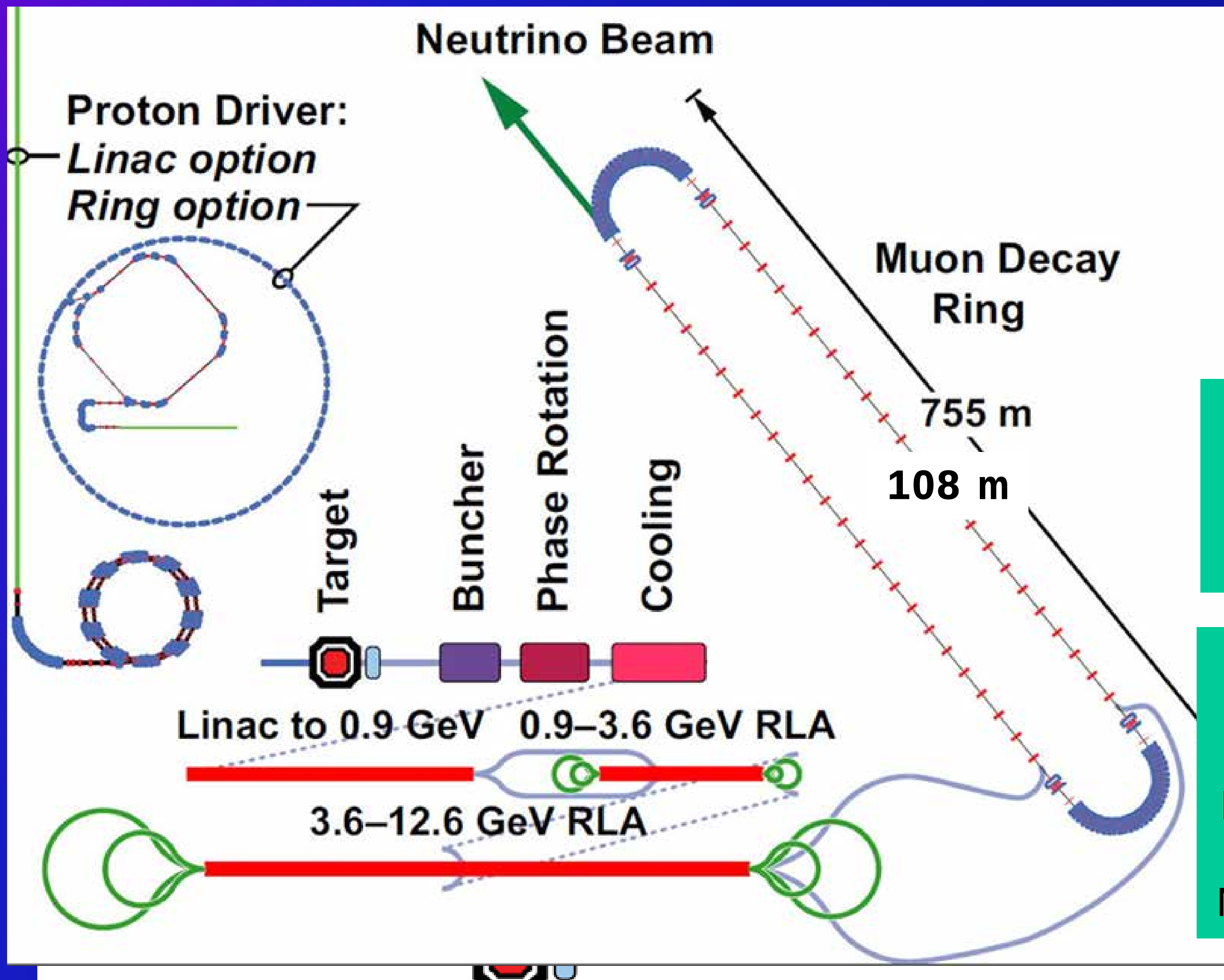
The Very-Low Energy Neutrino Factory (VLENF)

n physics with a μ storage ring

Fermilab

IDS-NF
VLENF
Single baseline, Lower E

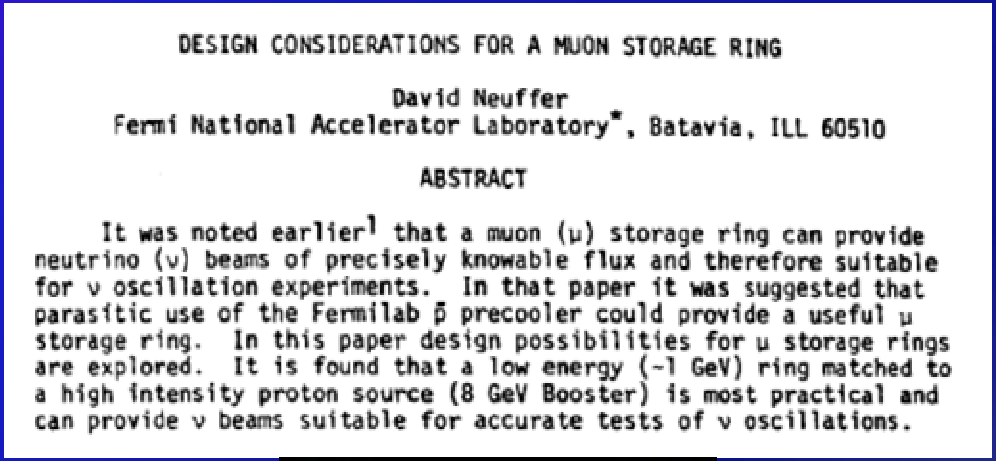


The VLENF is the simplest implementation of the NF

And DOES NOT Require the Development of ANY New Technology

30 Years in the Making

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



DESIGN CONSIDERATIONS FOR A MUON STORAGE RING

David Neuffer
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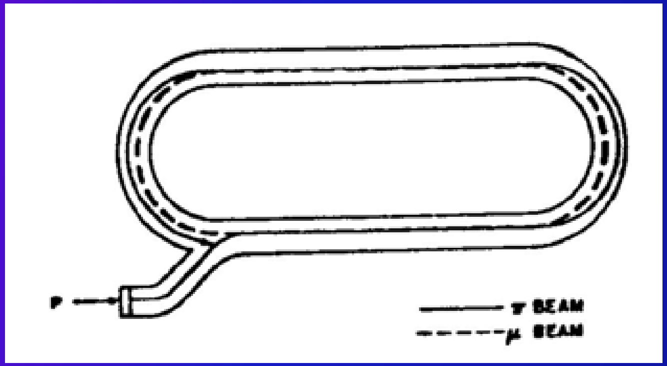
ABSTRACT

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 $\bar{p}$ 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.

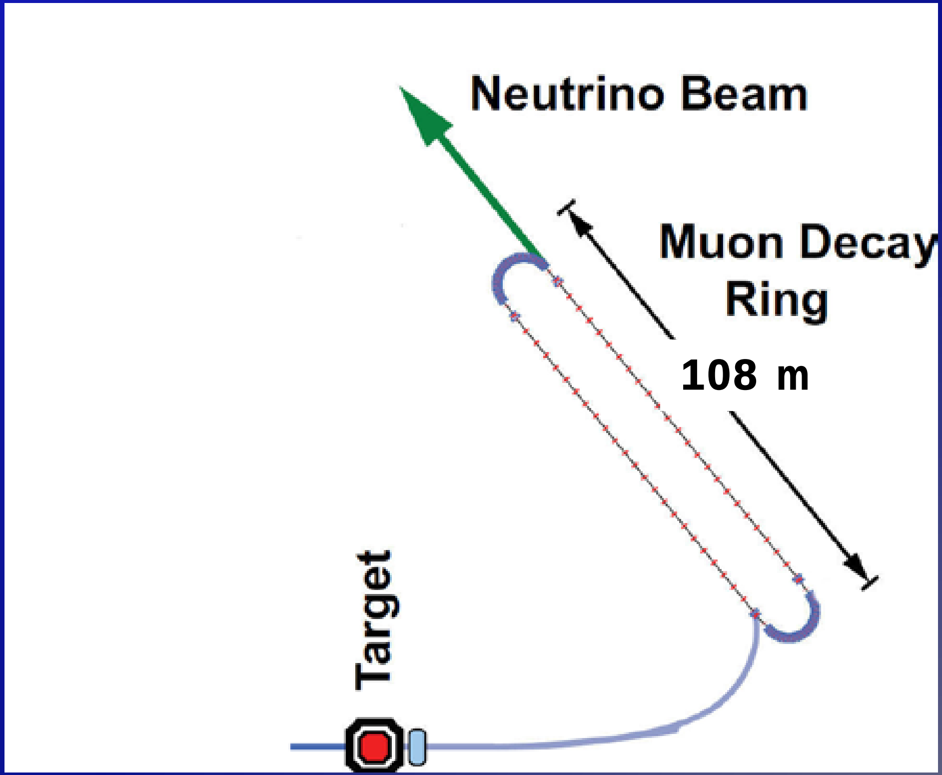


The technology existed then
&
It certainly exists now

The Facility

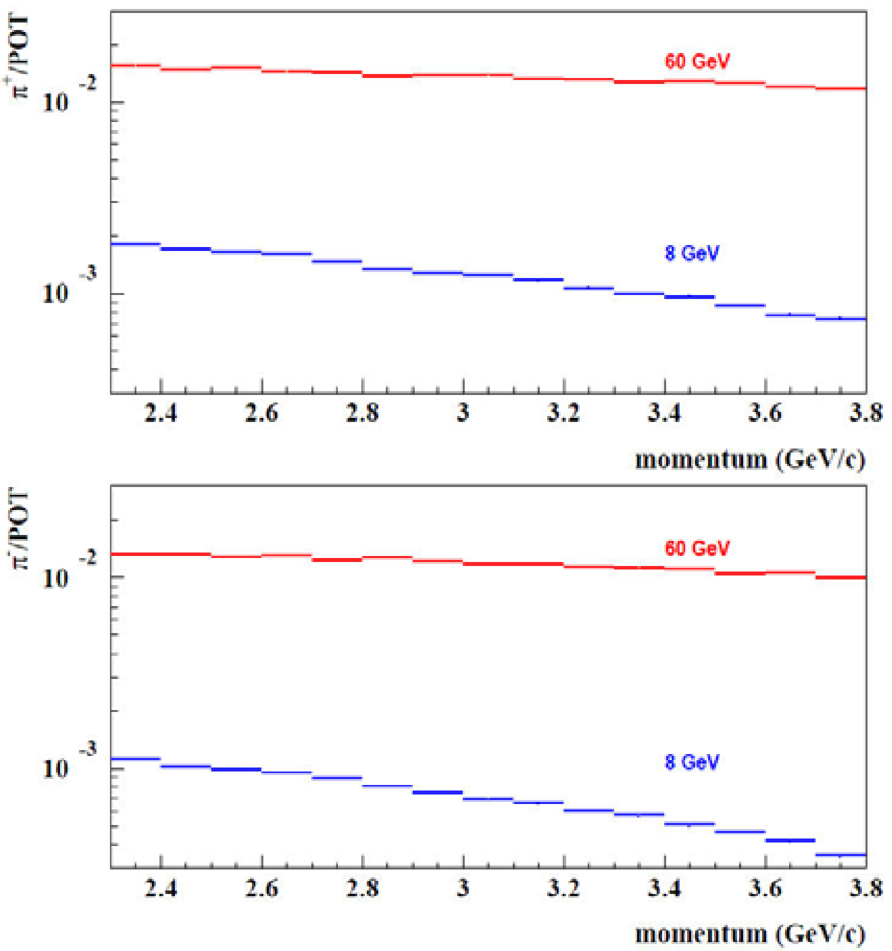
Baseline(s)

- 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 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



