Neutrinos from Stored Muons
nSTORM

n physics with a μ storage ring

The "Collaboration"

P. Kyberd,[1] D.R. Smith,[1] L. Coney,[2] S. Pascoli,[3] C. Ankenbrandt,[4] S.J. Brice,[4] A.D. Bross,[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

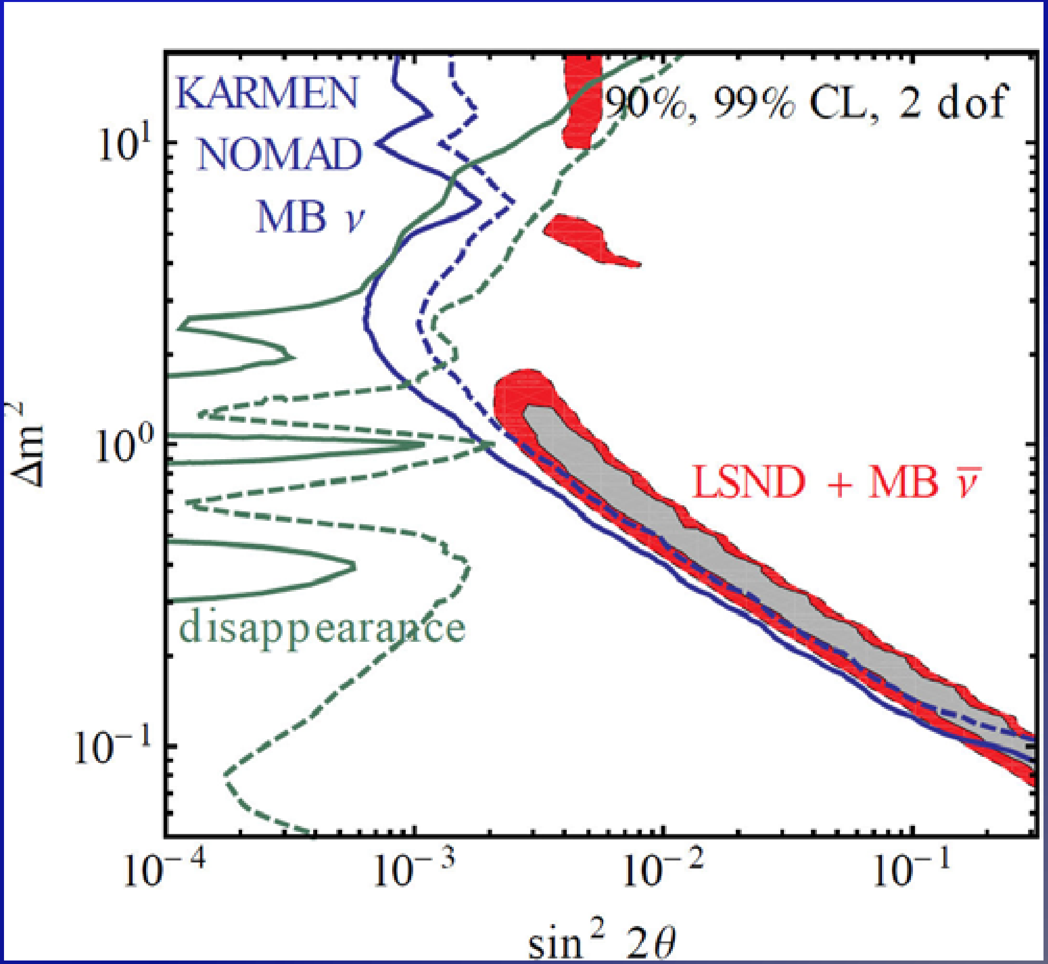
[6]University of Glasgow, [7]Imperial College London, [8]Instituto de Fisica Corpuscular, CSIC and Universidad de Valencia, [9]Thomas Jefferson National Accelerator Facility, [10]Kyoto University, [11]Northwestern University, [12]Osaka University, [13]Oxford University, Subdepartment of Particle Physics,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

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 Dm^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 n_e and n_e-bar cross-section measurements
  - Provide a technology test demonstration (mdecay ring) and m beam diagnostics test bed
  - Provide a precisely understood n beam for detector studies

Short-baseline n 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”

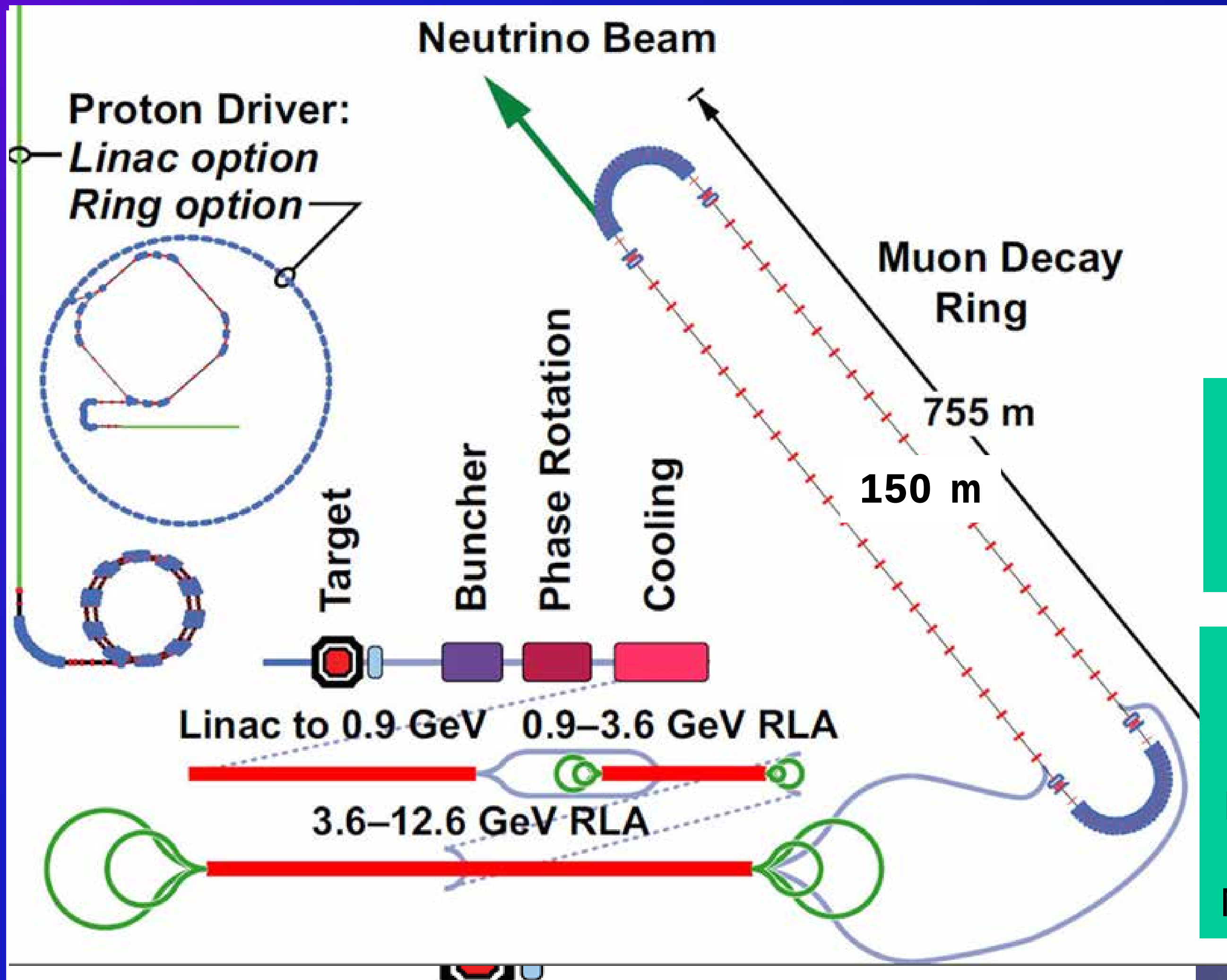


Global constraints on sterile n in a 3+1 model

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

m-based n beams

Well-understood neutrino source:

$$m^{+} ® \; e^{+}\bar{n}_{m}n_{e}$$

μ Decay Ring:

$$m^{-} ® \; e^{-}n_{m}\bar{n}_{e}$$

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

Oscillation channels

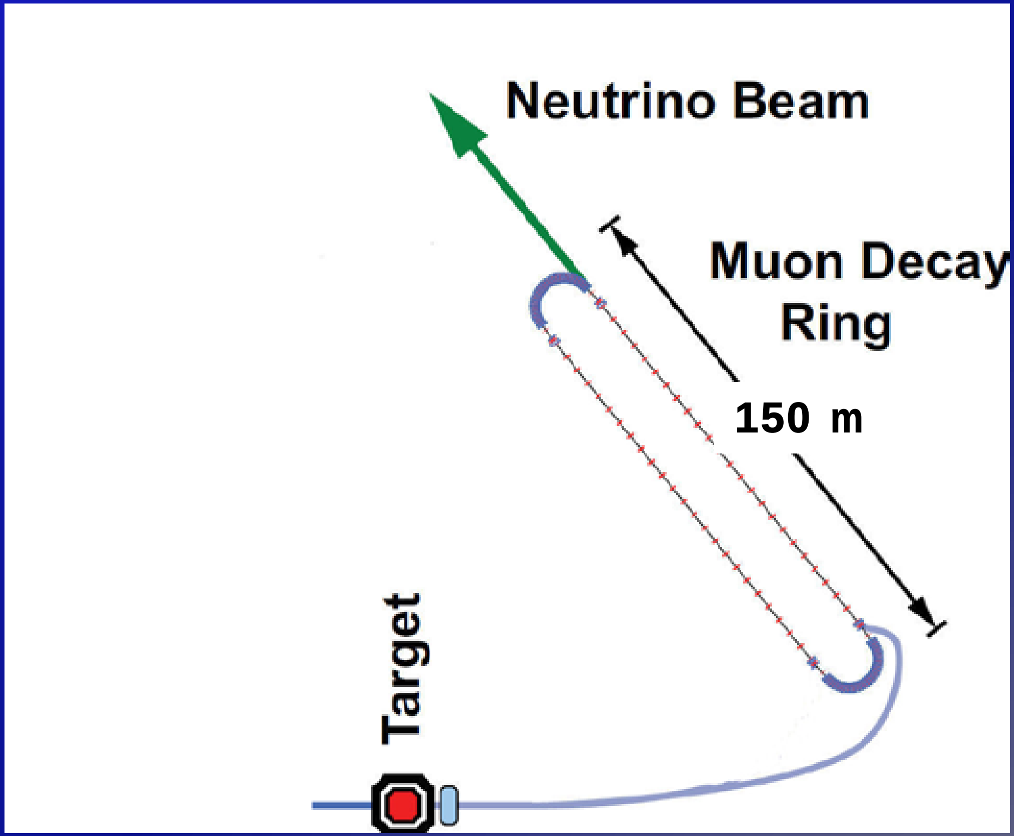
$\mu^+ \rightarrow e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \rightarrow e^- \overline{\nu}_e \nu_\mu$	
$\overline{\nu}_\mu \rightarrow \bar{\nu}_\mu$	$\nu_\mu \rightarrow \nu_\mu$	disappearance
$\overline{\nu}_\mu \rightarrow \bar{\nu}_e$	$\nu_\mu \rightarrow \nu_e$	appearance (challenging)
$\overline{\nu}_\mu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

8 out of 12 channels potentially accessible

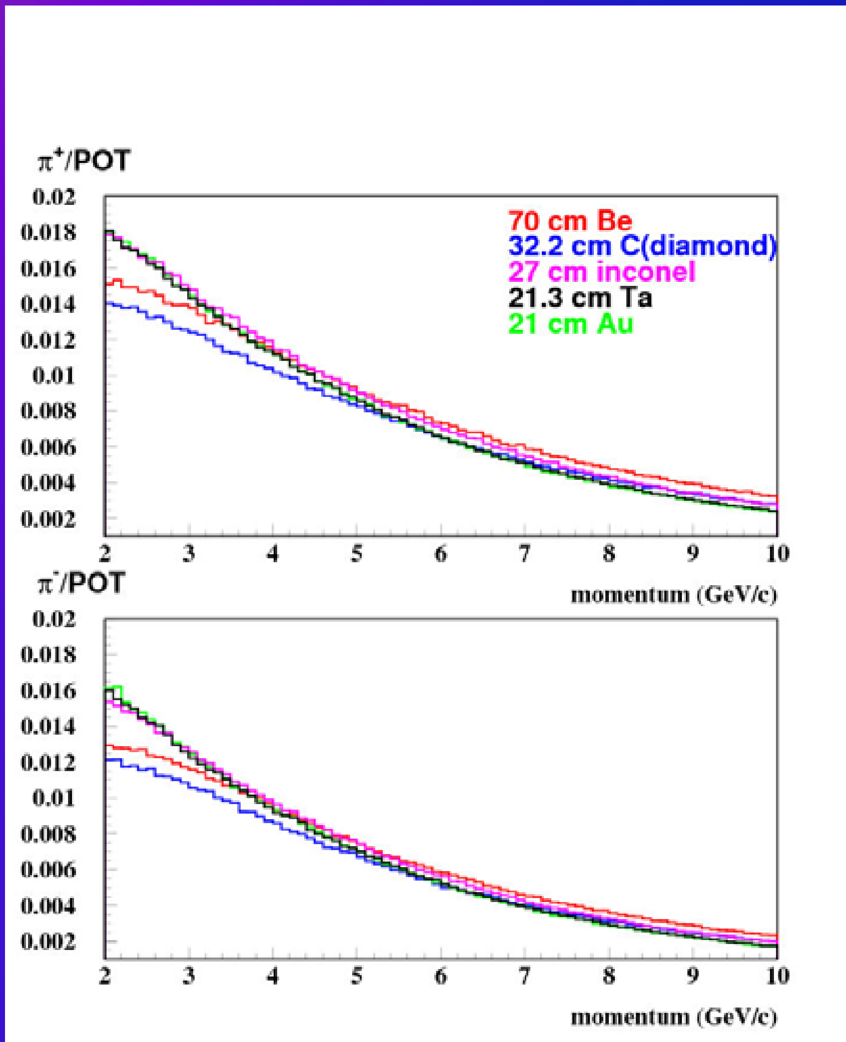
The Facility

Baseline(s)

- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Ta target
    - Optimization on-going
  - Horn collection after target
    - Li lens has also been explored
- Collection/transport channel
  - Two options
    - Stochastic injection of p
    - Kicker with p ® mdecay channel
    - At present **NOT** considering simultaneous collection of both signs
- Decay ring
  - Large aperture FODO
  - Racetrack FFAG
  - Instrumentation
    - BCTs, mag-Spec in arc, polarimeter



p production



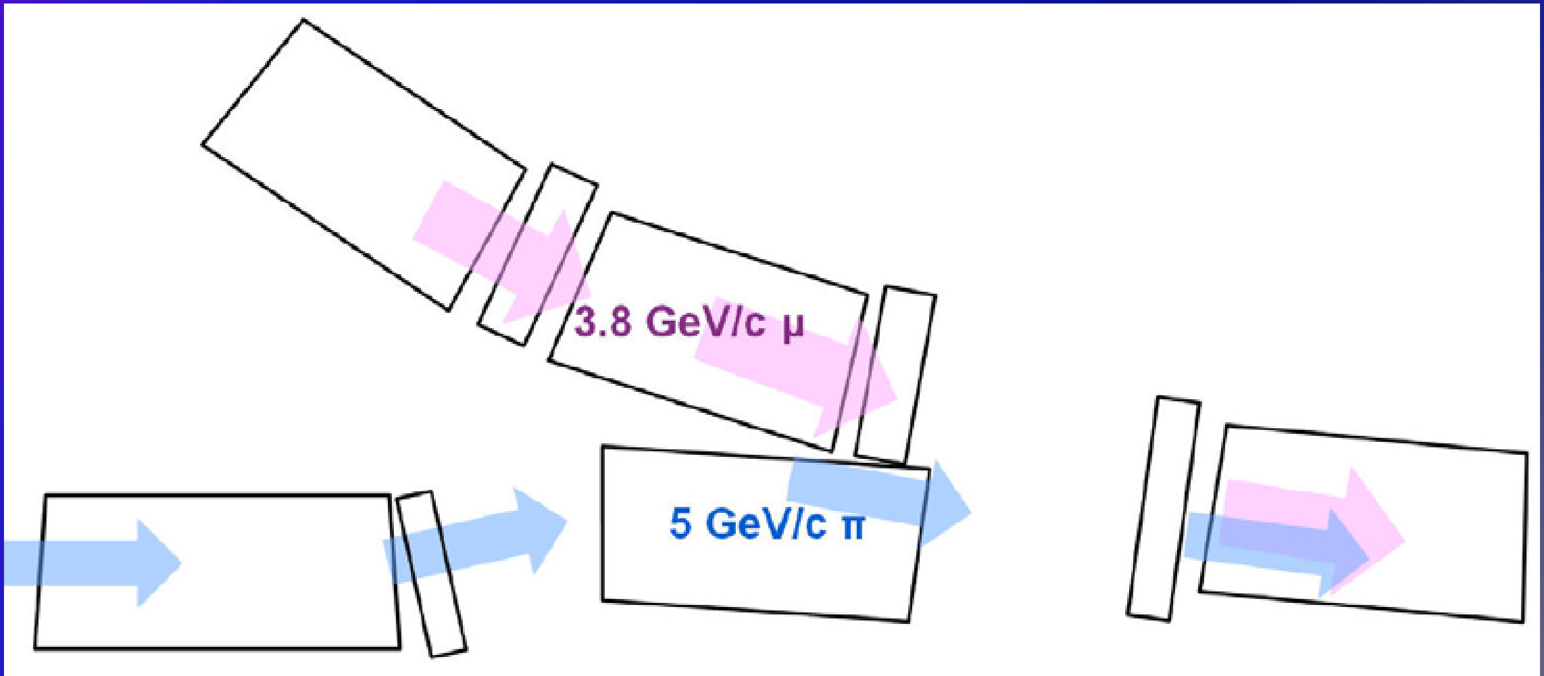
In momentum range
4.5 < 5.0 < 5.5
Obtain
» 0.11 p±/pot
with 60 GeV p

