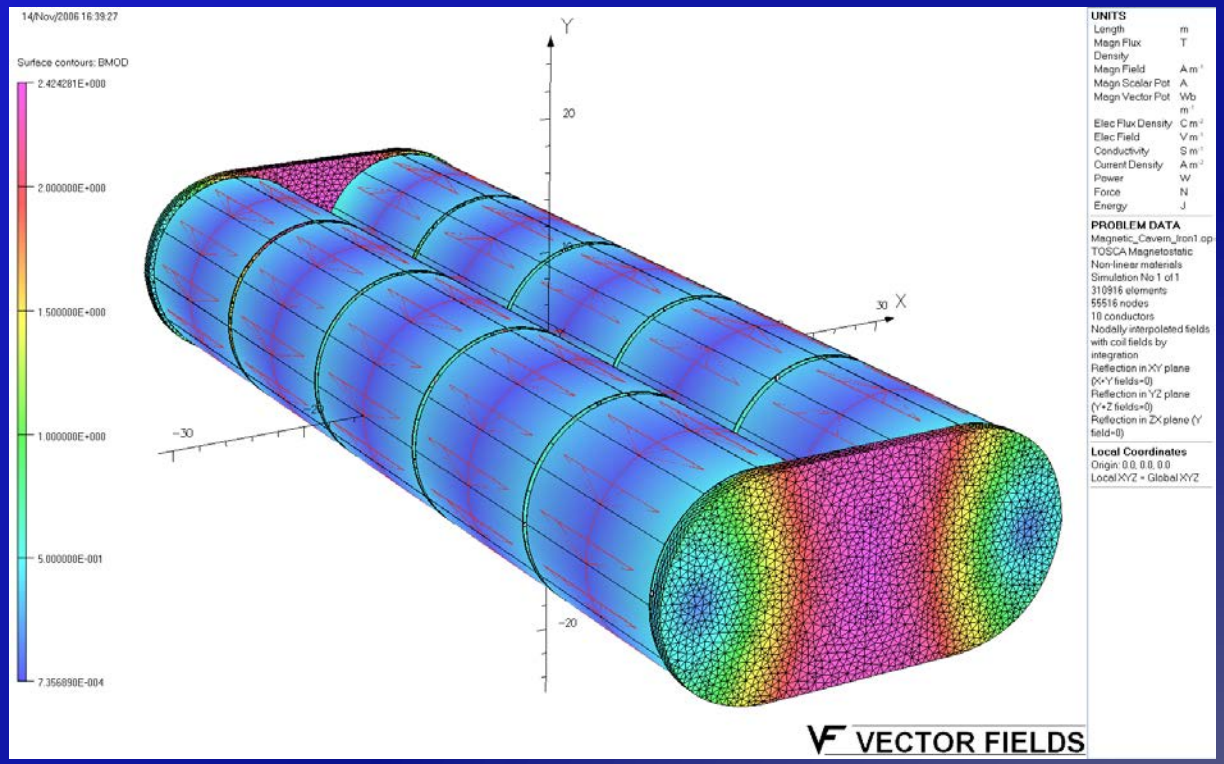
- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