Sergei Striganov
Fermilab

p production



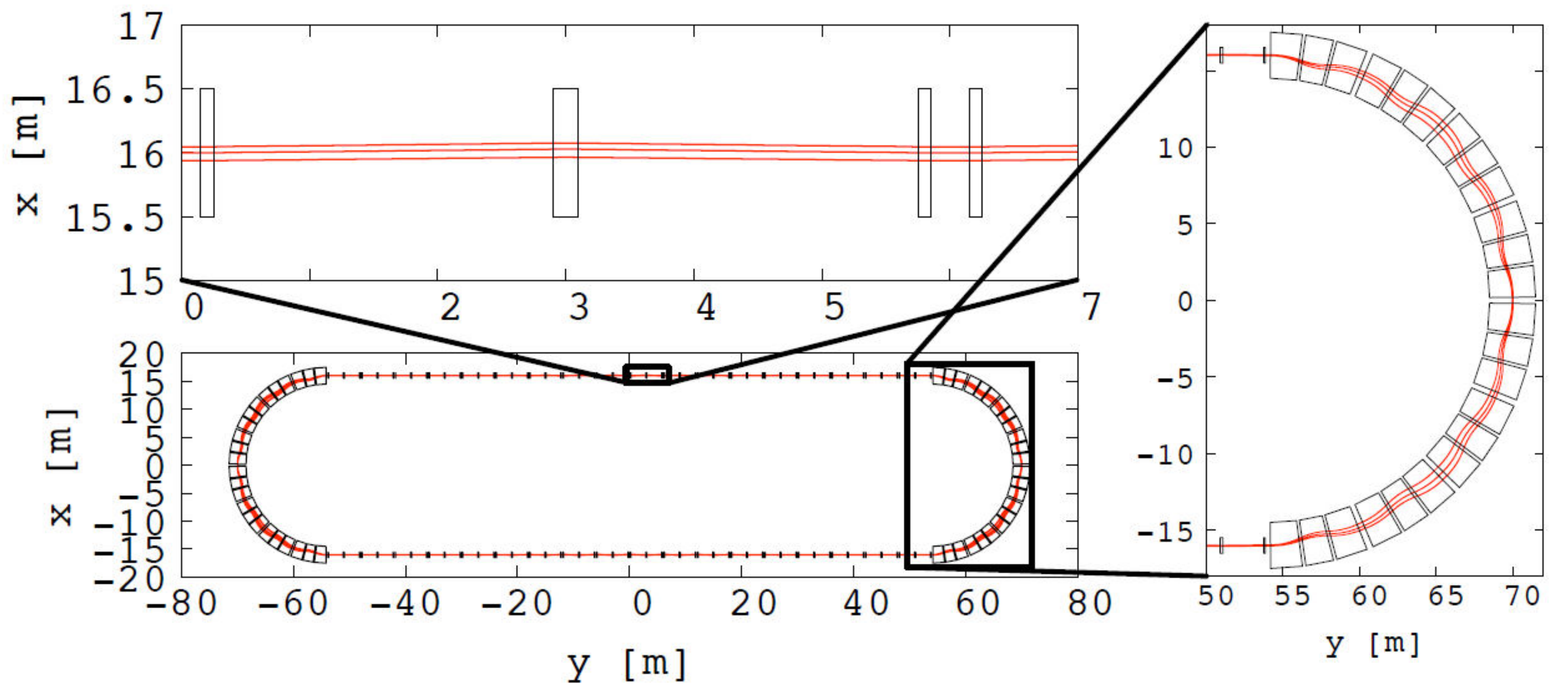
Pion production from 70 cm beryllium target (θ < 120 mrad)

In momentum range
2.7 < 3.0 < 3.3
Obtain
0.11 p^+/pot
0.10 p^-/pot
with 60 GeV p

Target/capture optimization in progress

Lagrange & Mori
Kyoto

FFAG Racetrack



dp/p » 15%

acc-kurri – 1119-01-2011

Low dispersion in straight

2 GeV/c

The Physics Reach

Assumptions

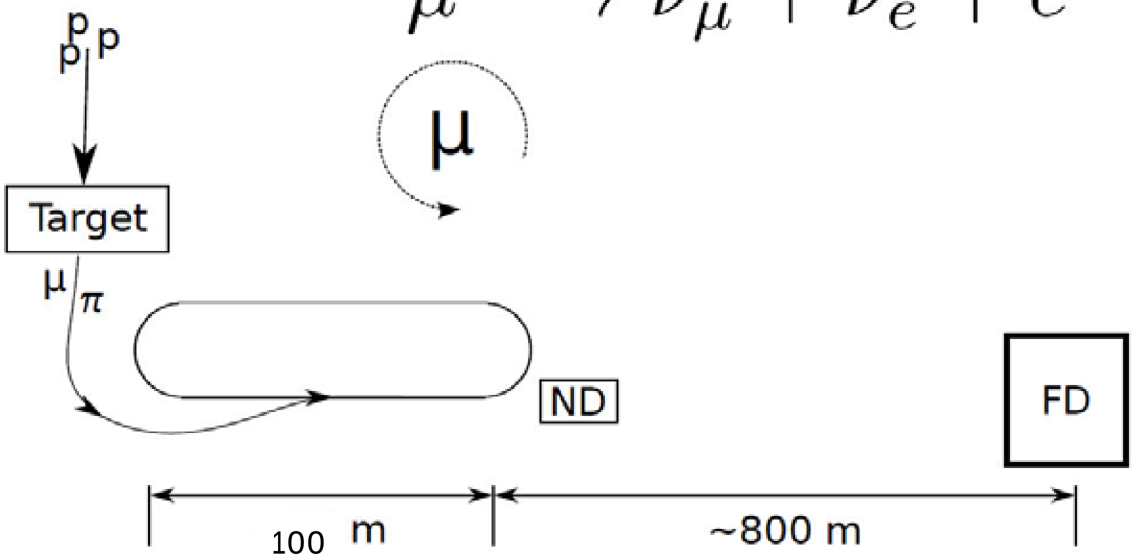
Ø N_m = (POT) X (p/POT) X $e_{collection}$ X e_{inj} X (m/p) X $A_{dynamic}$ X W

- Ø 10^{21} POT in 5 years of running @ 60 GeV in Fermilab PIP era
- Ø 0.1 p/POT
- Ø $e_{collection}$ = 0.9
- Ø e_{inj} = 0.9
- Ø m/p = 0.08 (gct X mcapture in p ® mdecay) [p decay in straight]
  - Ø Might do better with a p ® mdecay channel
- Ø $A_{dynamic}$ = 0.9 (from G4Beamline simulation)
- Ø W= Straight/circumference ratio (0.34)

Ø This yield 2 X 10^{18} useful mdecays

Experimental Layout

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



Appearance-only (though disappearance good too!)

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

Appearance Channel:

n_e ® n_m

Golden Channel

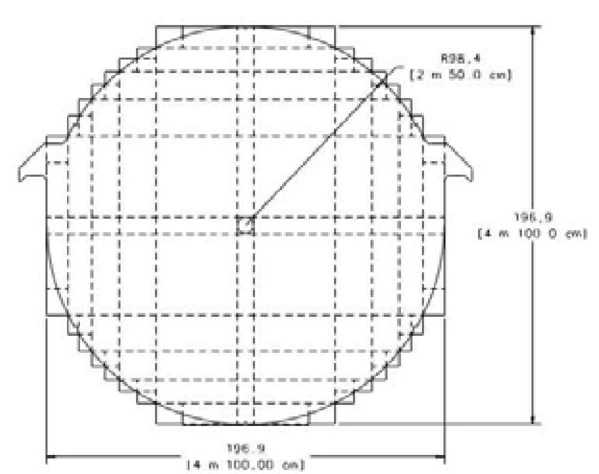
Must reject the "wrong" sign mwith great efficiency

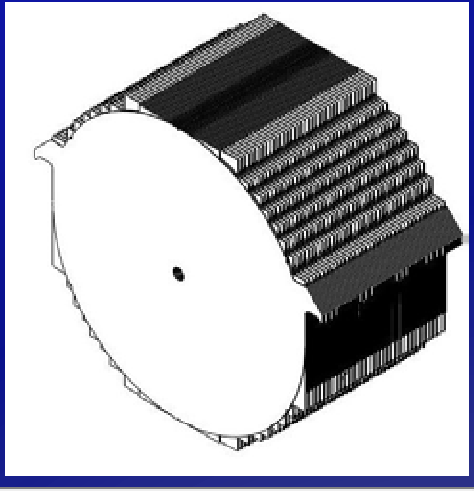
Why n_m® n_e Appearance Ch. not possible

Baseline Detector

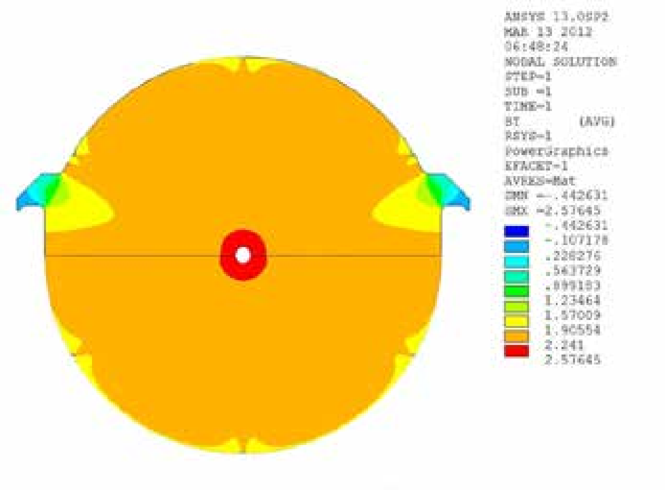
Super B Iron Neutrino Detector: SuperBIND

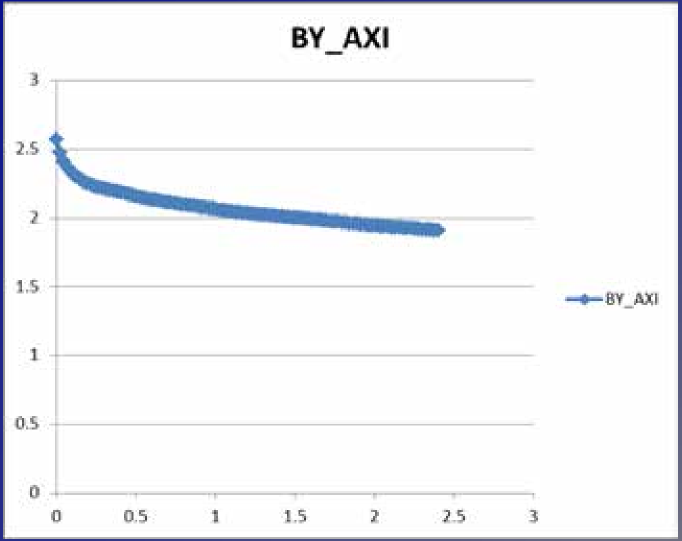
- Magnetized Iron
  - 1 kT fiducial volume
    - Following MINOS ND ME design
    - 1 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM





20 cm hole
For 3 turns
of STL

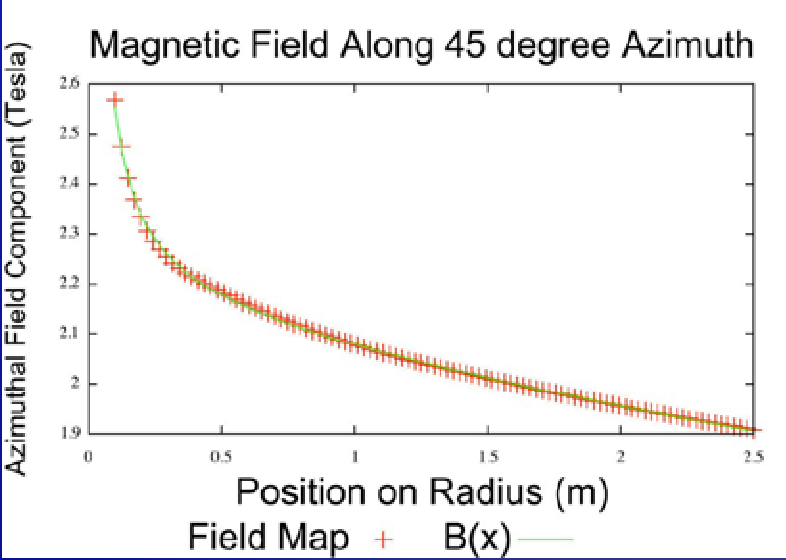




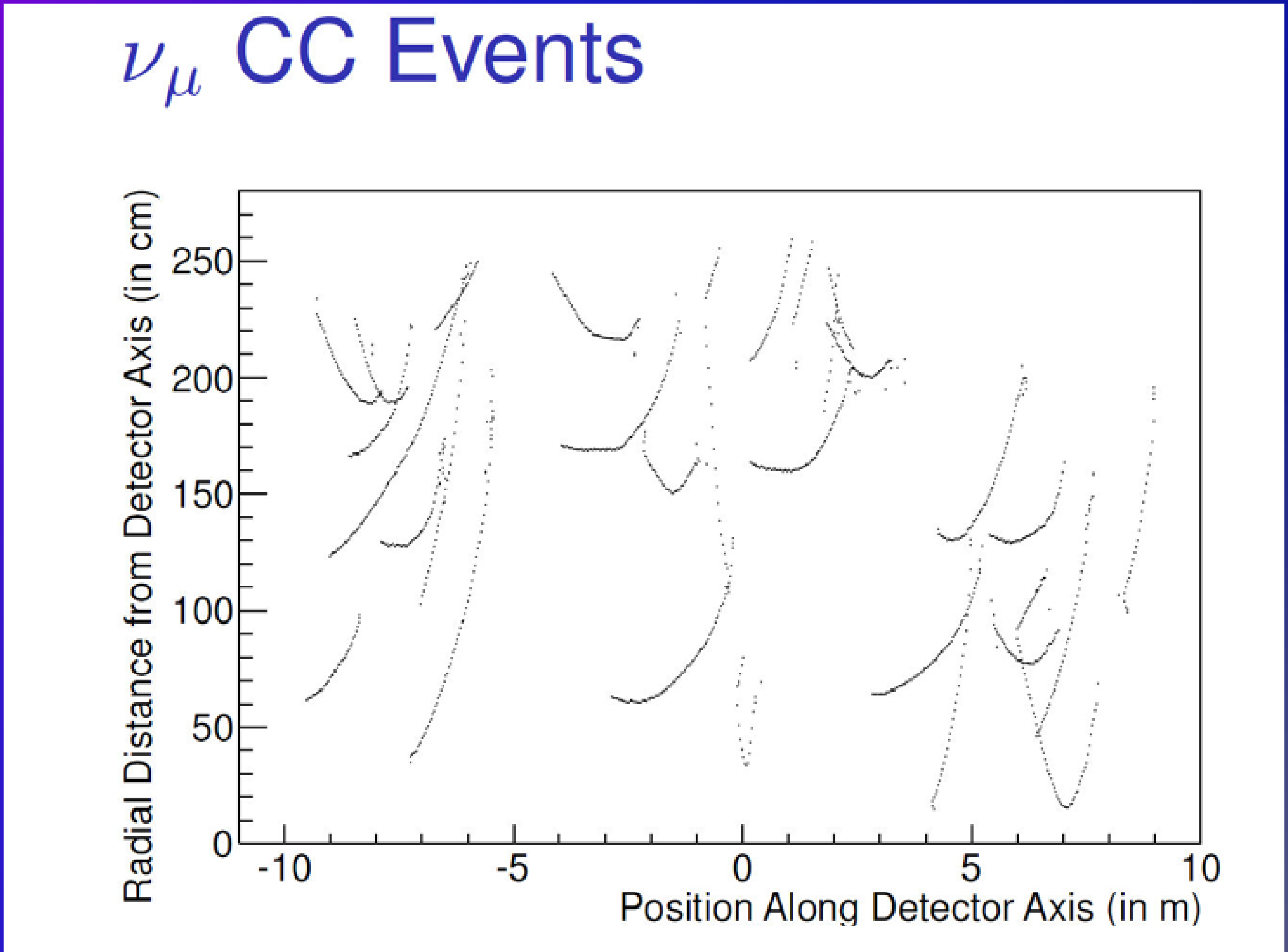
Ryan Bayes
Glasgow

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
    - Extrapolating from MIND (IDS-IDR)
    - $e_{event} = 0.7$
    - $Bkg_{rej} = 10^{-4}$



Event Candidates in SuperBIND



Hits
R vs. Z

Chris Tunnell
Oxford

Raw Event Rates

[$\bar{\nu}$-mode with stored μ^-]

Channel name	Number Events
$\bar{\nu}_e \to \bar{\nu}_\mu$ CC	72
$\nu_\mu \to \nu_\mu$ CC	211490
$\nu_\mu \to \nu_\mu$ NC	78457
$\bar{\nu}_e \to \bar{\nu}_e$ CC	71105
$\bar{\nu}_e \to \bar{\nu}_e$ NC	29613

[ν-mode with stored μ^+]

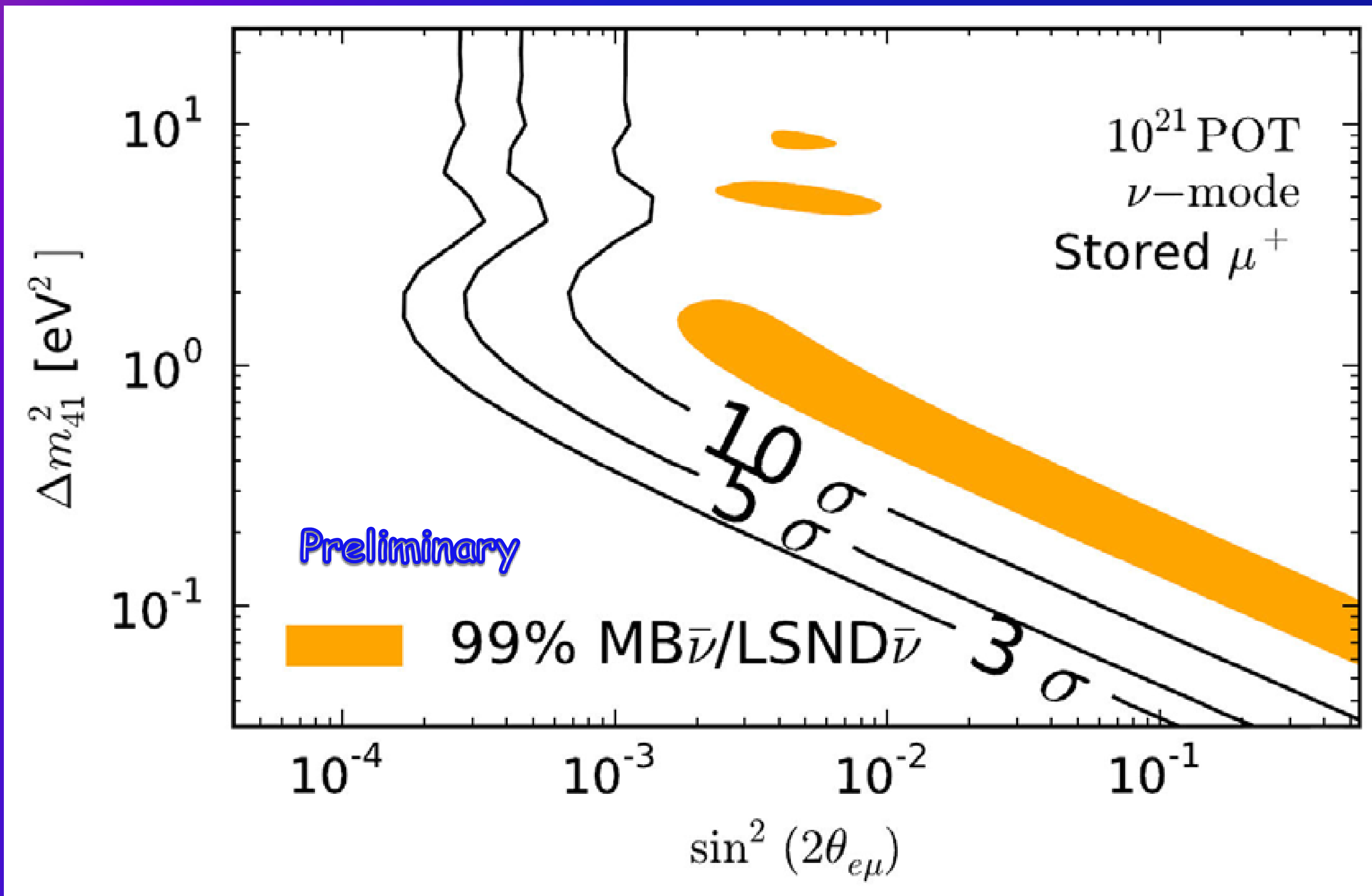
Channel name	Number Events
$\nu_e \to \nu_\mu$ CC	191
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ CC	87943
$\bar{\nu}_\mu \to \bar{\nu}_\mu$ NC	35993
$\nu_e \to \nu_e$ CC	179223
$\nu_e \to \nu_e$ NC	68552

Appearance channels

3+1
Assumption

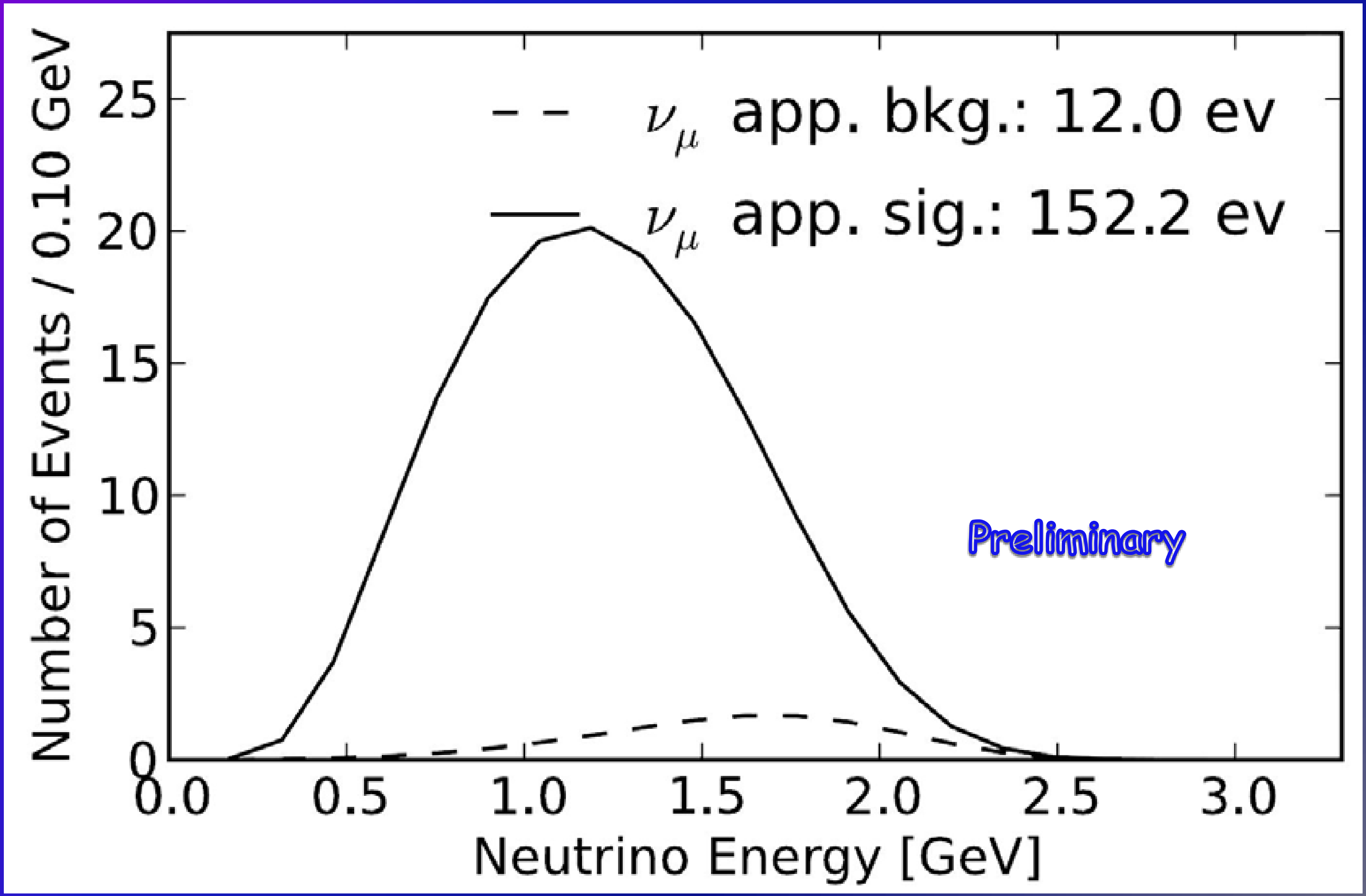
Contour plots
that follow from
GLoBES Analysis
e_{evt} = 0.7
Bkg_{rej} = 10^{-4}
Bkg uncertainty = 35%
Systematic uncertainty = 2%