Target/capture optimization ongoing

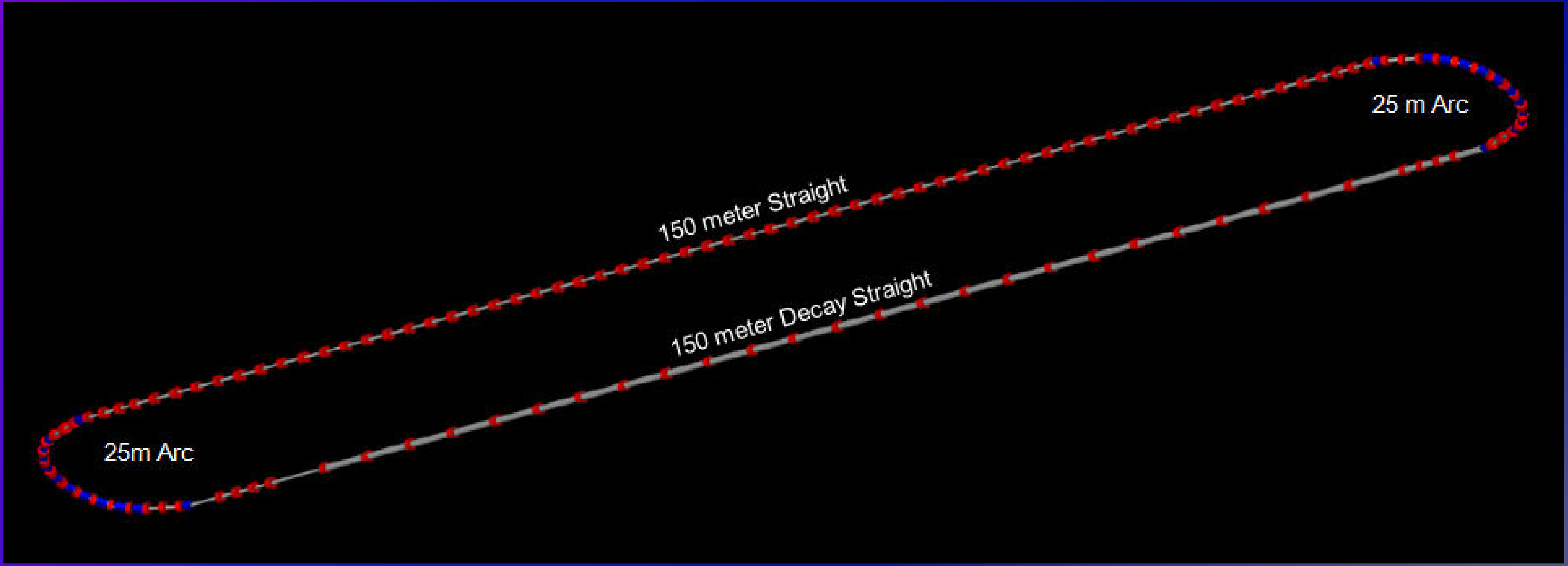
Injection Concept

- 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

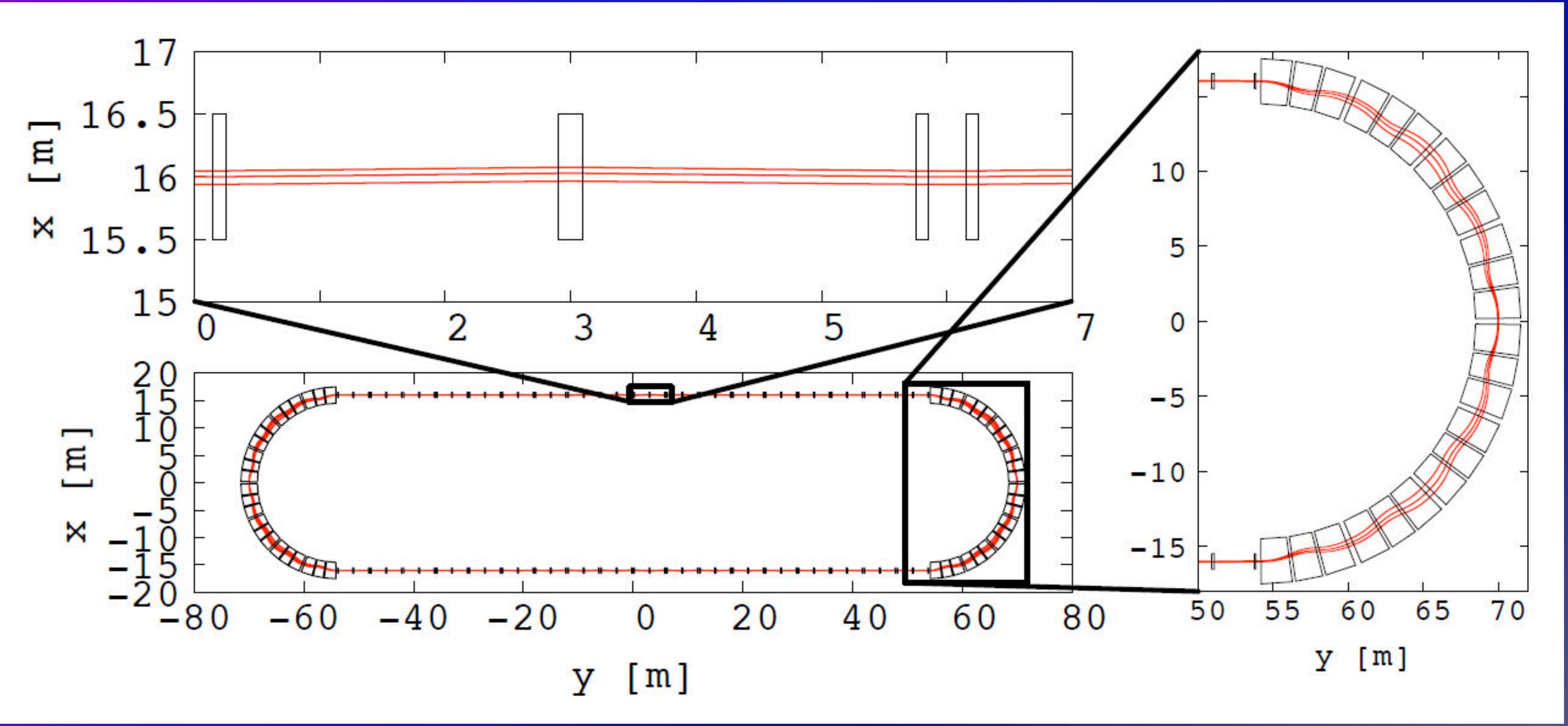


FODO Decay ring



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

FFAG Racetrack

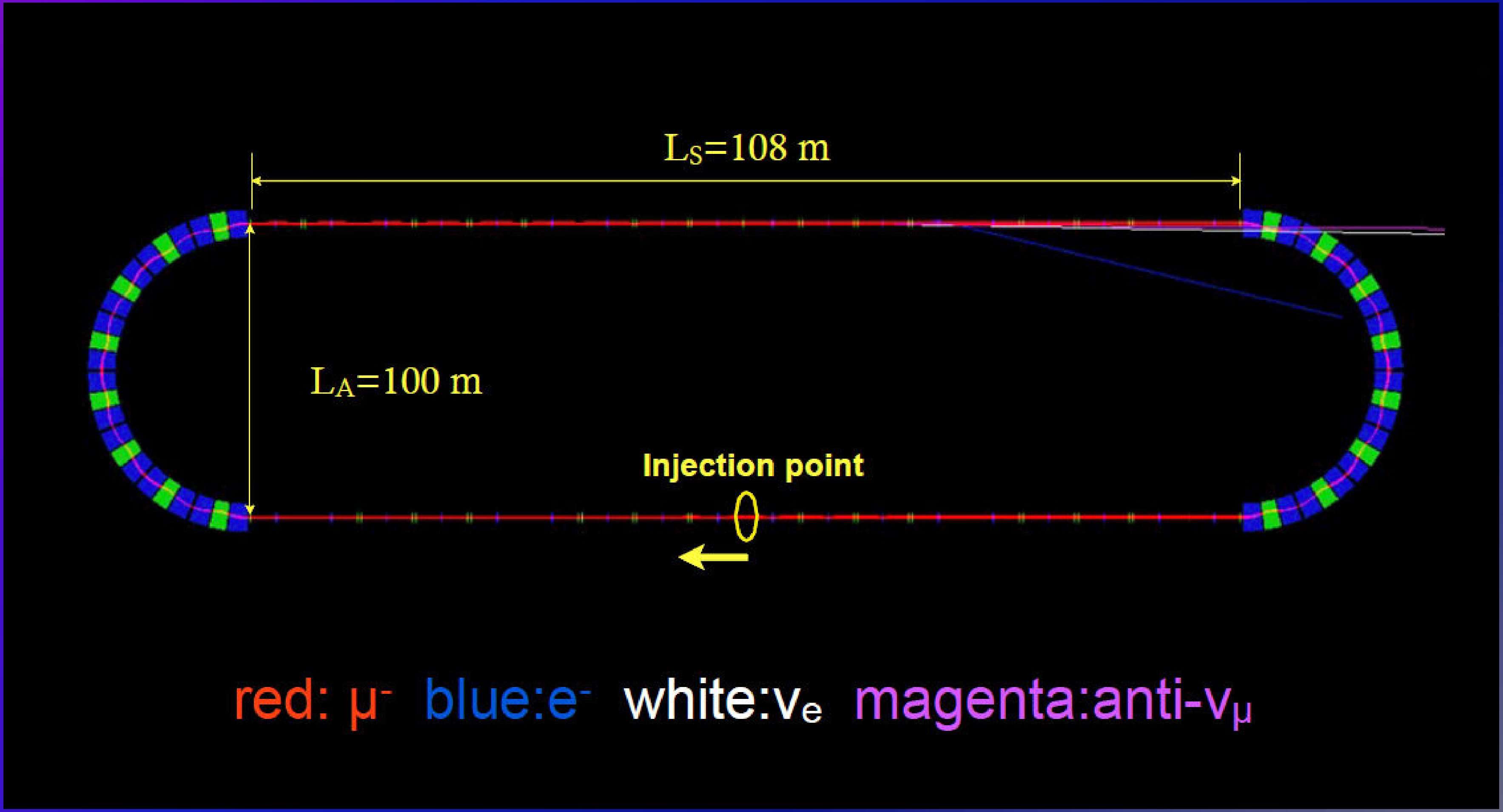


dp/p » 15%

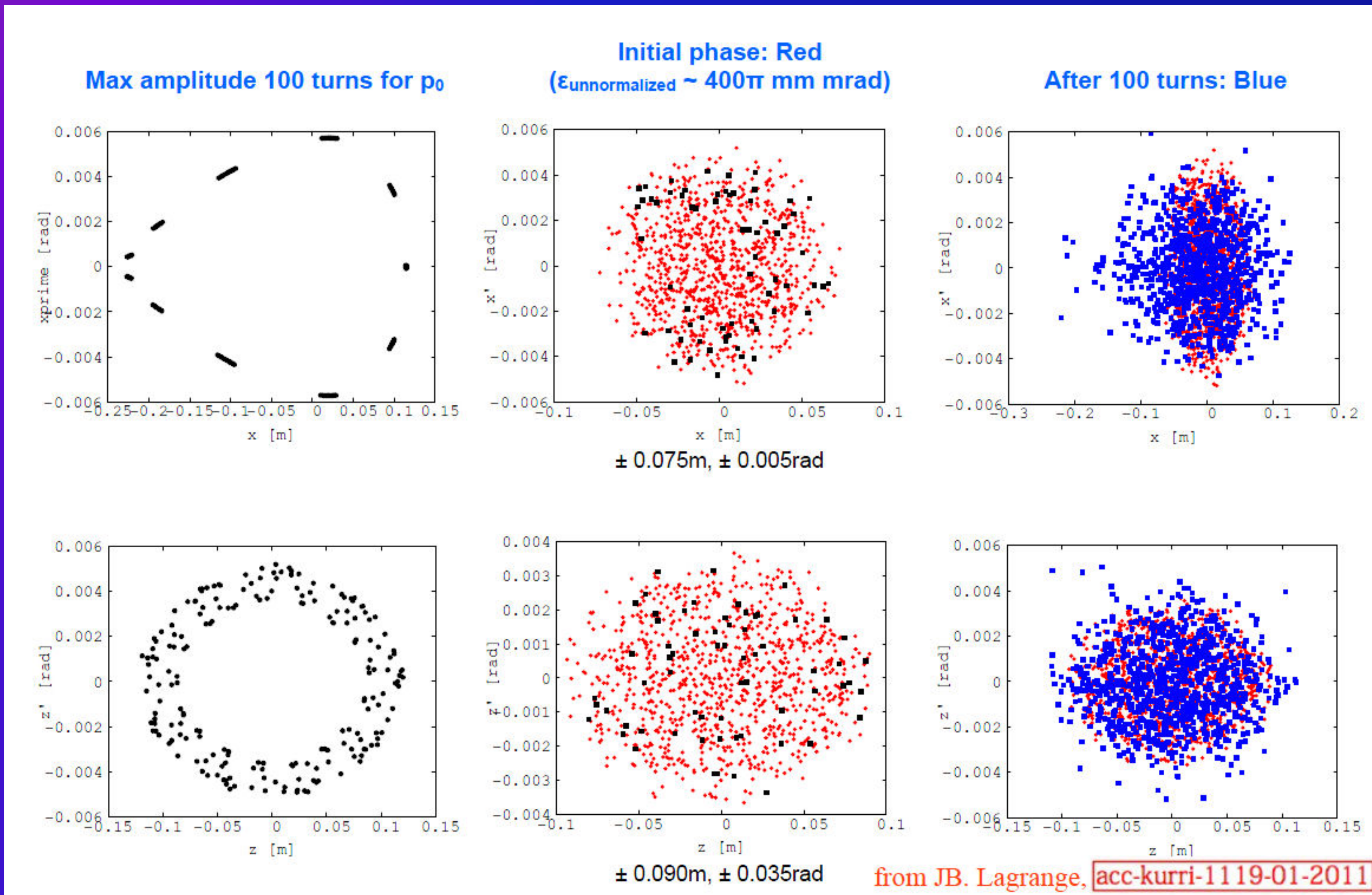
Low dispersion in straight

3.8 GeV/c

RFFAG Tracking Studies



FFAG Tracking



>90% dynamic aperture

FODO vs. RFFAG

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

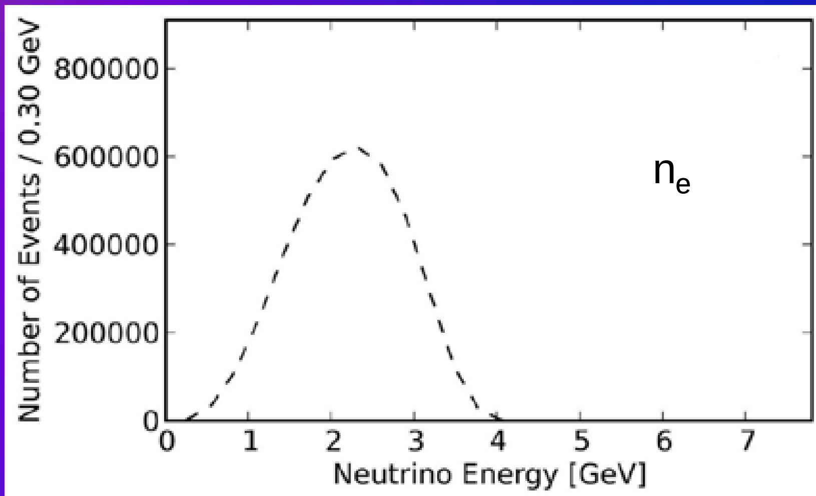
Parameter	FODO	RFFAG
$L_{straight}$ (m)	150	240
Circumference (m)	350	606
Dynamic aperture A_{dyn}	0.7	0.95
Momentum acceptance	$\pm$ 10%	$\pm$ 16%
π/POT within momentum acceptance	0.112	0.171
Fraction of π decaying in straight (F_s)	0.41	0.57
Ratio of $L_{straight}$ to ring circumference (Ω)	.43	.40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

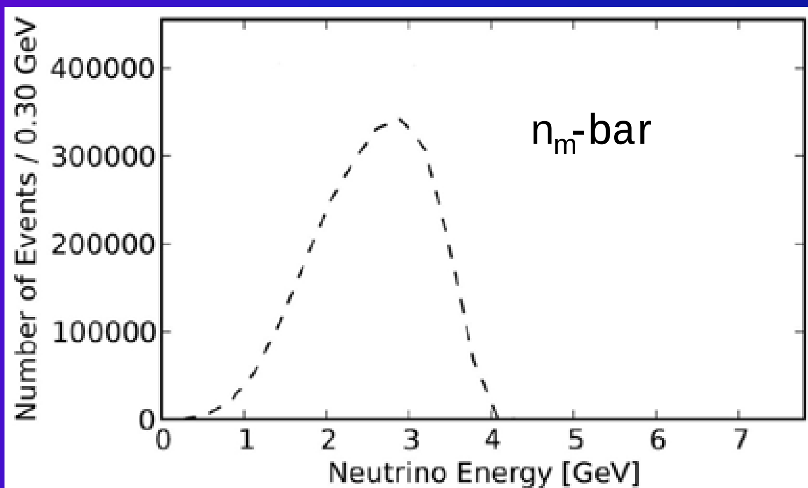
The Physics Reach

Assumptions

- N_m = (POT) X (p/POT) X $e_{collection}$ X e_{inj} X (m/p) X $A_{dynamic}$ X W
  - 10^{21} POT in 5 years of running @ 60 GeV in Fermilab PIP era
  - 0.1 p/POT (FODO)
  - $e_{collection}$ = 0.8
  - e_{inj} = 0.8
  - m/p = 0.08 (gct X mcapture in p ® mdecay) [p decay in straight]
    - Might do better with a p ® mdecay channel
  - $A_{dynamic}$ = 0.75 (FODO)
  - W= Straight/circumference ratio (0.43) (FODO)
- This yields » 1.7 X 10^{18} useful mdecays

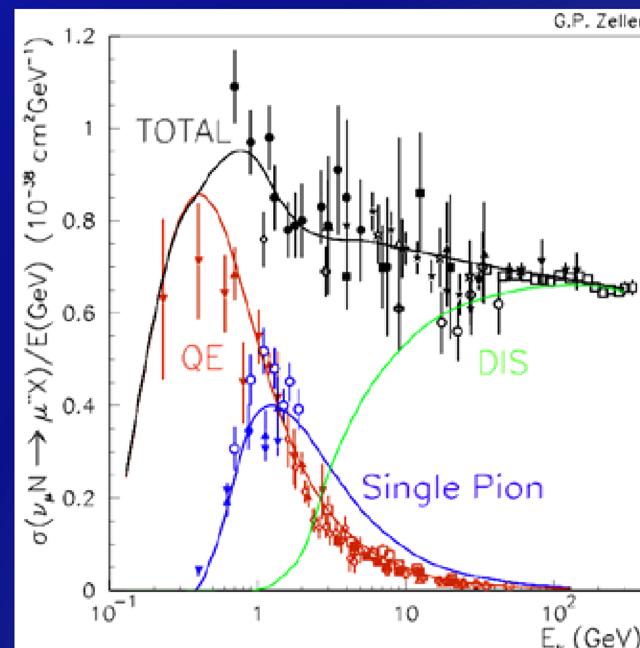
E_n spectra (m^+ stored)





Event rates/100T
at ND hall 50m
from straight with
m^+ stored

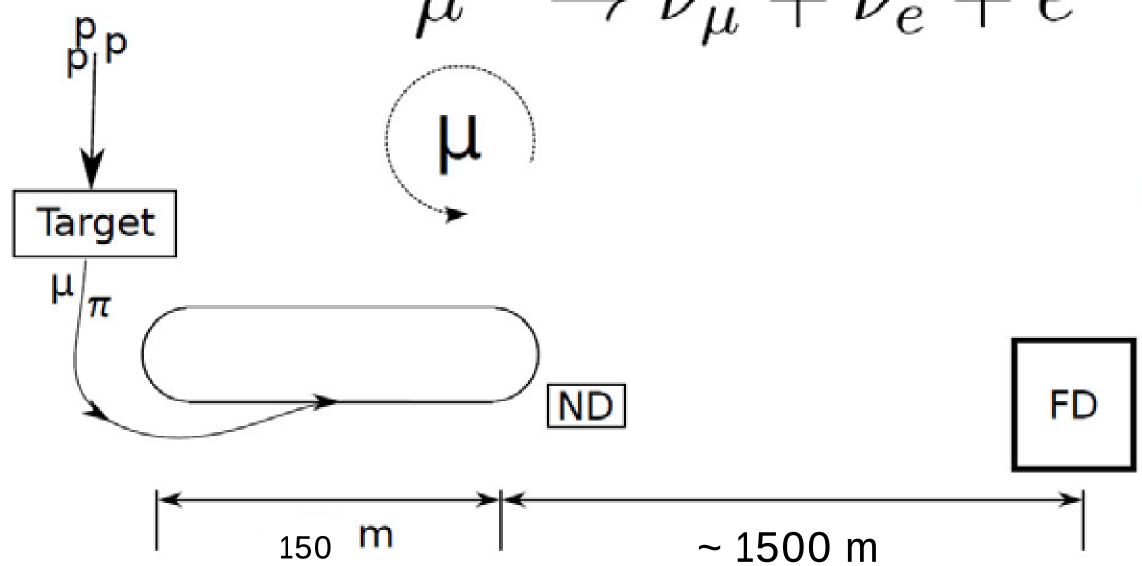
Channel	N_{evts}
$\bar{\nu}_\mu$ NC	844,793
ν_e NC	1,387,698
$\bar{\nu}_\mu$ CC	2,145,632
ν_e CC	3,960,421



νSTORM

Experimental Layout

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



Appearance-only (though disappearance good too!)