B = 0.5T

Magnet- Concept for IDS-NF

- VLHC SC Transmission Line
  - Technically proven
  - Affordable



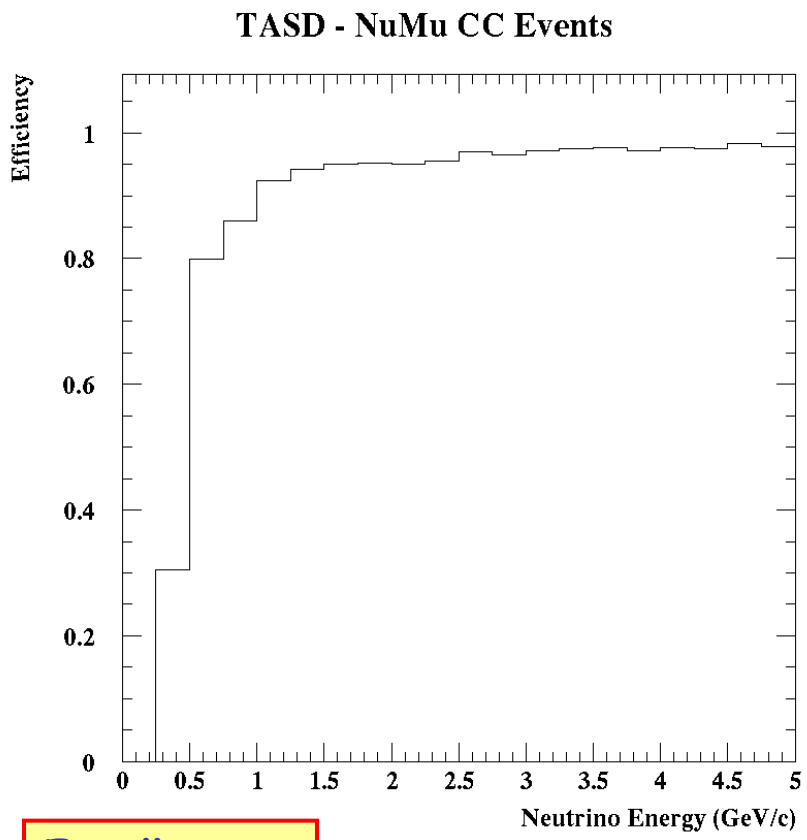


R&D to support concept
Has not been funded

1 m iron wall thickness.
~2.4 T peak field in the iron.
Good field uniformity

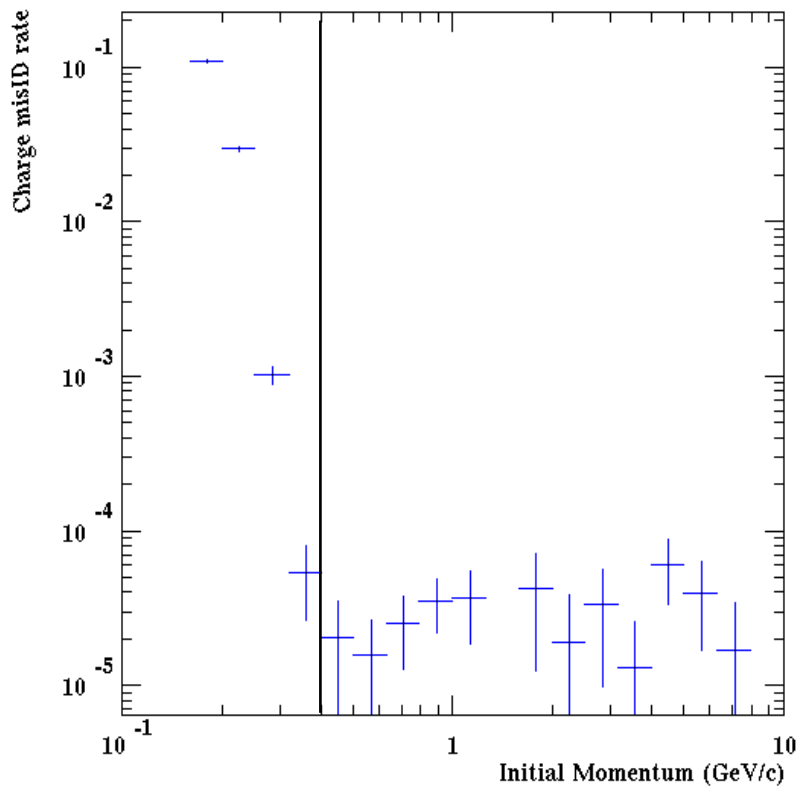
TASD Performance

ν Event Reconstruction ε



Excellent σ_E

Muon charge mis-ID rate



Detector Options

Technology check List

	Fid Volume	B	Recon	Costing Model
SuperBIND	☑	☑	☑	☑
Mag-TASD	☑	☑	☑	☑
Mag-LAr	☑	☑	☑	☑

☑	Yes - OK
☑	Maybe
☑	Not Yet

Disappearance Experiments

Raw Event Rates

Neutrino mode with stored μ^+.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\nu_e \to \nu_\mu$ CC	332	0	∞	∞
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	47679	50073	-4.8%	-10.7
$\nu_e \to \nu_e$ NC	73941	78805	-6.2%	-17.3
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	122322	128433	-4.8%	-17.1
$\nu_e \to \nu_e$ CC	216657	230766	-6.1%	-29.4

Anti-neutrino mode with stored μ^-.

Channel	$N_{\text{osc.}}$	N_{null}	Diff.	$(N_{\text{osc.}} - N_{\text{null}})/\sqrt{N_{\text{null}}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$ CC	197284	207274	-4.8%	-21.9

3+1 Assumption

Tremendous Statistical Significance

Appearance channels

Disappearance channels

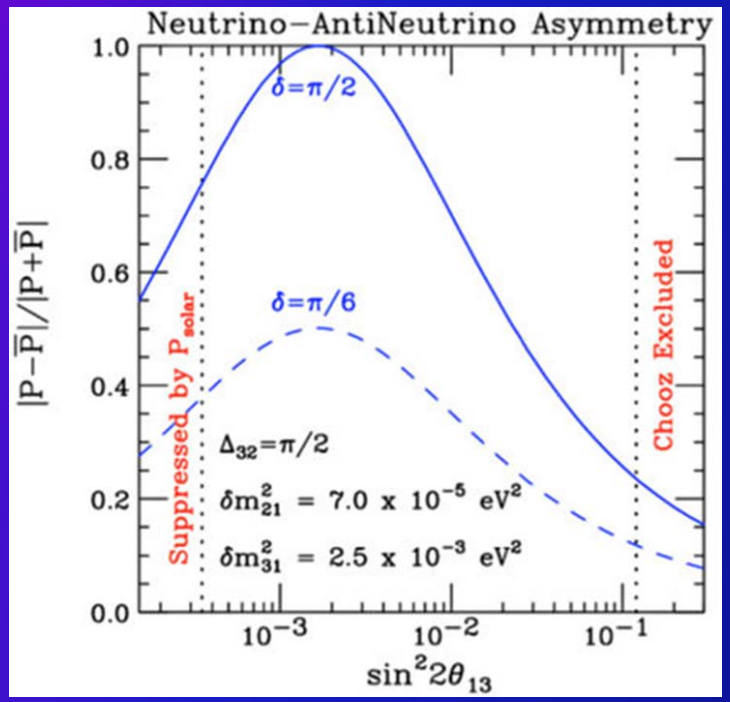
But:

- Need self-consistent two-detector simulation including (bin-to-bin) uncorrelated shape error ~ 10%
- A challenge: there may be oscillations already in near detectors
  - Geometry important for $\Delta m^2 \sim 10^1 - 10^3$ eV^2
- Suitability of SuperBIND for ν_e channels needs to be studied

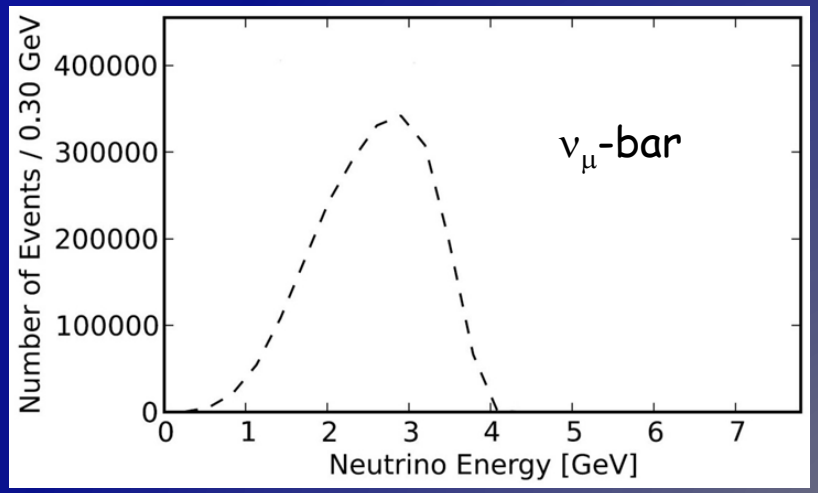
Cross-Section Measurements
&
Disappearance Searches

ν Cross-section measurements

- 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
      - E_ν matched well to needs of these experiments



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



Outlook

Future Work:

- Facility
  - Targeting, capture/transport & Injection
    - Need detailed design and simulation
  - Decay Ring optimization
    - Continued study of both RFFAG & FODO decay rings
  - Decay Ring Instrumentation
    - Define and simulate performance of BCT, polarimeter, Magnetic-spectrometer, etc.
  - Produce full G4Beamline simulation of all of the above to define ν flux
    - And verify the precision to which it can be determined.

Outlook II

Future Work:

- Detector simulation
  - For oscillation studies, continue MC study of backgrounds & systematics
    - Also investigate disappearance channels
  - In particular the event classification in the reconstruction needs optimization.
    - Currently assumes "longest track" is interaction muon.
    - Plan to assign hits to and fit multiple tracks.
    - Vertex definition must also be improved.
  - For cross-section measurements need detector baseline design
    - Learn much from detector work for LBNE & IDS-NF
      - Increased emphasis on ν_e interactions, however
    - Near Detector hall could be envisioned as ν detector test facility
- Produce Full Proposal

νSTORM: Conclusions

The Physics case:

- Initial simulation work indicates that a L/E ≈ 1 oscillation experiment using a muon storage ring can confirm/exclude at 10σ (CPT invariant channel) the LSND/MiniBooNE result
- ν_μ and (ν_e) disappearance experiments delivering at the <1% level look to be doable
  - Systematics need careful analysis
  - Detailed simulation work on these channels has not yet started
- Cross section measurements with near detector(s) offer a unique opportunity

The Facility:

- Presents very 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

νSTORM : Conclusions II

The Detector:

- Is based on demonstrated technology and follows engineering principles from existing detectors
  - Technology extrapolations (scintillator readout) are perfectly aligned with development work within Fermilab's existing program (μ2e)
  - Magnetization is based on technology that was fully vetted over 10 years ago
    - But has been in a dormant state

νSTORM :

- Delivers on the physics for the study of sterile ν
  - Offering a new approach to the production of ν beams setting a 10 σ benchmark to confirm/exclude LSND/MiniBooNE ν-bar data
- Can add significantly to our knowledge of ν cross-sections, particularly for ν_e interactions
- Provides an accelerator technology test bed
- Provides a powerful ν detector test facility

νSTORM : Sterile ν

Of the 30+ concepts that have recently been discussed in the literature to search for/study sterile neutrinos, νSTORM is the only one that can do all of:

- Make a direct test of the LSND and MiniBooNE anomalies.
- Provide stringent constraints for both ν_e and ν_μ disappearance to over constrain 3+N oscillation models and to test the Gallium and reactor anomalies directly.
- Test the CP- and T-conjugated channels as well, in order to obtain the relevant clues for the underlying physics model, such as CP violation in 3 + 2 models.

END

Thank You