n$_e$ ® n$_m$ appearance
CPT invariant channel to MiniBooNE

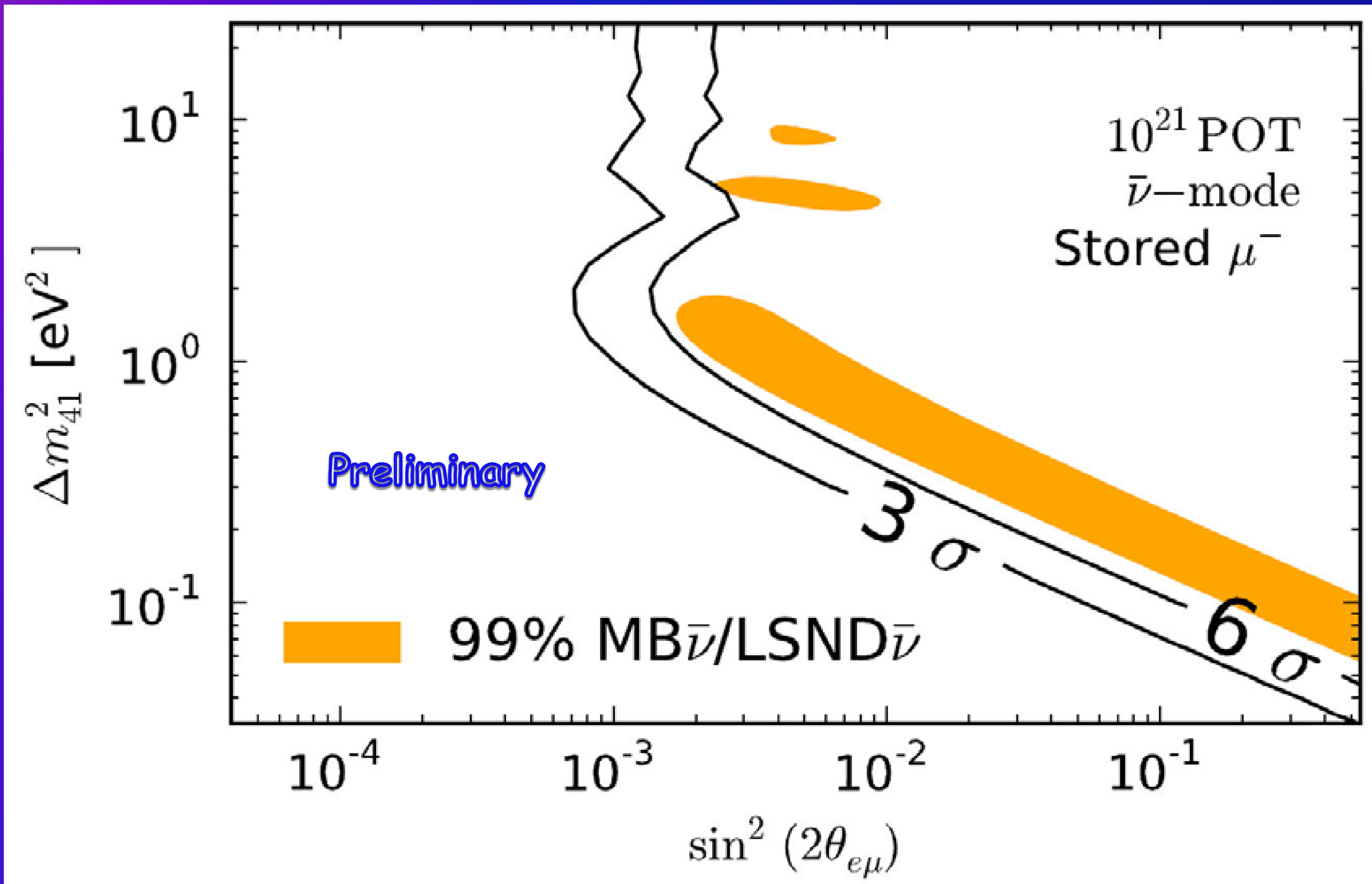


3+1 Assumption

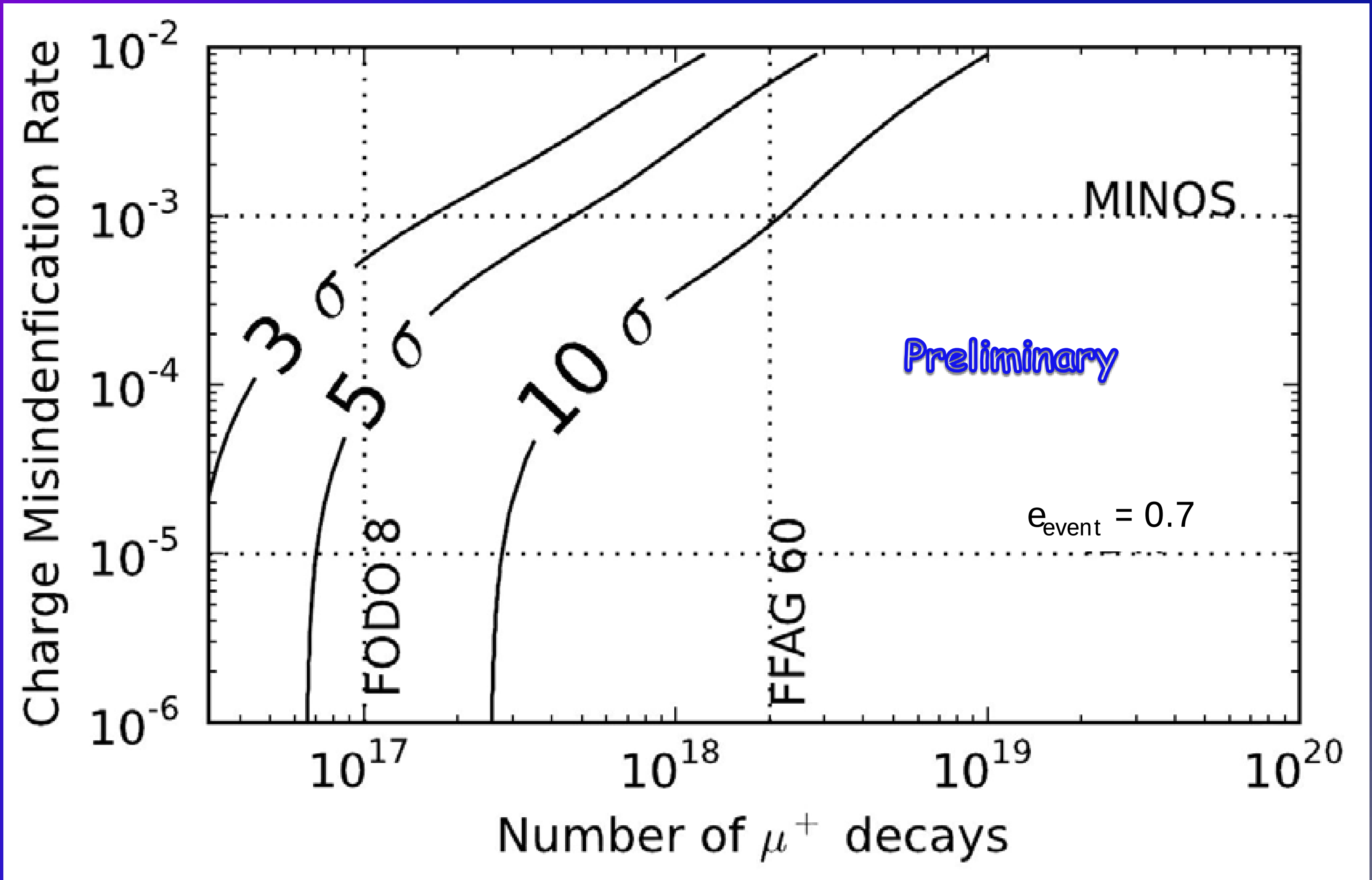
E_n of appearance events



$\bar{n}_e$ ® $\bar{n}_m$ appearance



Sensitivity in
m charge mis-ID rate - # m plane

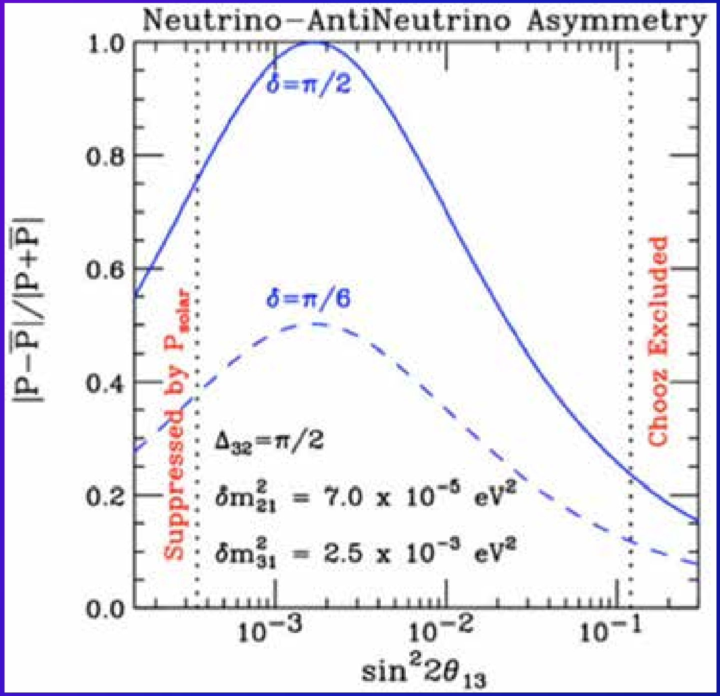


Cross-Section Measurements
&
Disappearance Searches

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



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

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

$n_{e,}$ n_m Disappearance Searches *Rates*

- Ø Detector mass – Near & Far
  - ø 100T Near
  - ø 1kT Far
- Ø 10^{21} POT exposure (m+)
  - ø Number of n_e events (CC):
    - ø $N_{evts\text{-}near}$ » 1.8M
    - ø $N_{evts\text{-}far}$ » 200k
  - ø Number of $\bar{n}_m$ events (CC):
    - ø $N_{evts\text{-}near}$ » 0.9M
    - ø $N_{evts\text{-}far}$ » 100k
- Ø < 1% Measurements certainly possible from # events available
  - ø n_e disappearance might require re-optimization *(global)* of detectors
- Ø In addition, NC disappearance would provide very strong case for new physics
  - ø » 140k n$[\bar{n}_m + n_e]$ NC interactions
    - ø Look for n + p ® n + p

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 n flux
    - And verify the precision to which it can be determined.

Outlook II

Future Work:

- Ø 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 n_e interactions, however
    - Near Detector hall could be envisioned as n detector test facility

VLENF: Conclusions

The Physics case:

- Ø 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
- Ø n_e and n_m disappearance experiments delivering at the <1% level look to be doable
  - ø Systematics need careful analysis
  - ø Detailed simulation work on these channels has not yet started
- Ø Cross section measurements with near detector(s) offer a unique opportunity

The Facility:

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

VLENF: Conclusions II

The Detector:

- Is based on demonstrated technology and follows engineering principles from existing detectors
  - Technology extrapolations (scintillator readout) is 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

The VLENF:

- 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 n-bar data
- Can add significantly to our knowledge of n cross-sections, particularly for n_e interactions
- Provides an accelerator technology test bed
  - But can also utilize existing accelerator infrastructure
- Provides a powerful n detector test facility

END

Thank You

Acknowledgements

Chuck Ankenbrandt[5], Ryan Bayes[2], Alex Bogacz[8], Herman Cease[1], John Cobb[7], Malcolm Ellis[9], Jim Kilmer[1], Joachim Kopp[1], Jean-Baptist Lagrange[4], Ken Long[3], Nikolai Mokhov[1], Yoshi Mori[4], David Neuffer[1], Jaroslaw Pasternak[3], Milorad Popovic[1], Tom Roberts[5], Akira Sato[6], Edward Santos[3], Paul Soler[2], Sergei Striganov[1], Chris Tunnell[7], Bob Wands[1], Walter Winter[10]