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

Appearance Channel:

n_e ® n_m

Golden Channel

Must reject the “wrong” sign mwith great efficiency

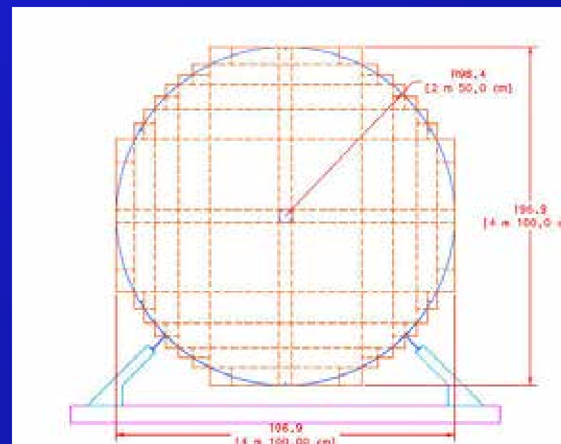
Why n_m® n_e Appearance Ch. not possible

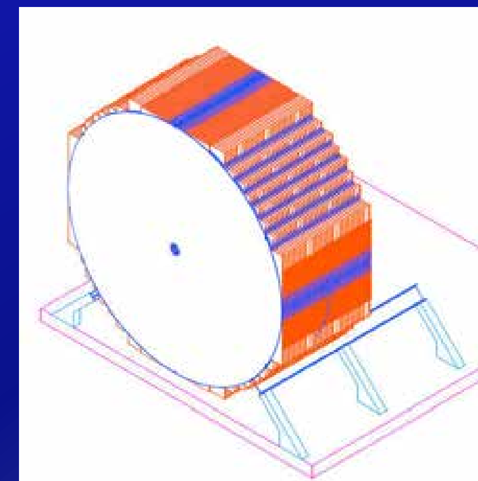
νSTORM

Baseline Detector

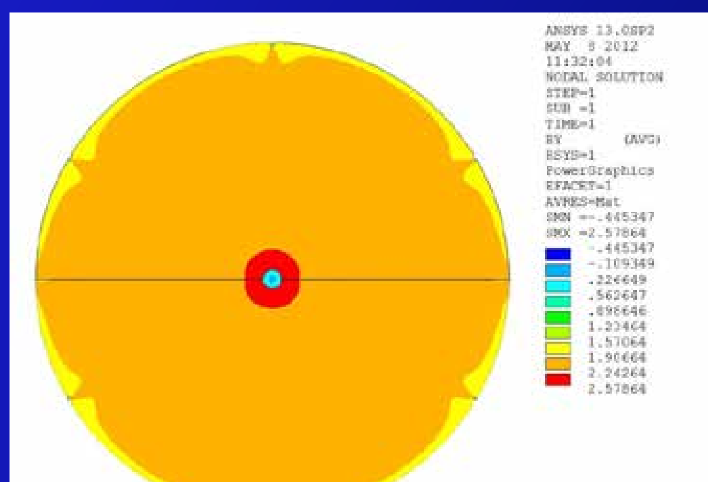
Super B Iron Neutrino Detector: SuperBIND

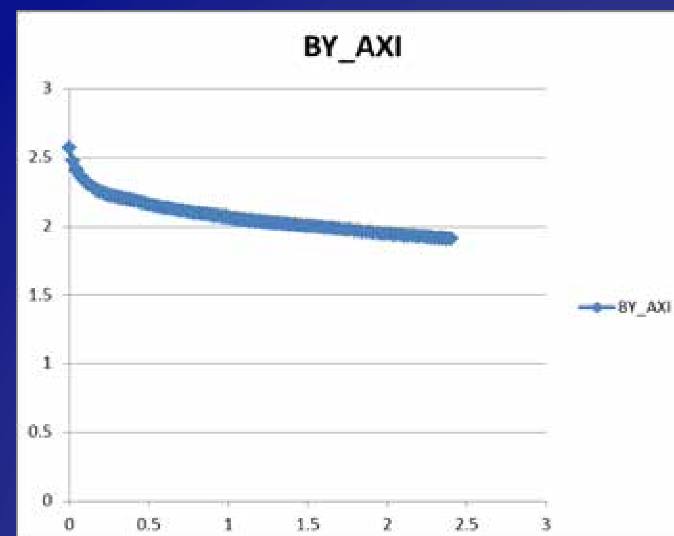
- Magnetized Iron
  - 1.3 kT
    - Following MINOS ND ME design
    - 1-2 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM



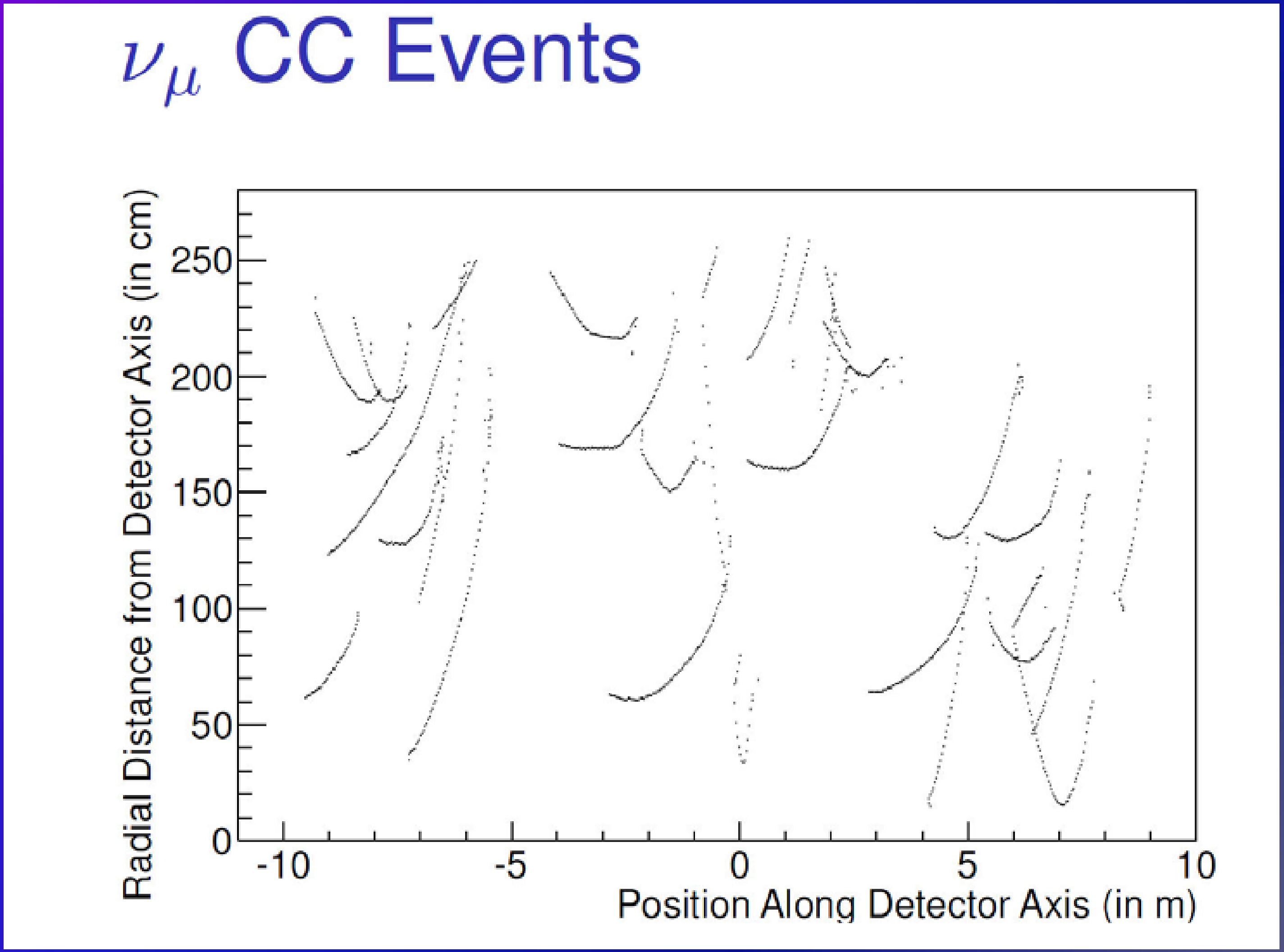


20 cm hole
For 3 turns
of STL





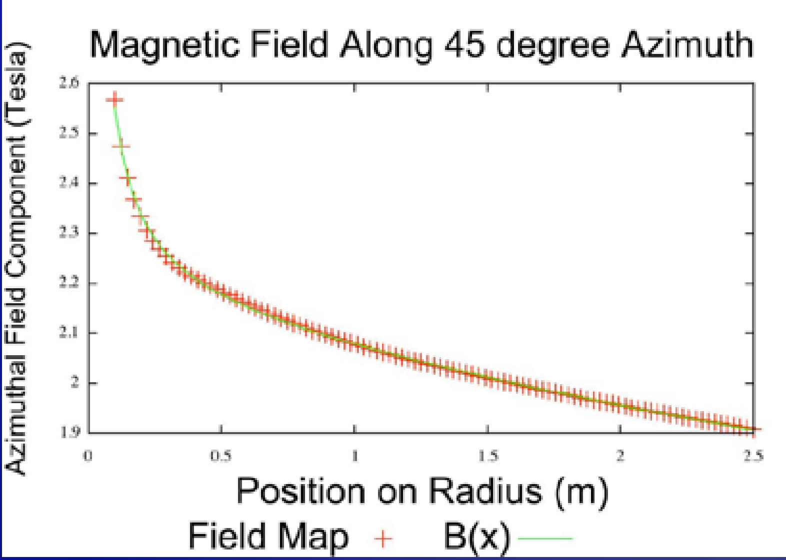
Event Candidates in SuperBIND



Hits
R vs. Z

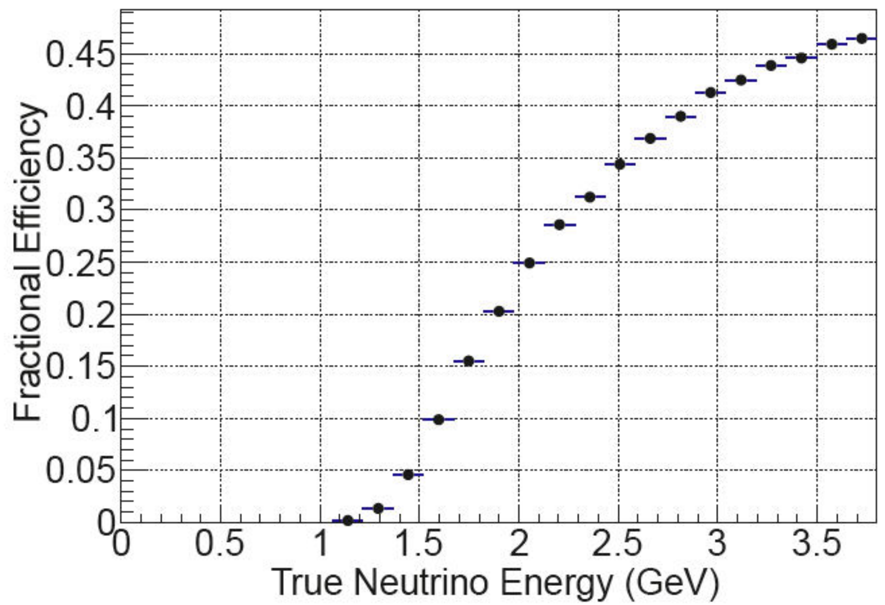
Simulation – n_m appearance

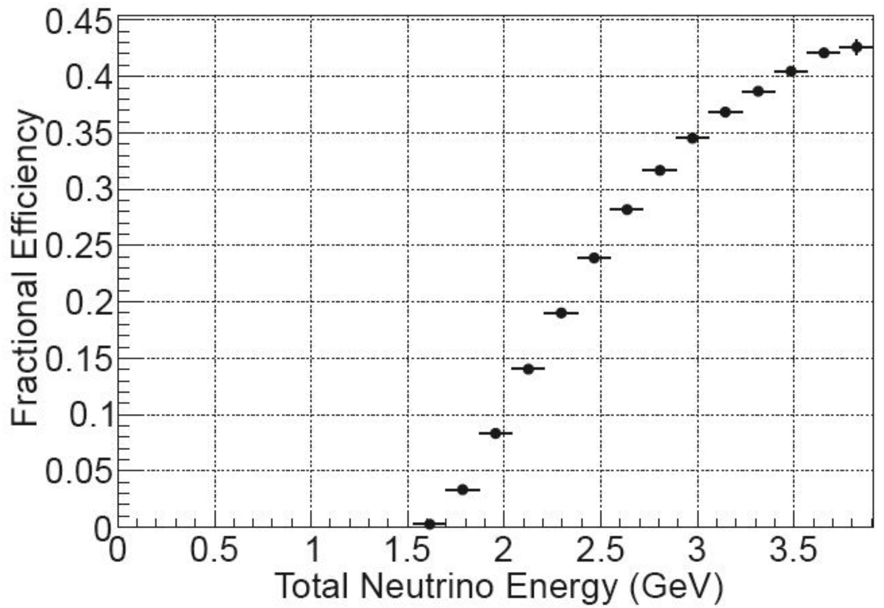
- Ø Full GEANT4 Simulation
  - Extrapolation from ISS and IDS-NF studies for the MIND detector
  - Uses GENIE to generate the neutrino interactions.
  - Involves a flexible geometry that allows the dimensions of the detector to be altered easily (for optimization purposes, for example).
  - Does not 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)	$\log(P(N_{hit}\|CC)/P(N_{hit}\|NC)) > 6.5$