[1]Fermilab

[2]University of Glasgow

[3]Imperial College London

[4]Kyoto University

[5]Muons Inc

[6]Osaka University

[7]Oxford University

[8]TJNL

[9]Westpac-HEPh

[10]Universität Würzburg

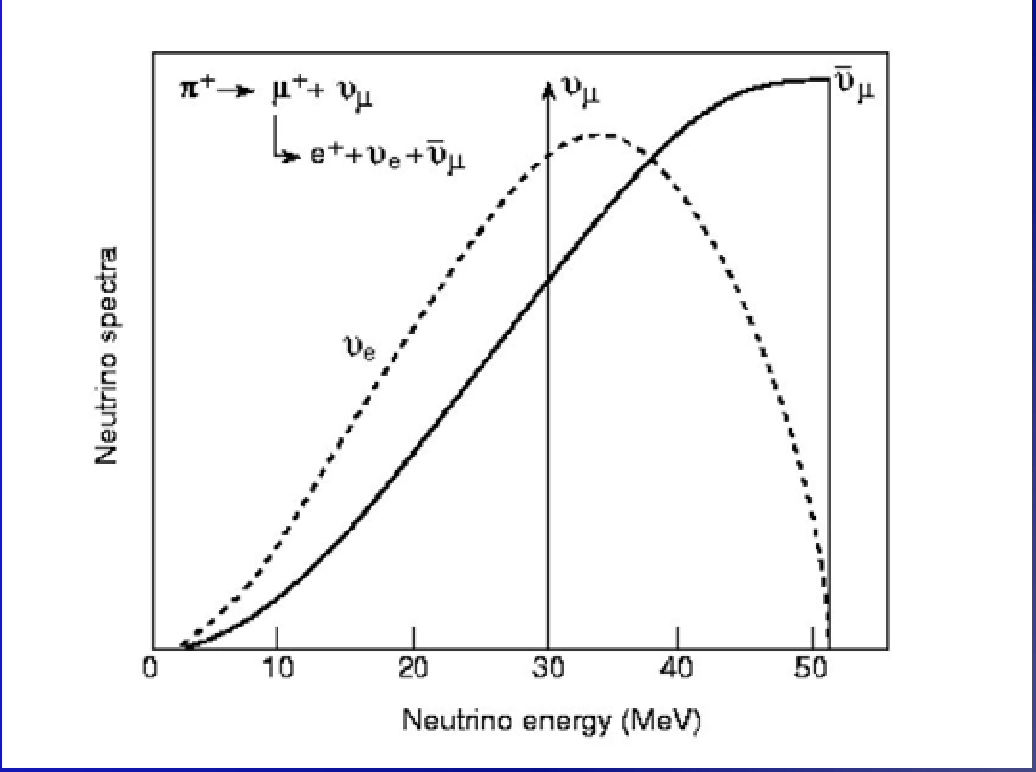
BACK UPS

ns from muon decay

- Running with m

$$m^{-} \circledR e^{-} + n_{m} + \bar{n}_{e}$$

- Well defined flavor composition & energy

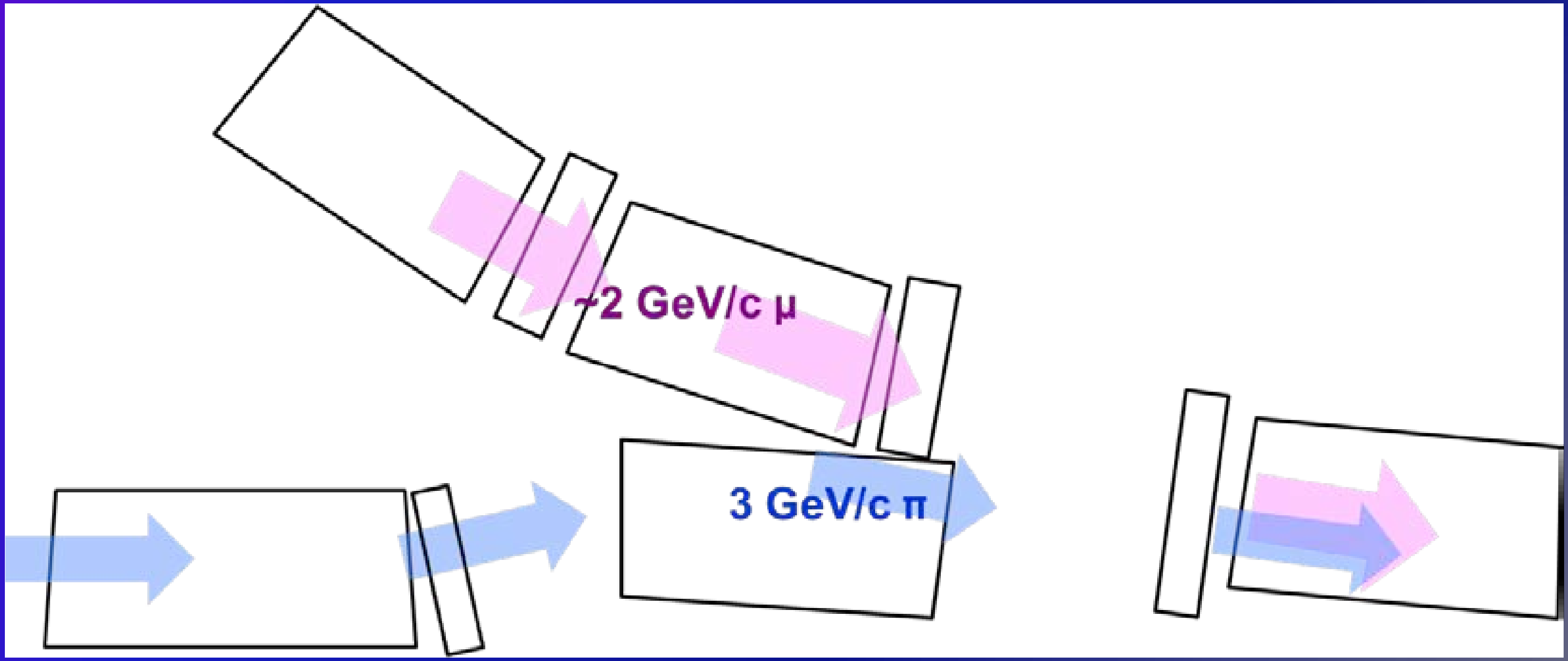


David Neuffer

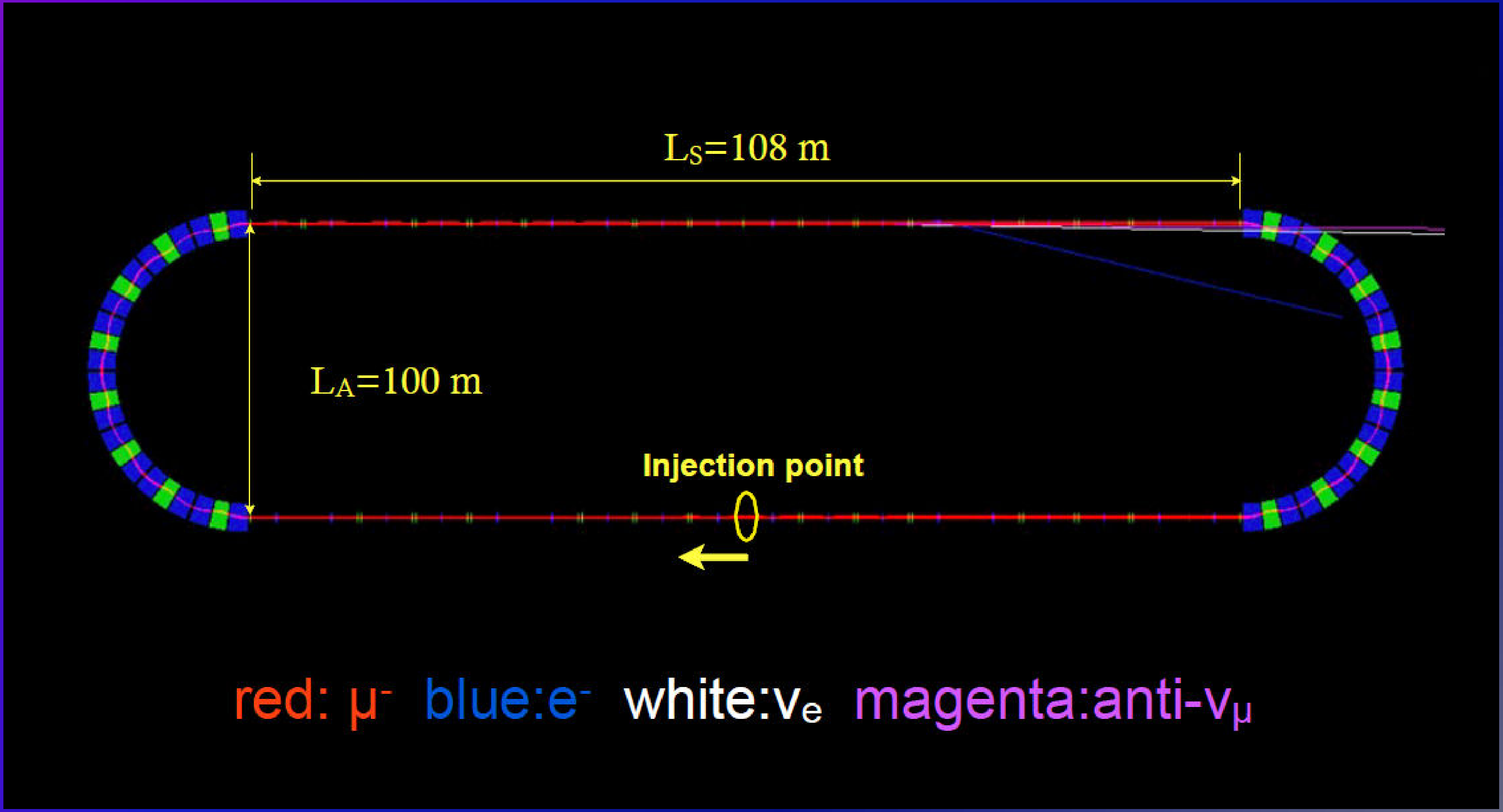
Injection Concept

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

- Concept works for FODO lattice
- Work in progress for RFFAG



RFFAG Tracking Studies



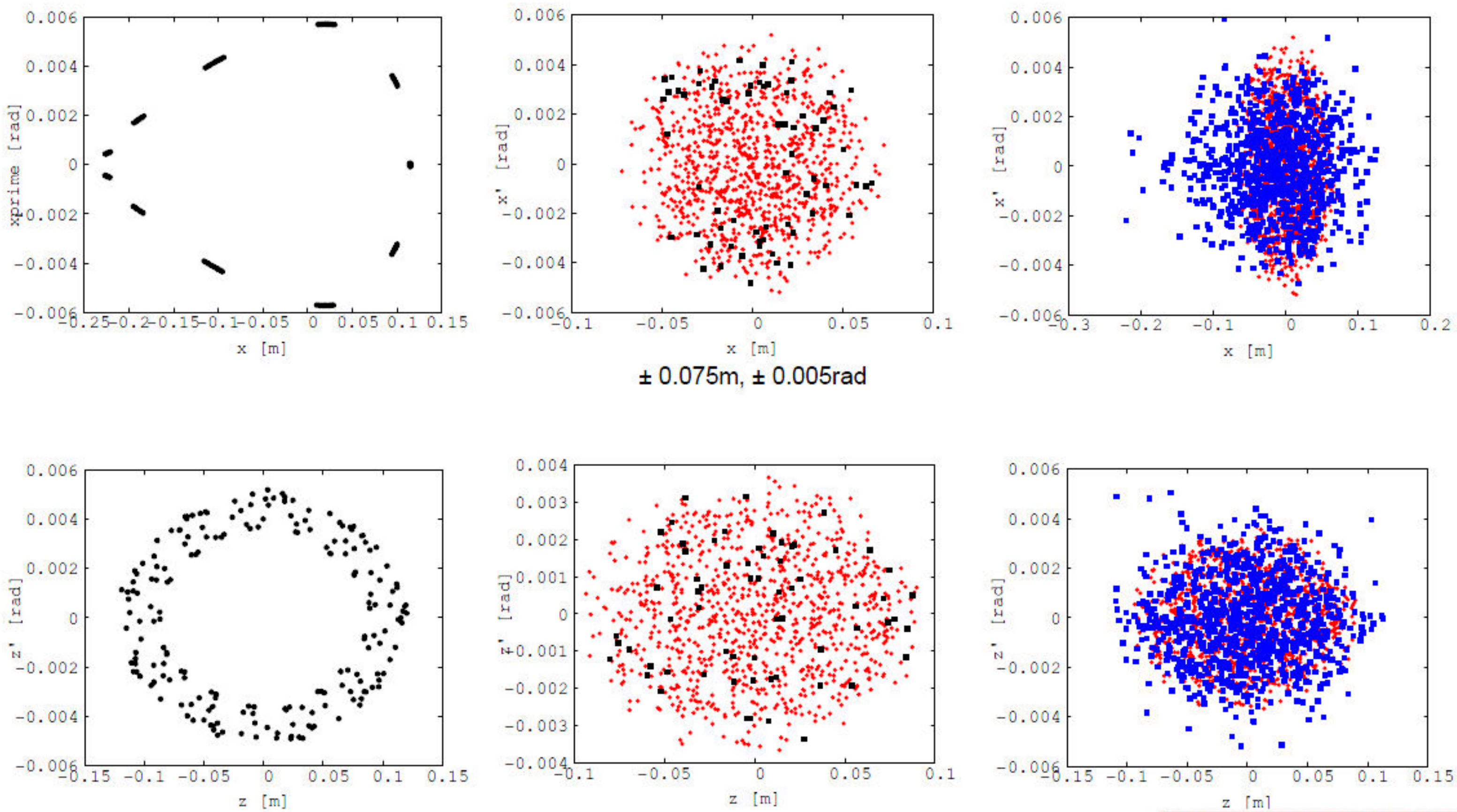
Akira Sato
Osaka University

FFAG Tracking

Max amplitude 100 turns for p_0

Initial phase: Red
($\varepsilon_{unnormalized}$ ~ 400π mm mrad)