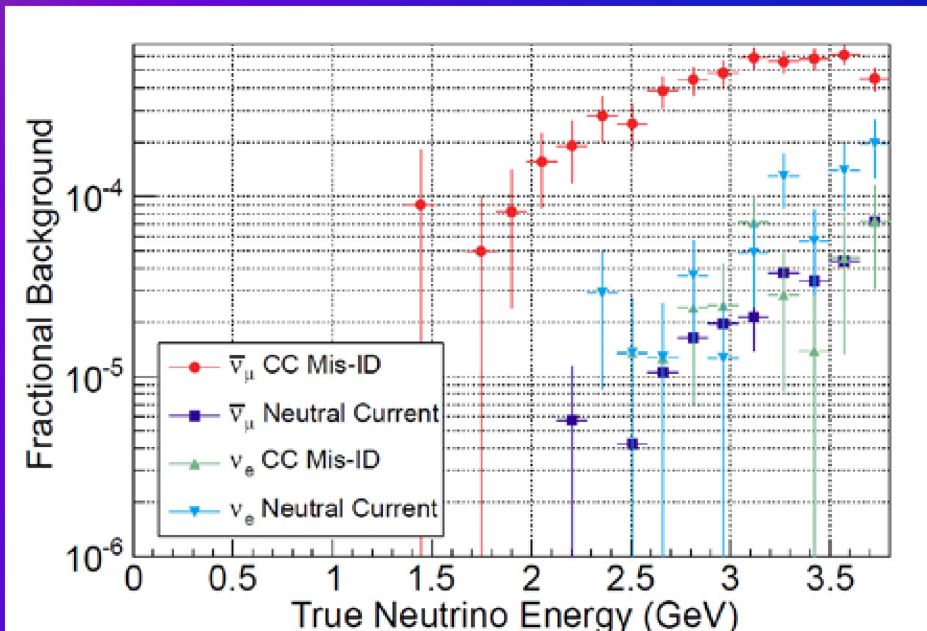
Event reconstruction efficiency

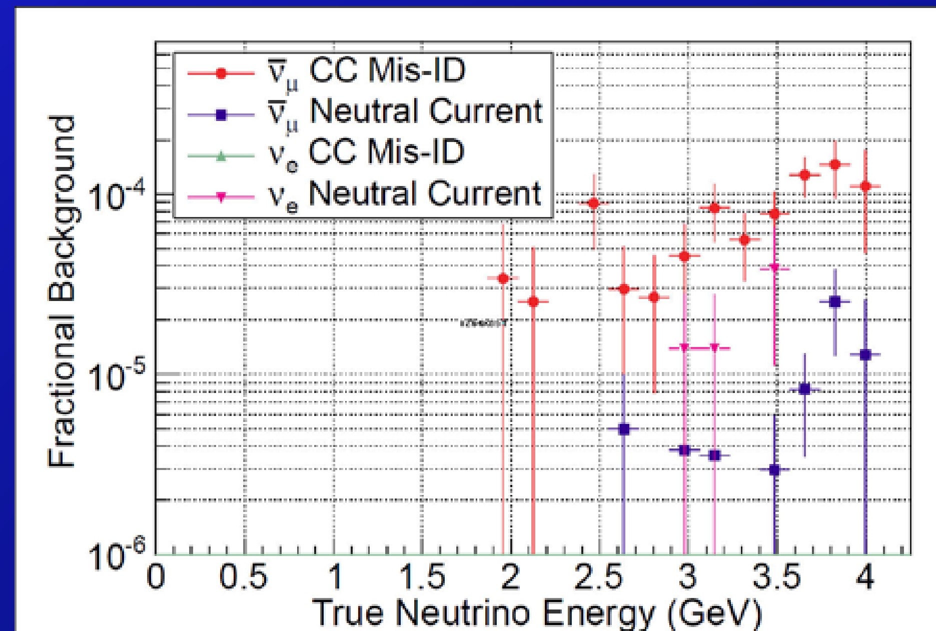




Left: 1 cm plates, Right: 2 cm plates

Backgrounds





Left: 1 cm plates

Right: 2 cm plates

νSTORM

Raw Event Rates

Neutrino mode with stored μ^+.

Channel	$N_{osc.}$	N_{null}	Diff.	$(N_{osc.} - N_{null})/\sqrt{N_{null}}$
$\nu_e \to \nu_\mu$ 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^-.

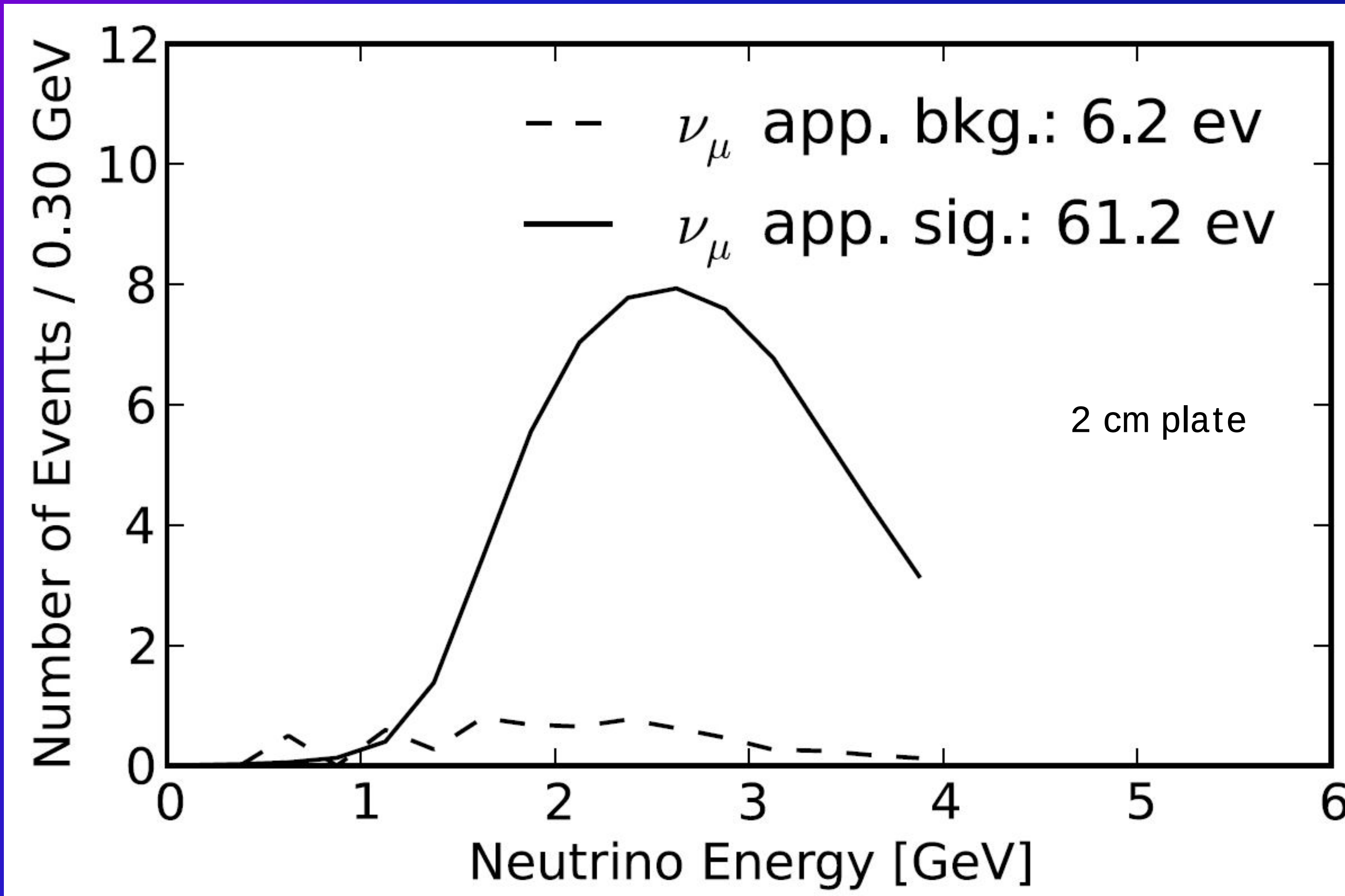
Channel	$N_{osc.}$	N_{null}	Diff.	$(N_{osc.} - N_{null})/\sqrt{N_{null}}$
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	117	0	∞	∞
$\bar{\nu}_e \to \bar{\nu}_e$ NC	30511	32481	-6.1%	-10.9
$\nu_\mu \to \nu_\mu$ NC	66037	69420	-4.9%	-12.8
$\bar{\nu}_e \to \bar{\nu}_e$ CC	77600	82589	-6.0%	-17.4
$\nu_\mu \to \nu_\mu$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