After 100 turns: Blue



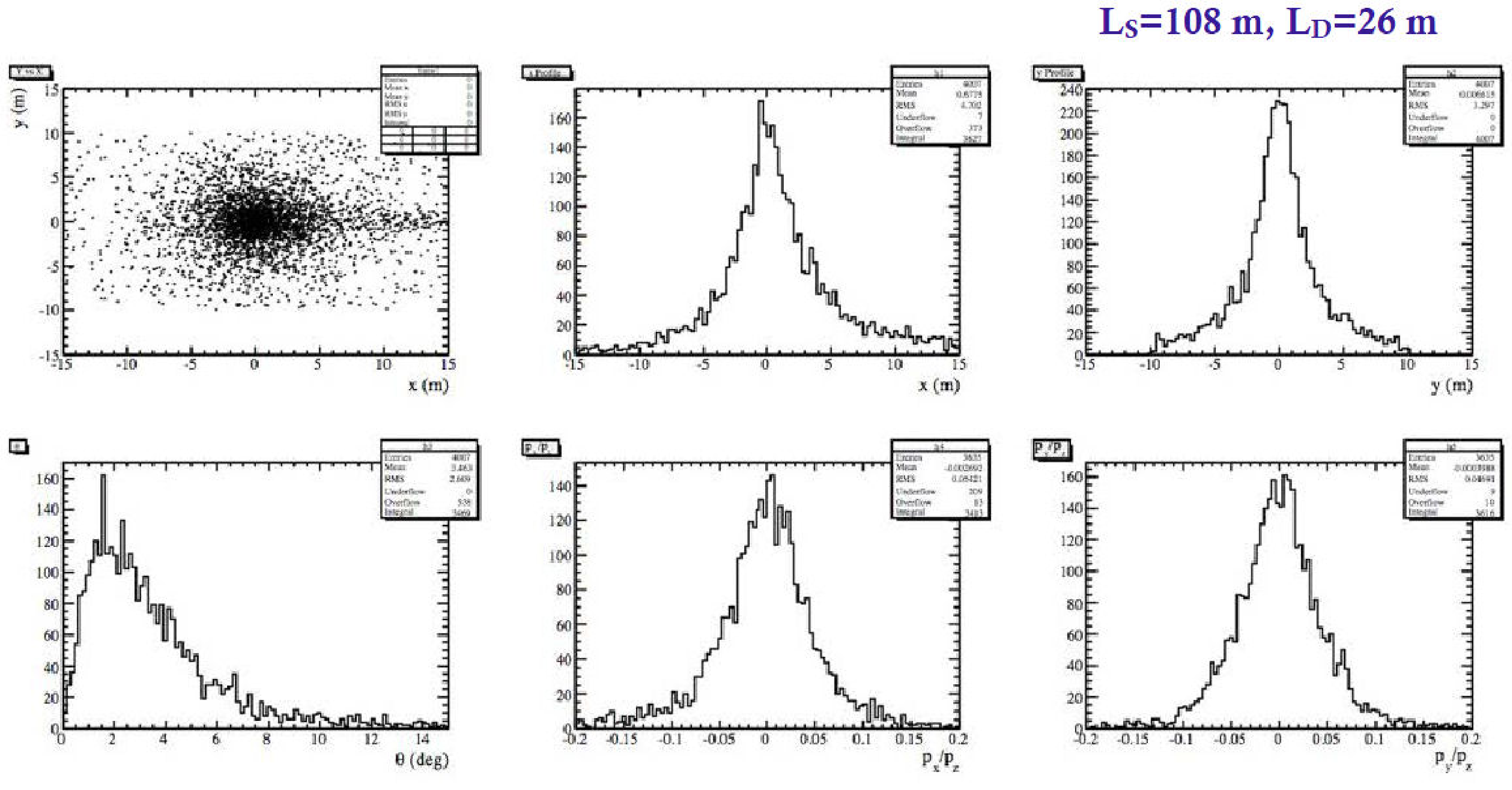
± 0.075m, ± 0.005rad

± 0.090m, ± 0.035rad

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

>90% dynamic aperture

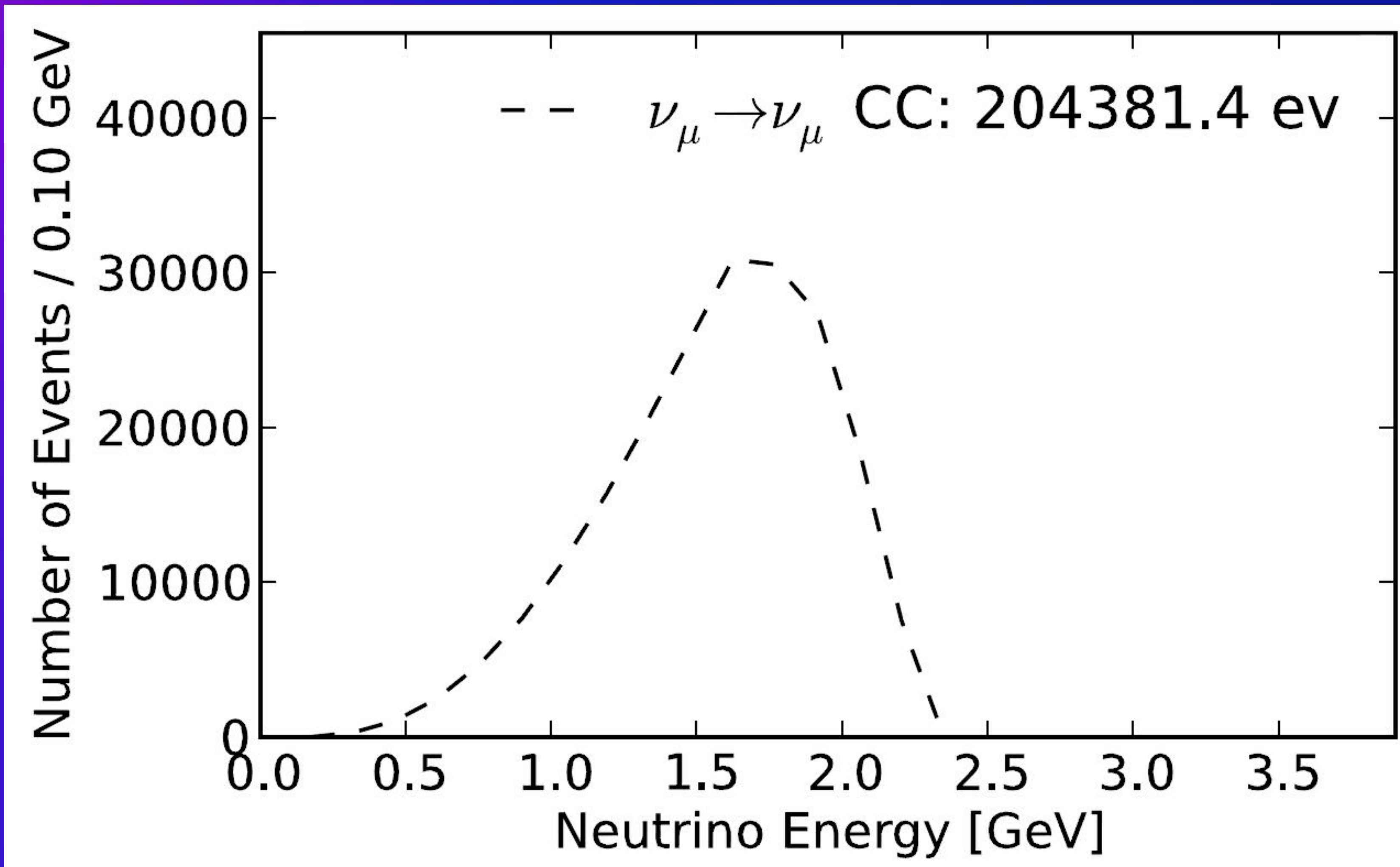
G4Beamline Simulation Output
n beam at monitor detector at L_D=26m



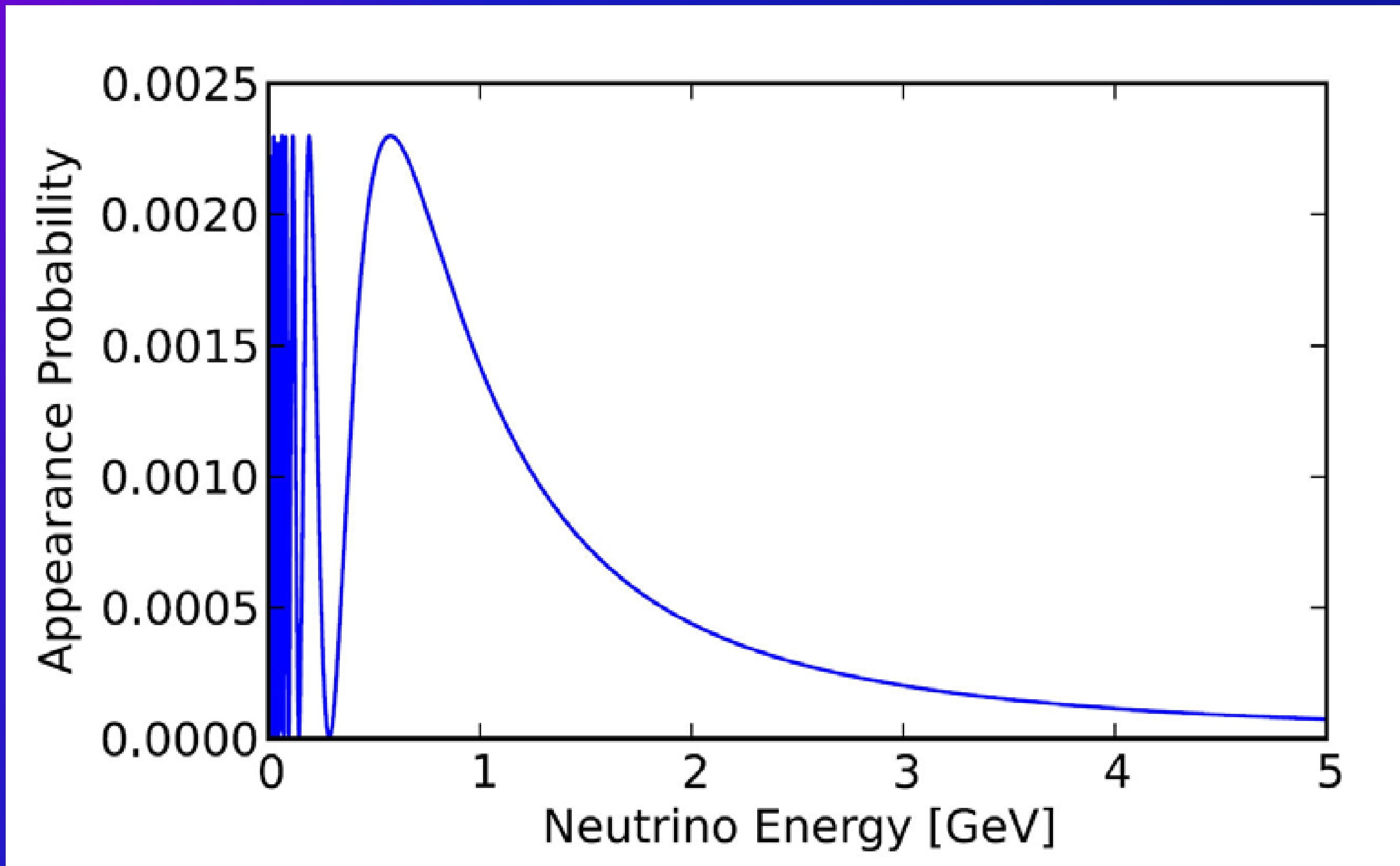
Accelerator Science

- A technology proving ground and a test bed for mstorage 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)
- Pathway to future macccelerator facilities

m+ stored: n_m spectra @ FD



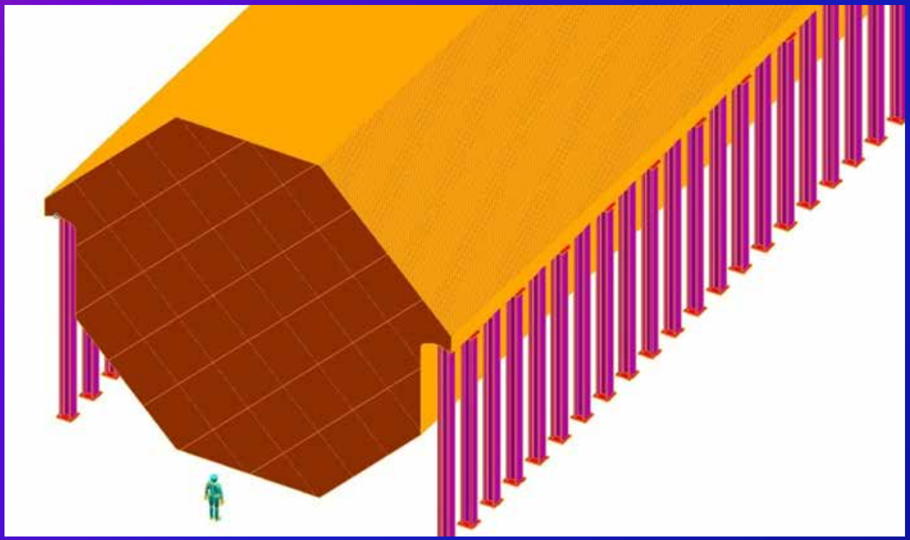
Oscillation Probability



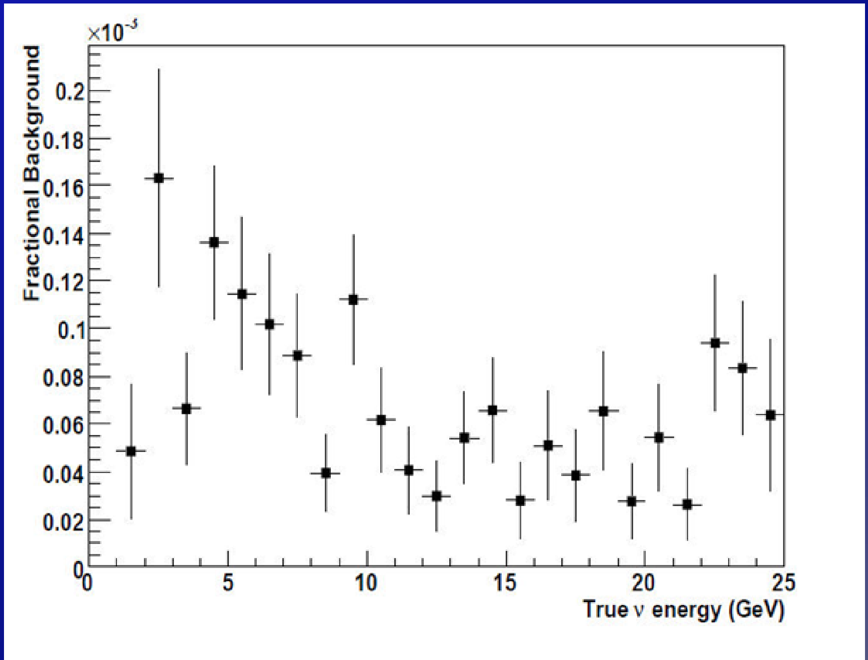
The oscillation probability for the “golden channel” n_e ® n_m, the (3+1) oscillation formalism & the LSND/MiniBooNE best-fit parameters