3+1
Assumption

Appearance channels

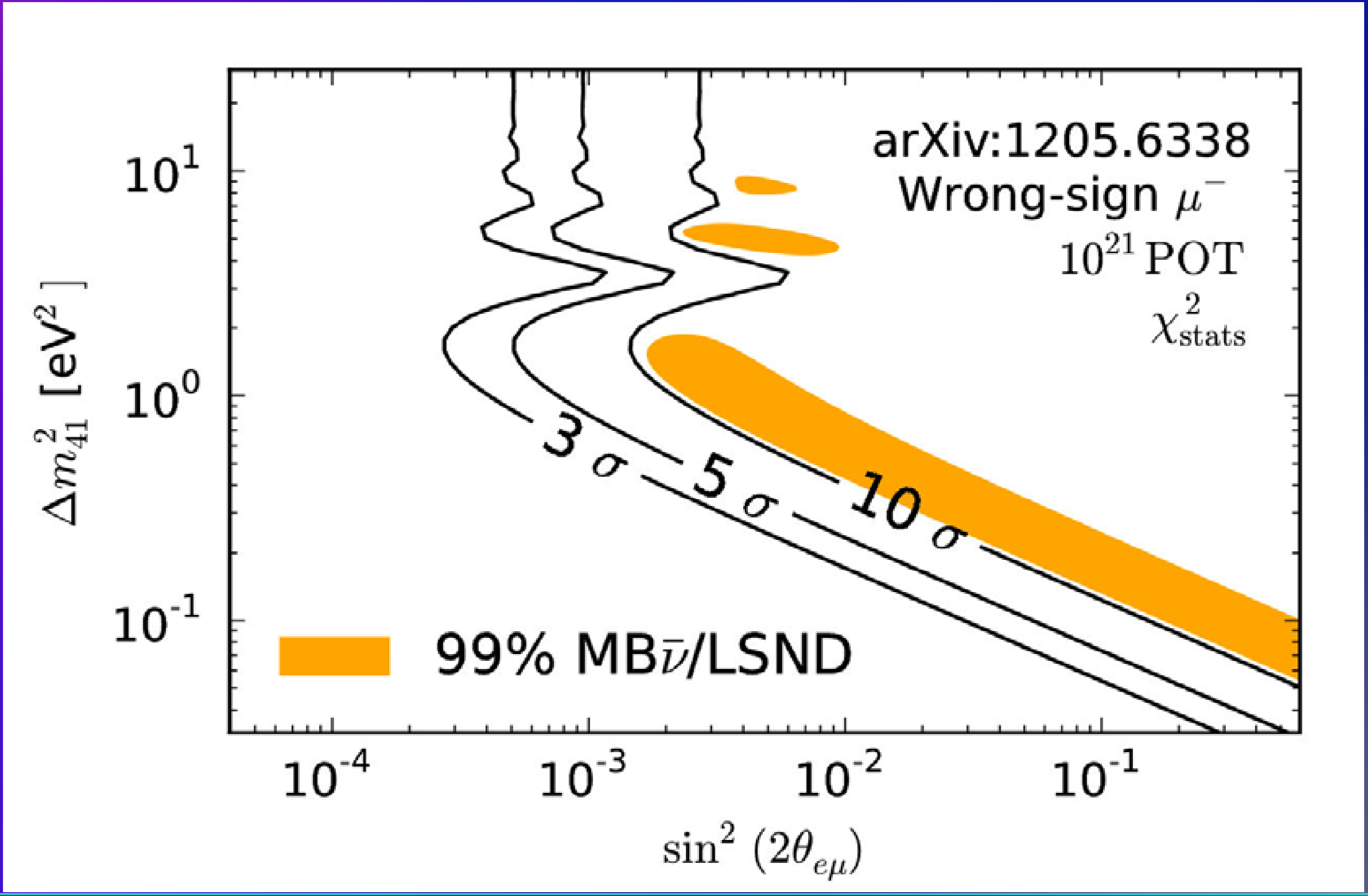
n_e ® n_m appearance

CPT invariant channel to MiniBooNE



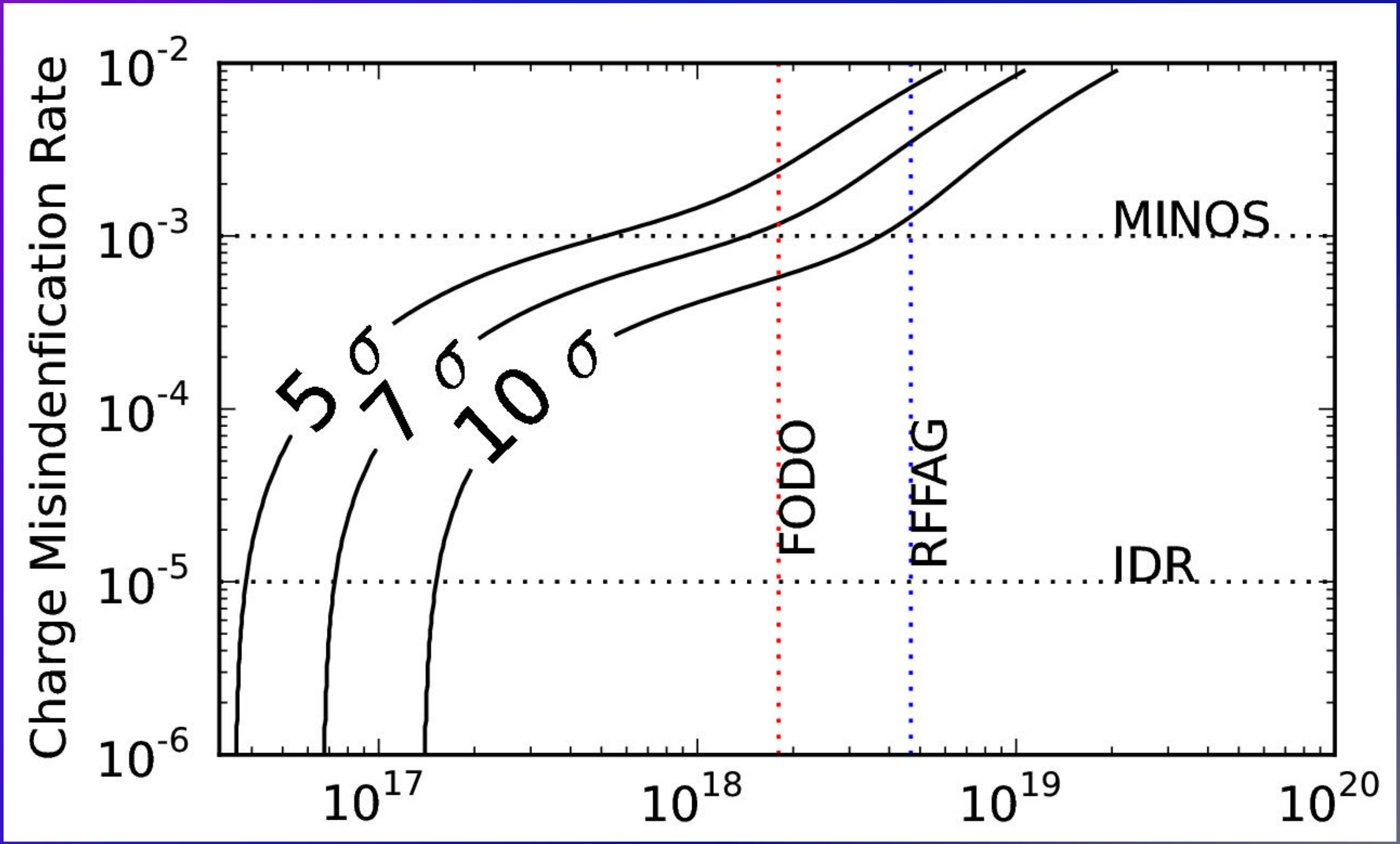
n_e ® n_m appearance

CPT invariant channel to MiniBooNE



3+1 Assumption

Required mcharge mis-ID rate needed for given sensitivity



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

vSTORM

Disappearance channels

But:

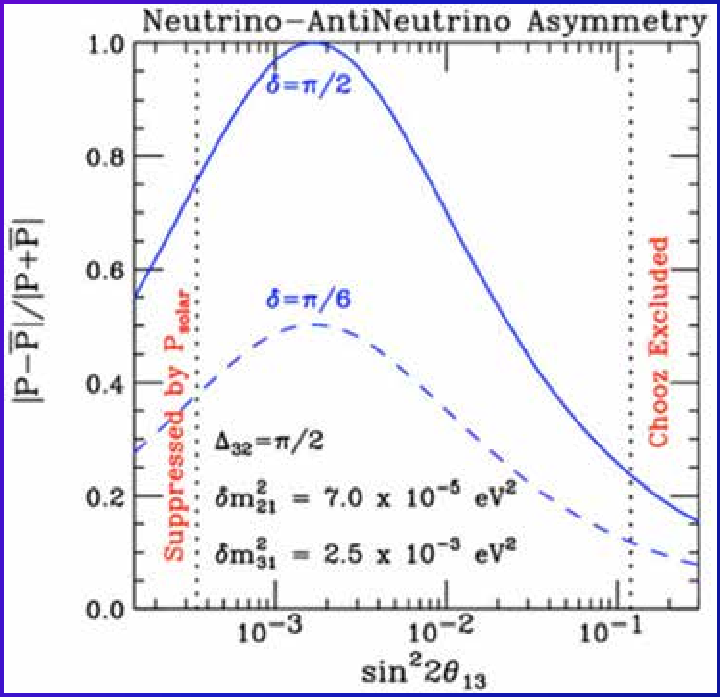
- Ø Need self-consistent two-detector simulation including (bin-to-bin) uncorrelated shape error ~ 10%
- Ø A challenge: there may be oscillations already in near detectors
  - Ø Geometry important for $Dm^2 \sim 10^1 – 10^3$ eV^2
- Ø Suitability (& optimization) of SuperBIND for n_e channels still needs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

Cross-Section Measurements

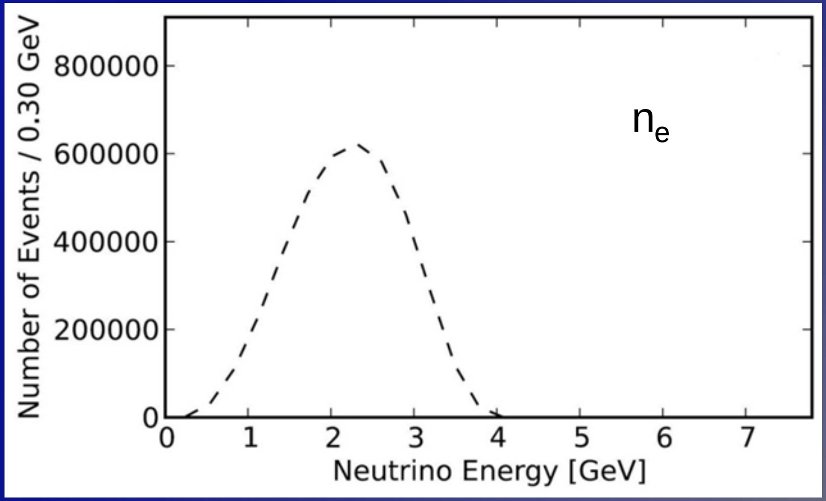
n Cross-section measurements

Ø Cross-section measurements

- Ø mstorage ring presents only way to measure n_m & n_e & (n and $\bar{n}$) x-sections in same experiment
  - Ø Supports future long-baseline experiments
    - Ø E_n matched well to needs of these experiments



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



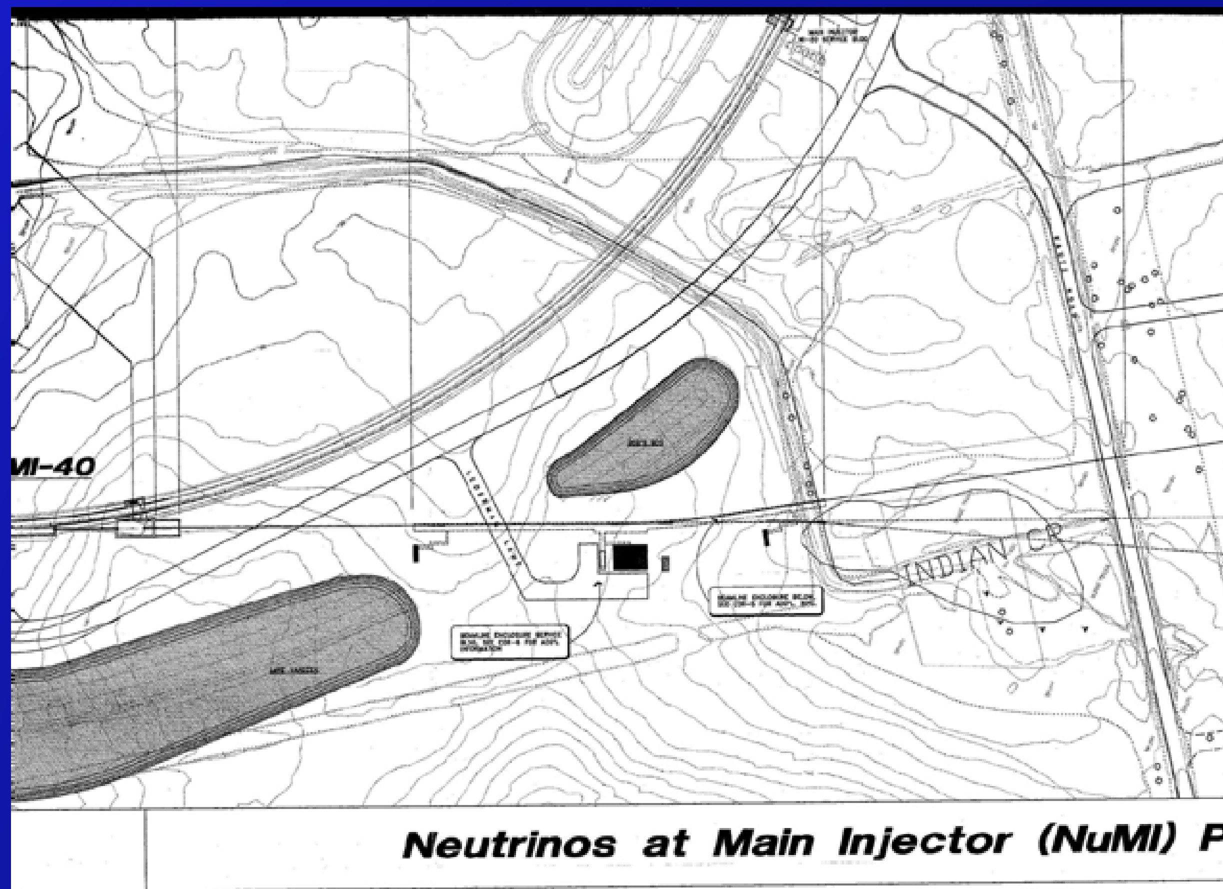
Project Considerations

Impact Statements

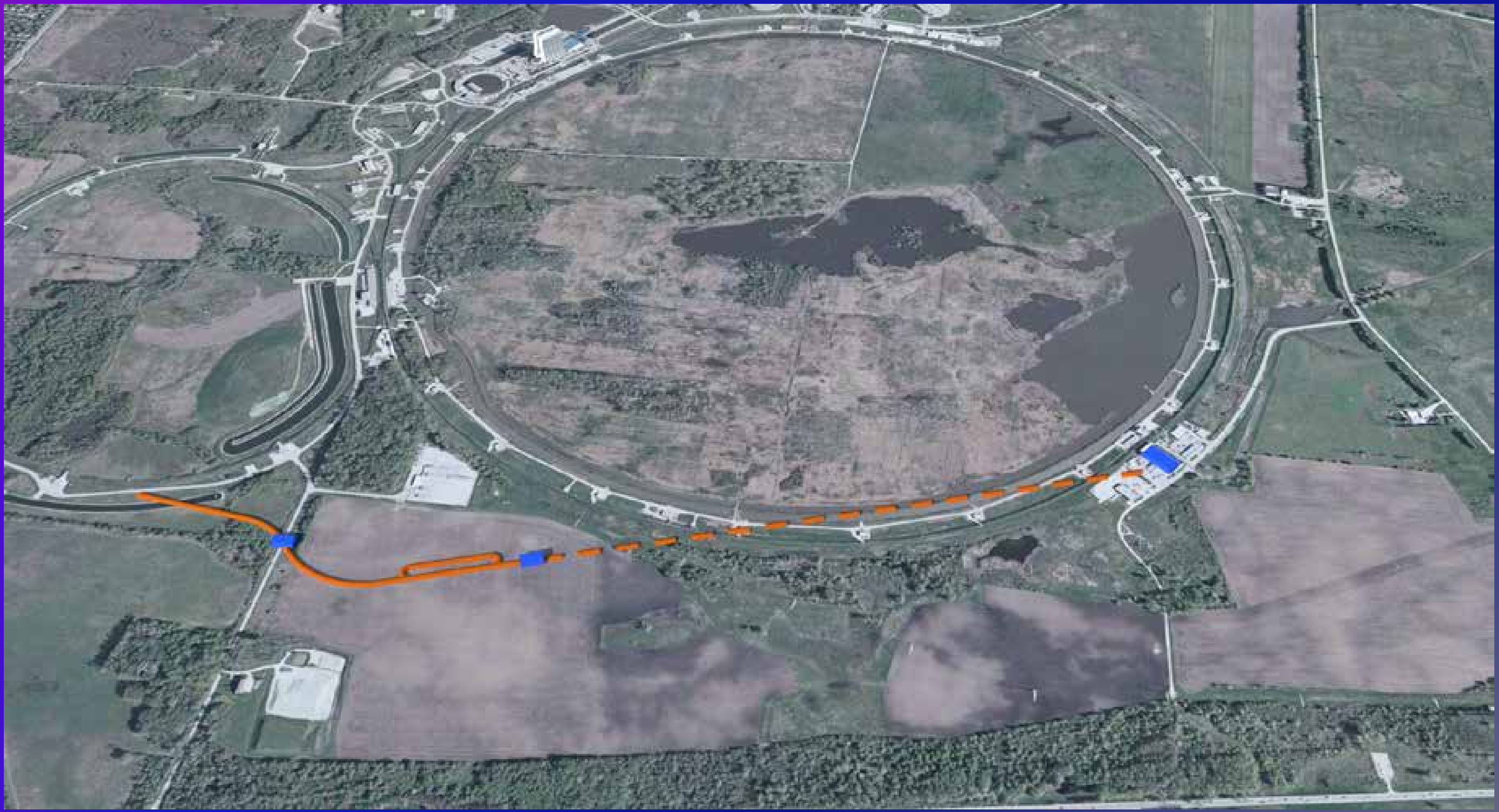
- PPD
  - It is understood that LBNE may not proceed with near detector hall in Phase I. However, we believe that regardless of the final decision regarding the ND in LBNE Phase I, studies/simulation will occur and they will be synergistic with the needs of nSTORM
- AD
  - We agree that AP0 is not appropriate and this option is dropped. I will address the siting plan next.