Magnetized Iron Neutrino Detector (MIND)

Re-Optimize for lower energy



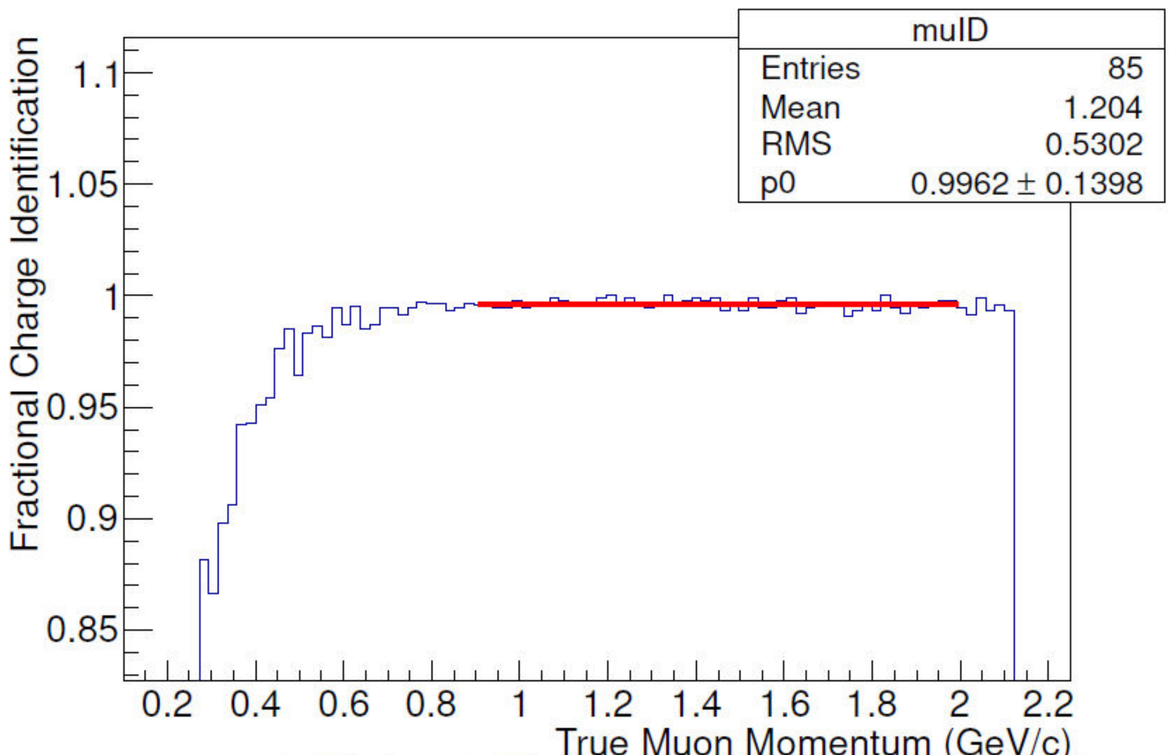
Andrew Laing
Glasgow

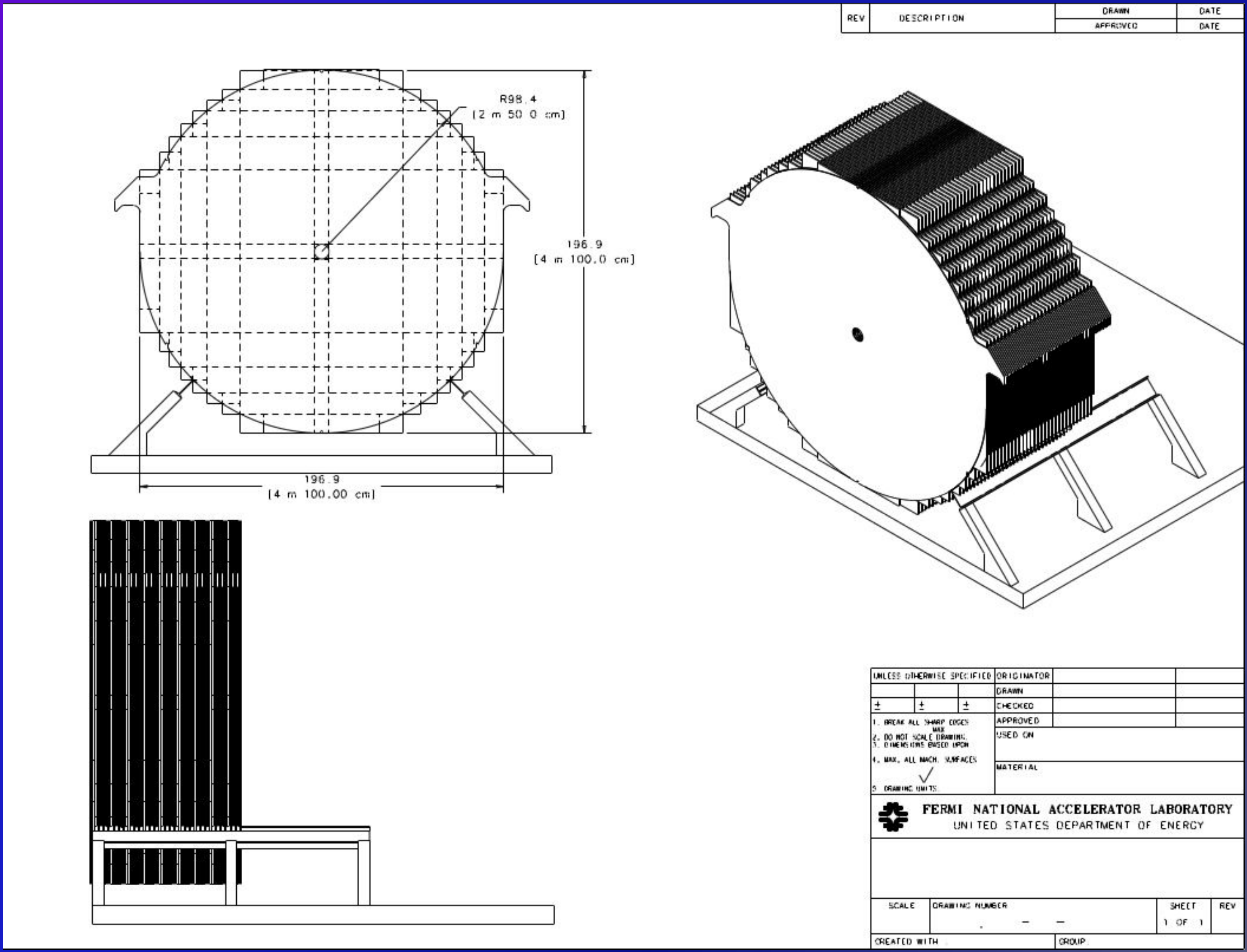


- Ø MIND was optimized for the "Golden" channel at the NF (25 GeV mstorage ring)
- Ø Optimization for FD for L/E » 1
  - ø Essentially Minos ND with upgrades
    - ø Reduce plate thickness (1 cm)
    - ø 250 kA-turn excitation (SCTL)
    - ø XY readout between planes

MCS not an issue

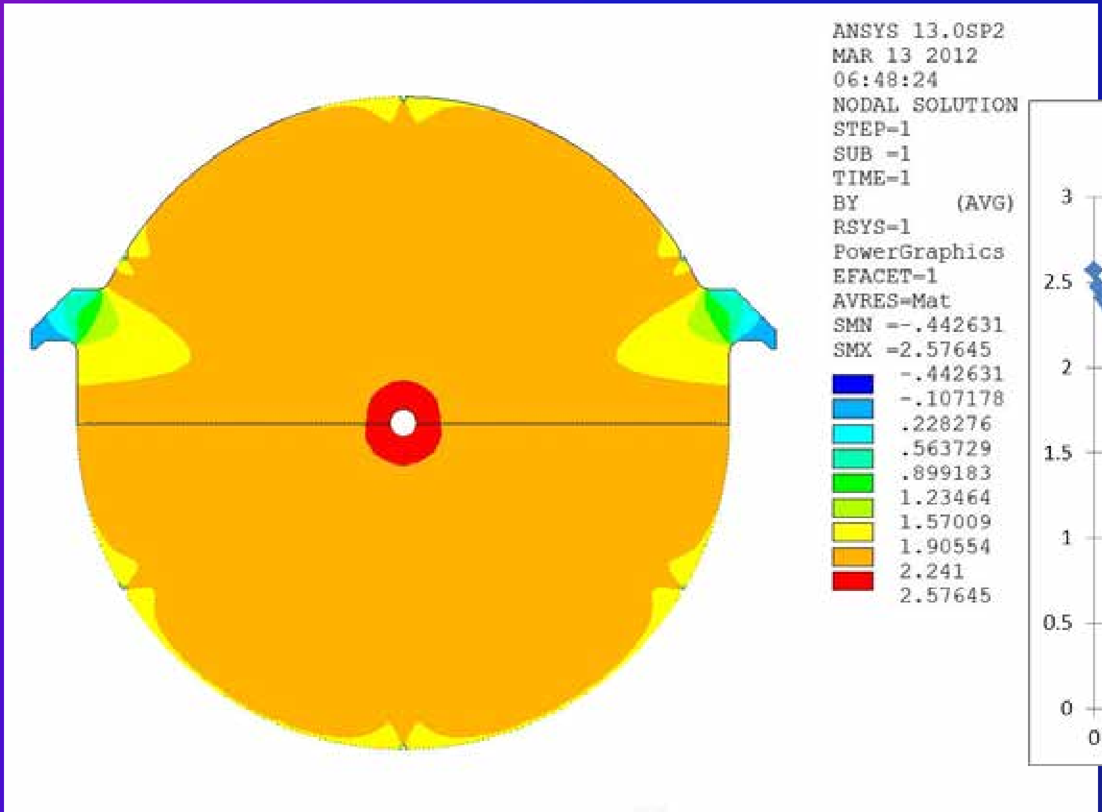
Detector simulated with 2 cm Fe Plate

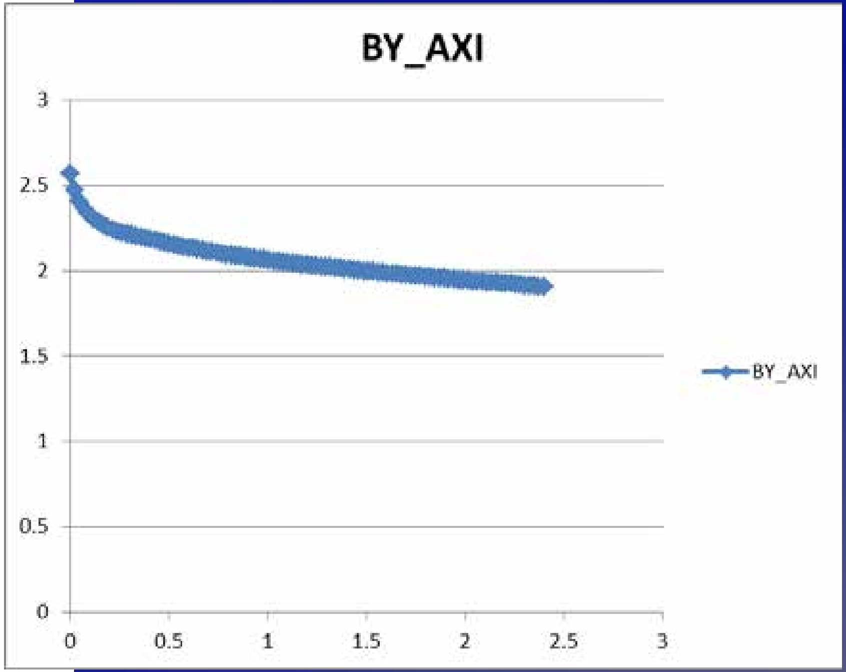




REV
DESCRIPTION
DRAWN
DATE
APPROVED
DATE
R98.4
[2 m 50.0 cm]
196.9
[4 m 100.0 cm]
196.9
[4 m 100.00 cm]
UNLESS OTHERWISE SPECIFIED
ORIGINATOR
DRAWN
CHECKED
APPROVED
USED ON
MATERIAL
FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
SCALE
DRAWING NUMBER
SHEET
REV
1 OF 1
CREATED WITH
GROUP