Siting

- The favored concept is to follow the plan that was developed for the NuMI Project (no not that one) – SBL MI-40, short BL n_t (1994).
- Utilize MI abort line



Siting Concept

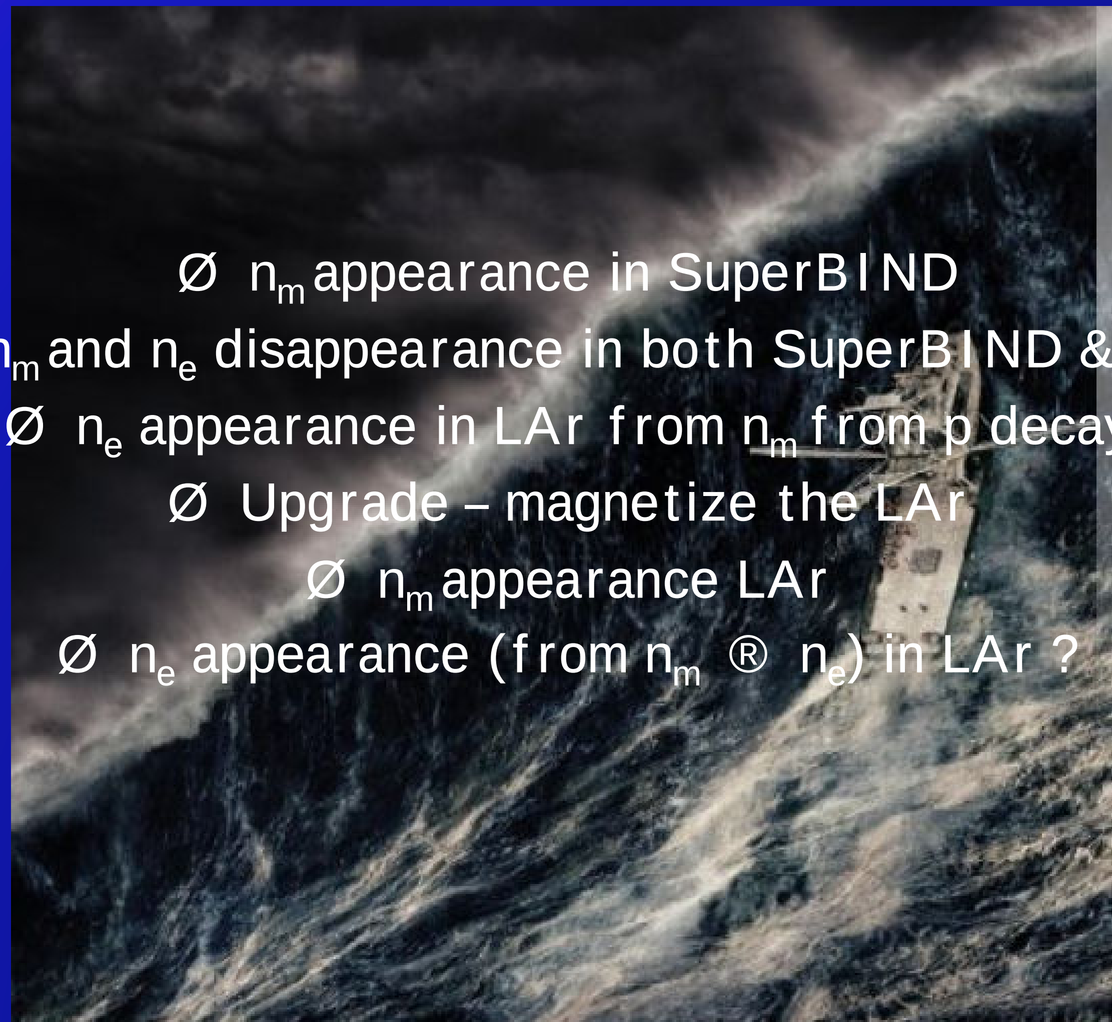


A Perfect nSTORM?

- Ø LAr1 in D0 pit
- Ø SuperBIND fits in the D0 high bay
- Ø n_m beam (fr. p decay, Turn 1)
- Ø mdecay n beam

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

- Ø With 40k evts/ton add small LAr detector at near hall in addition to the 1-200T of SuperBIND



- Ø n_m appearance in SuperBIND
- Ø n_m and n_e disappearance in both SuperBIND & LAr
- Ø n_e appearance in LAr from n_m from p decay
- Ø Upgrade – magnetize the LAr
- Ø n_m appearance LAr
- Ø n_e appearance (from n_m ® n_e) in LAr ?

Preliminary Cost Estimate

- Major Components
  - Beamline, Target Station & Horn
  - Transport line
  - Decay ring
  - Detectors (Far & Near)
  - Project Office
  - Total

Component	Cost
Beamline, Target Station & Horn	$30M
Transport line	9
Decay ring	54
Detectors (Far & Near)	18
Project Office	15
Total	$126M

- Basis of Estimation (BOE)
  - Took existing facilities (MiniBooNE beam line and target station, MINOS detector, vetted magnet costing models, m2e civil construction costs, EuroNu detector costing, have added all cost loading factors and have escalated to 2012 $ when necessary.

Moving Forward

Moving forward:

Ø Facility

- Targeting, capture/transport & Injection
  - Need to complete 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 n flux
  - And verify the precision to which it can be determined.

Moving forward:

- Detector simulation
  - For oscillation studies, continue MC study of backgrounds & systematics
    - Start study of 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.
    - Multivariate analysis.
  - For cross-section measurements need detector baseline design
    - Learn much from detector work for LBNE & IDS-NF
      - Increased emphasis on n_e interactions, however

Produce Full Proposal

Estimate effort to produce full proposal

Table X. Estimated effort to produce full proposal

Task	ΣFTE
Target Station	0.75
Capture & transport	1.25
Injection	0.25
Decay ring	2
Far Detector (Engineering)	1
Far Detector (Sim & Analysis)	2
Near Detector (Engineering)	1
Near Detector (Sim & Analysis)[a]	3.5
Costing	1
Total	**12.75**

nSTORM: Conclusions

The Physics case:

- Initial simulation work indicates that a L/E » 1 oscillation experiment using a muon storage ring can confirm/exclude at 10s (CPT invariant channel) the LSND/MiniBooNE result
- n_m and (n_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
    - Detector implications?
- 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 msource for 6D cooling experiment with intense pulsed beam

nSTORM : Conclusions I I

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 (m2e)
  - Magnetization is based on technology that was fully vetted over 10 years ago
    - But has been in a dormant state

nSTORM :

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

nSTORM : Sterile n

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

- Ø Make a direct test of the LSND and MiniBooNE anomalies.
- Ø Provide stringent constraints for both n_e and n_m disappearance to over constrain 3+N oscillation models and to test the Gallium and reactor anomalies directly.
- Ø 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.

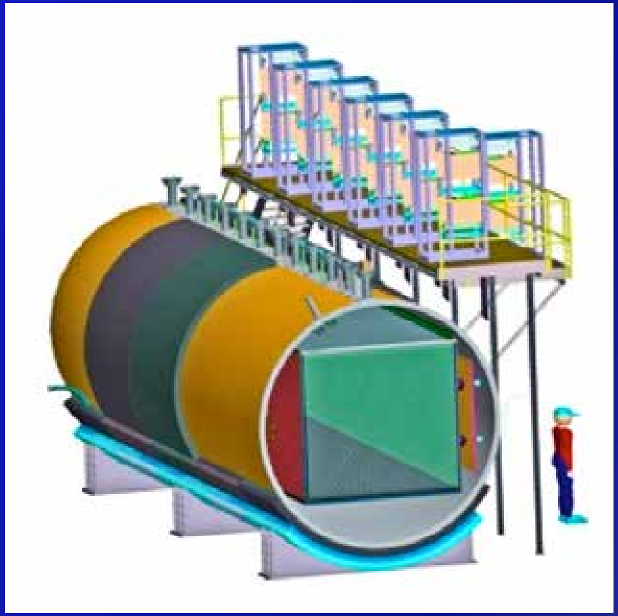
END

Thank You

Back Ups

Detector Considerations

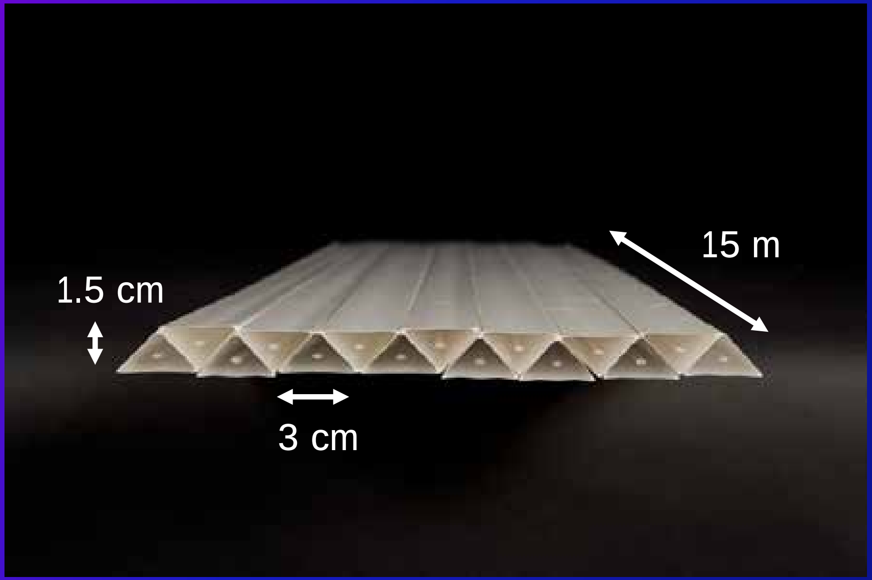
- Other options
  - Totally Active Scintillator - TASD
  - LAr
  - Present opportunity to measure n_e appearance?
- Must be Magnetized, however
  - A hybrid approach (external mspectrometer) is a possibility

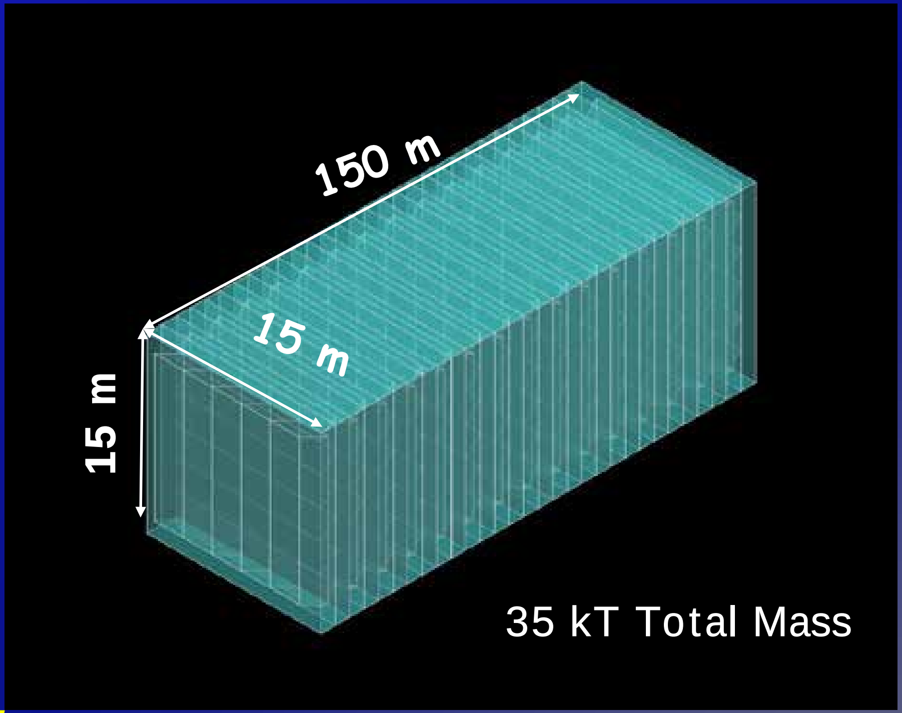


Fine-Resolution Totally Active Segmented Detector (IDS-NF)

Simulation of a Totally Active Scintillating Detector (TASD) using Nona and Minerna concepts with Geant4

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



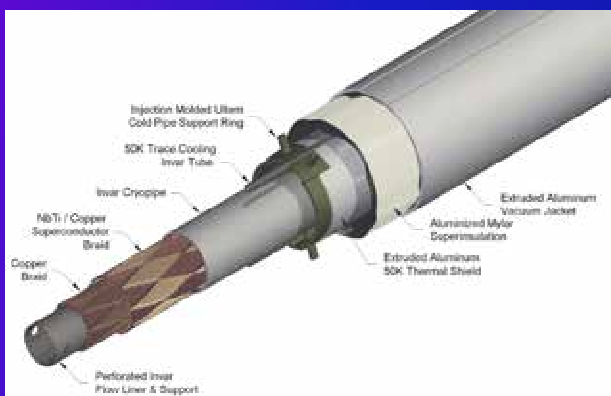


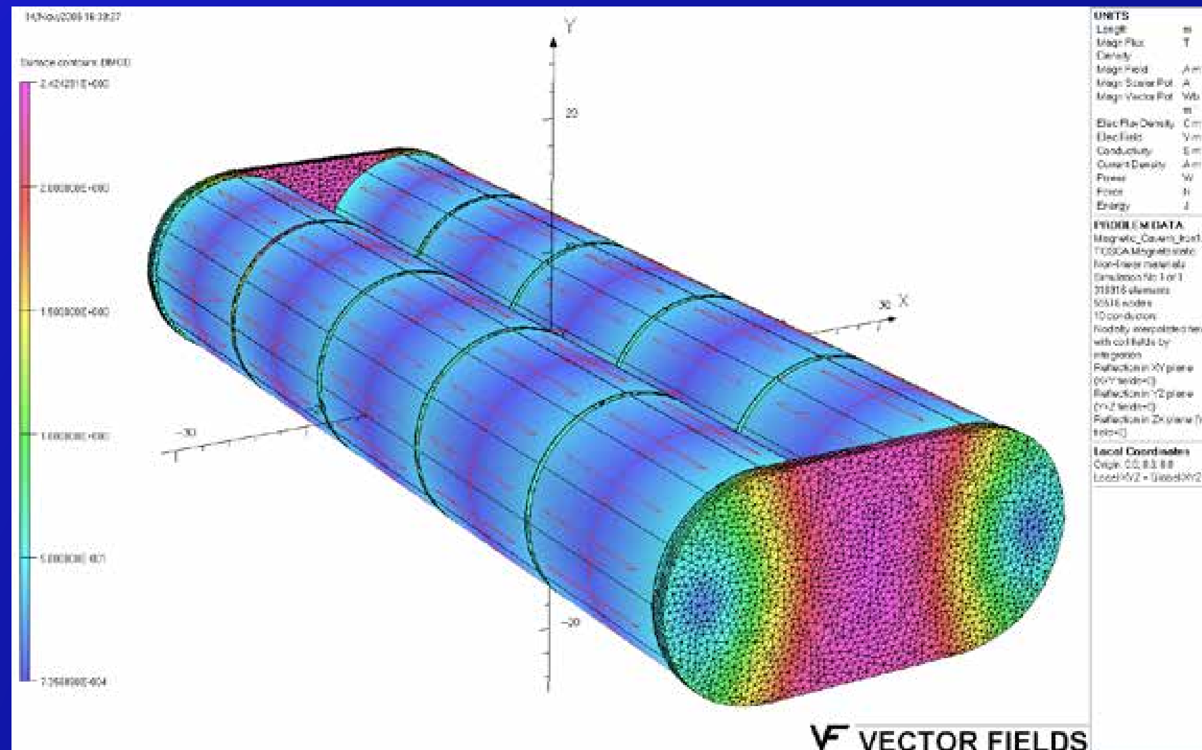
- **Momenta between 100 MeV/c to 15 GeV/c**
- **Magnetic field considered: 0.5 T**
- **Reconstructed position resolution ~ 4.5 mm**

B = 0.5T

Magnet- Concept for IDS-NF

- VLHC SC Transmission Line
  - Technically proven
  - Affordable



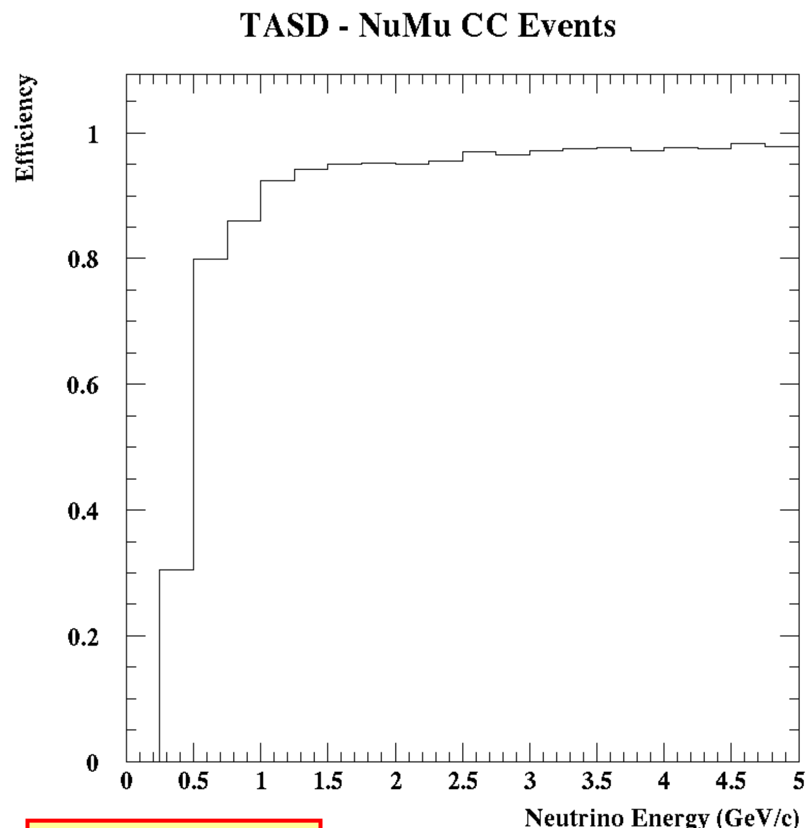


R&D to support concept
Has not been funded

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

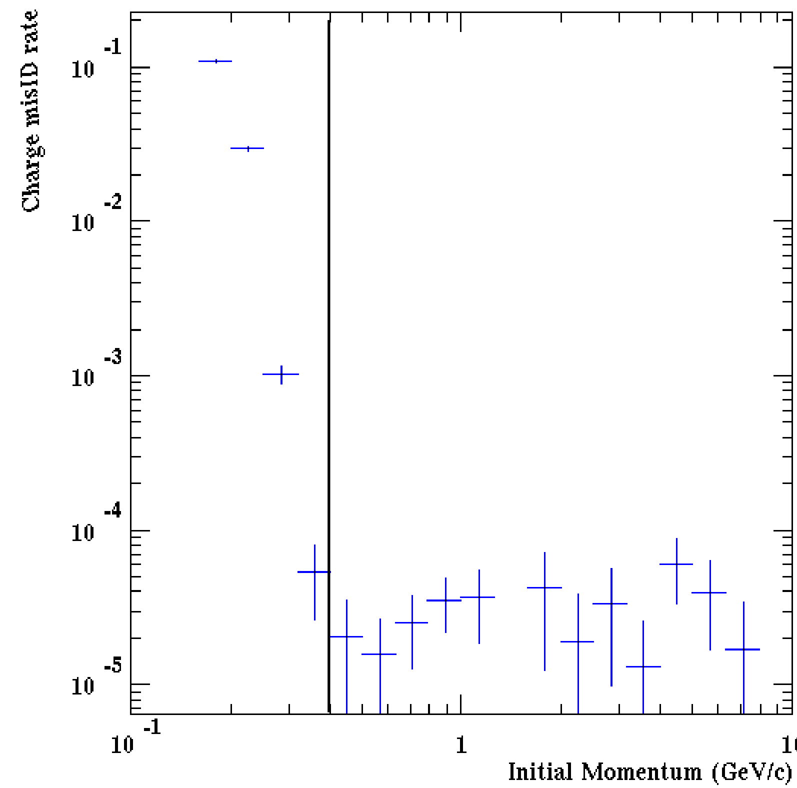
TASD Performance

n Event Reconstruction e



Excellent s_E

Muon charge mis-ID rate



νSTORM

Detector Options

Technology check List

	Fid Volume	B	Recon	Costing Model
SuperBIND	☑ (blue)	☑ (blue)	☑ (blue)	☑ (blue)
Mag-TASD	☑ (blue)	☑ (red)	☑ (blue)	☑ (black)
Mag-LAr	☑ (black)	☑ (red)	☑ (black)	☑ (red)

☑ (blue)	Yes - OK
☑ (black)	Maybe
☑ (red)	Not Yet

Costing Details

Beamline & Target Station

- Based on MiniBooNE
  - Horn & PS, misc electrical equipment — $6.0M
  - Instrumentation — .5
  - Civil (~ 2XMiniBooNE) — 6.3
  - Beam line — 1.5
  - Total — $14.3
- Escalating factors
  - 1.5 – to include fully loaded SWF
  - 1.35 – in 2012 $
- Total: $30M

Decay Ring

- Magnets (Used Strauss & Green Costing Model) – V. Kashikhin

nuStorm Superconducting Magnets cost estimation June 14, 2012											
		Pole field	Length	Aperture	Quantit y	Gradient	Magnet Cost*	Total cost		3.142	Cryo
Name	Type	Bp, T	Lm, m	Da, m	Qty	G, T/m	C, M$	Total C, M$			Cr,M$
D1	Dipole	3.9	0.85	0.3	24	0	0.4787	11.488			1.56
Q1	Quadrupole	3.8	0.5	0.3	30	6.33	0.2070	6.210			1.95
Q2	Quadrupole	1.6	0.6	0.3	33	2.67	0.1295	4.273			2.145
Q3	Quadrupole	0.4	0.6	0.3	63	0.67	0.0526	3.313			4.095
					150			25.3	M$		9.8
* - magnet cost calculated using the magnetic field energy volume where Lm is the magnet length											

Decay Ring – Estimate II

- From Alex Bogacz (ring designer)

19 June 2012 – KBB														
May 15 13:20 Ring_new.opt														
qty		name		Lcm	aperture	Bkgcm[i]	Bkgcm[i]		width[cm]	height[cm]	radius[cm]	storedenergy[MJ]	cost/ea	cost/type
24		dAin		85	15	38.9138	0		15	15		0.1184	$30,804	$739,303
4		qD1		50	15	0	-2.68838				15	0.1143	$290,562	$1,162,249
4		qD2		50	15	0	-2.56058				15	0.1037	$263,594	$1,054,374
4		qD3		50	15	0	-2.43127				15	0.0935	$237,643	$950,571
2		qD4		50	15	0	-2.45204				15	0.0951	$241,720	$483,441
12		qDD		60	30	0	-0.108				30	0.0035	$9,003	$108,041
2		qDDa		30	30	0	-0.108				30	0.0018	$4,502	$9,003
28		qDS		60	15	0	-1.086				15	0.0224	$56,898	$1,593,151
4		qF1		50	15	0	2.38574				15	0.0900	$228,825	$915,302
4		qF2		50	15	0	2.48112				15	0.0974	$247,488	$989,951
4		qF3		50	15	0	2.57227				15	0.1047	$266,006	$1,064,023
4		qF4		50	15	0	2.53313				15	0.1015	$257,972	$1,031,889
12		qFD		60	30	0	0.108				30	0.0035	$9,003	$108,041
36		qFS		60	15	0	1.086				15	0.0224	$56,898	$2,048,337
2		qFSa		30	15	0	1.086				15	0.0112	$28,449	$56,898
2		qMD1		50	15	0	-0.804088				15	0.0102	$25,994	$51,987
2		qMD2		50	15	0	1.10154				15	0.0192	$48,782	$97,564
2		qMD3		50	15	0	-0.76149				15	0.0092	$23,312	$46,625
2		qMD4		50	15	0	0.354415				15	0.0020	$5,050	$10,100
2		qMS1		50	15	0	-2.05816				15	0.0670	$170,301	$340,601
2		qMS2		50	15	0	1.87905				15	0.0559	$141,950	$283,900
2		qMS3		50	15	0	-1.61757				15	0.0414	$105,192	$210,385
2		qMS4		50	15	0	1.41665				15	0.0317	$80,683	$161,366
														$13,517,101.53

Decay Ring

- Used bigger number for magnets

- PS & Instrumentation - $1M
- Vacuum - $2M
- Civil - $15.7M
  - Based on m2e tunnel costs (&depth) ($9.5k/foot) times 1.5 to fully load, EDIA…

- Total: 53.8M
- Note: Transport line costed at 17% (by length) of DR - $9M

Detectors

- Assumed total of 1.5 kT mass
- Option 1
  - Took MINOS as built and added overhead to SWF (includes all R&D) and escalated to 2012 $ (1.35) - $10M/kT and then added $3M for STL R&D – Total $18M
- Option 2
  - Took EuroNu cost model for NF detector – magnetized iron neutrino detector (MIND), added OH to SWF - $8M/kT
    - Technology changes from MINOS:
      - SiPMs
      - ASIC electronics
      - STL magnetization
- Used Bigger Number