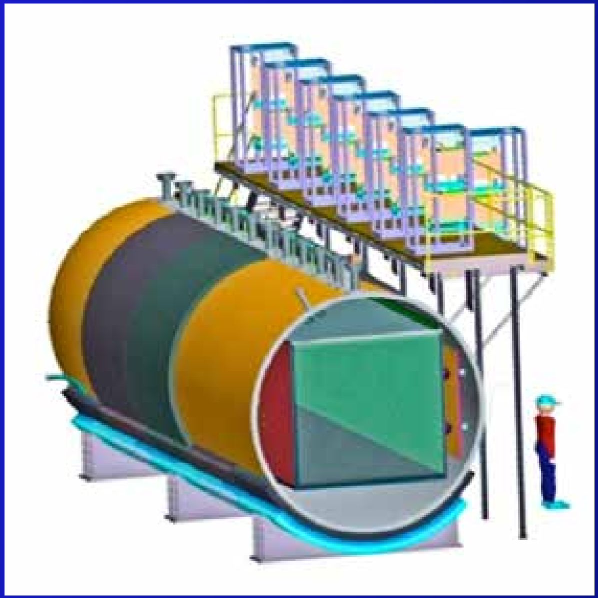
B Field Simulation





Detector Considerations

- Other options
  - Totally Active Scintillator - TASD
  - Lar
  - Present opportunity to measure n_e appearance?
- Must Be Magnetized, however

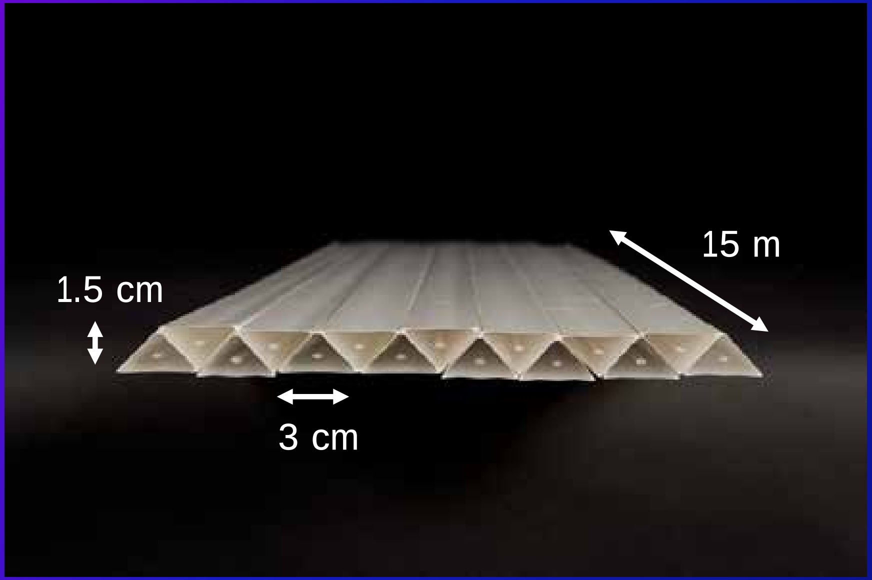


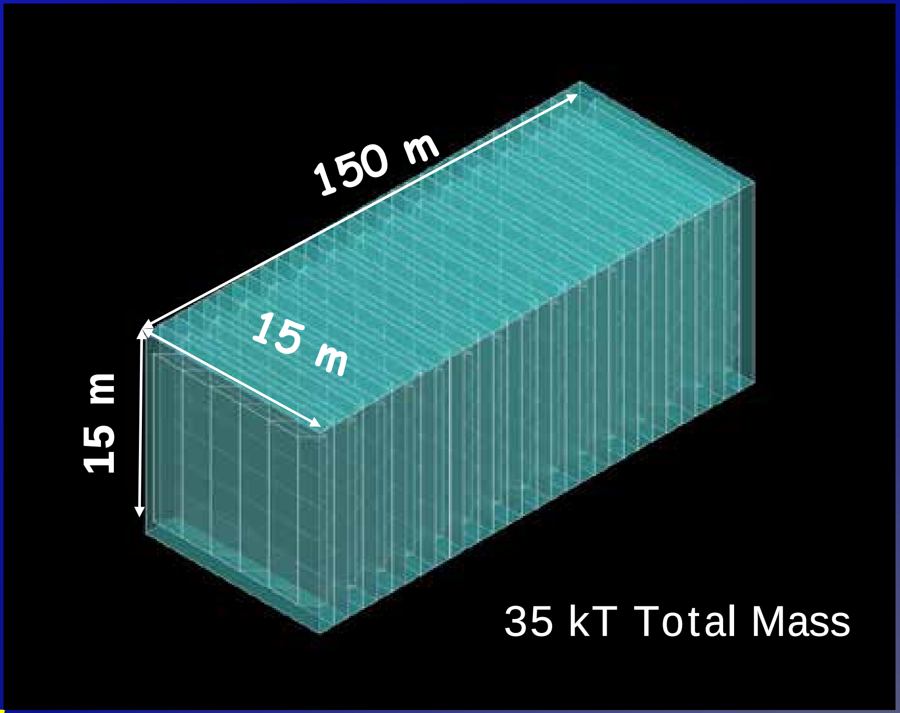
I bring this up because we have shown that at least one detector concept meets all our performance goals.

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**



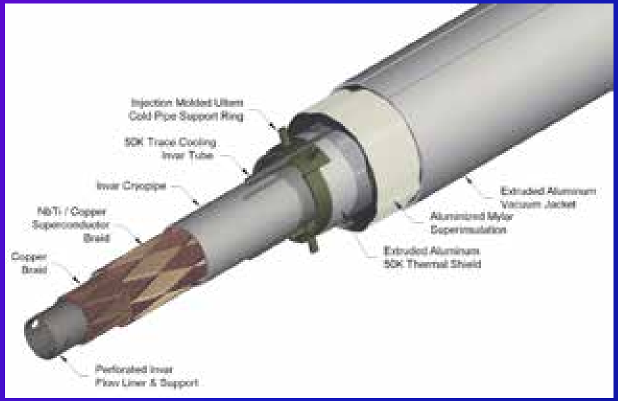


- **Momenta between 100 MeV/c to 15 GeV/c**
- **Magnetic field considered: 0.5 T**
- **Reconstructed position resolution ~ 4.5 mm**

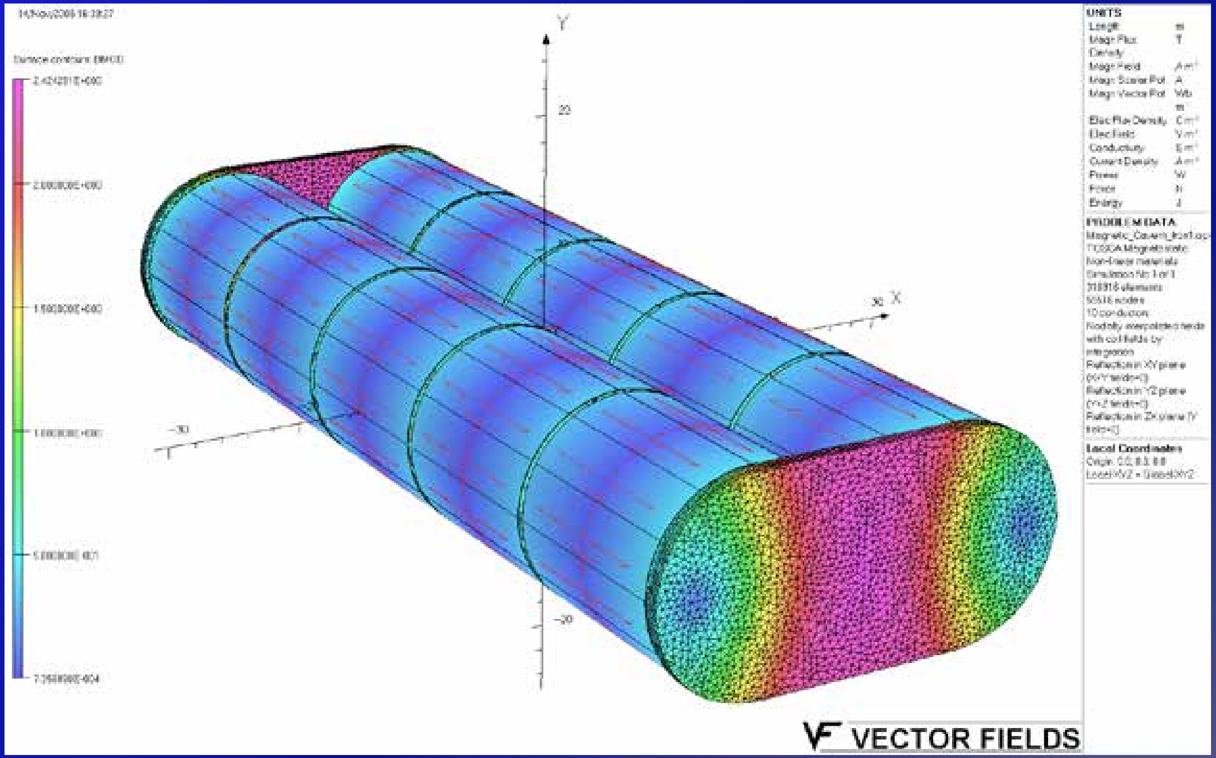
B = 0.5T

Magnet - Concept for IDS-NF

- VLHC SC Transmission Line
  - Technically proven
  - Affordable



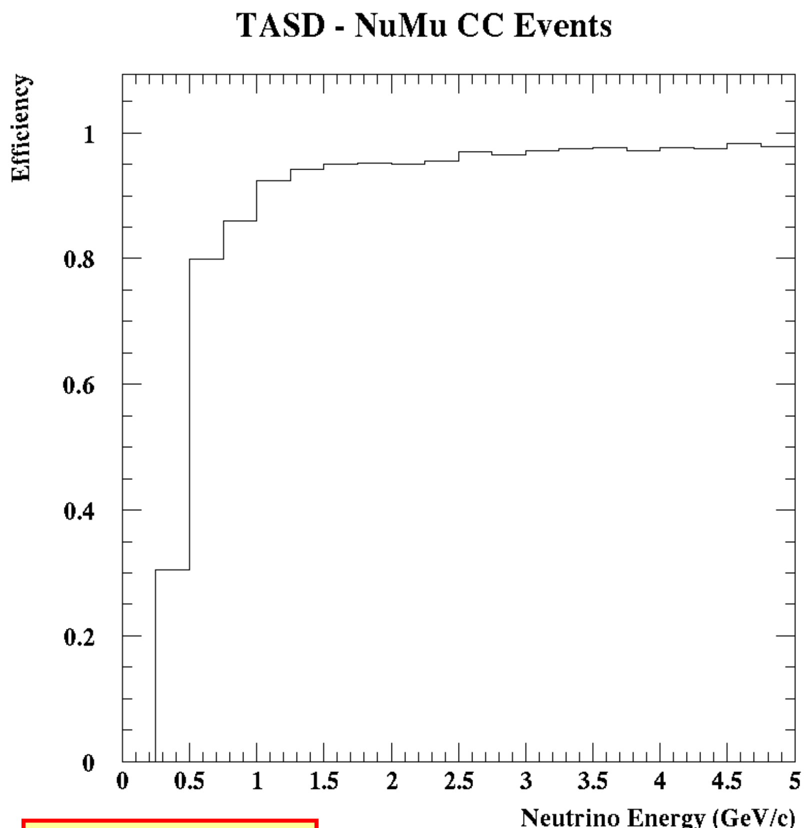
R&D to support concept
Has not been funded



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

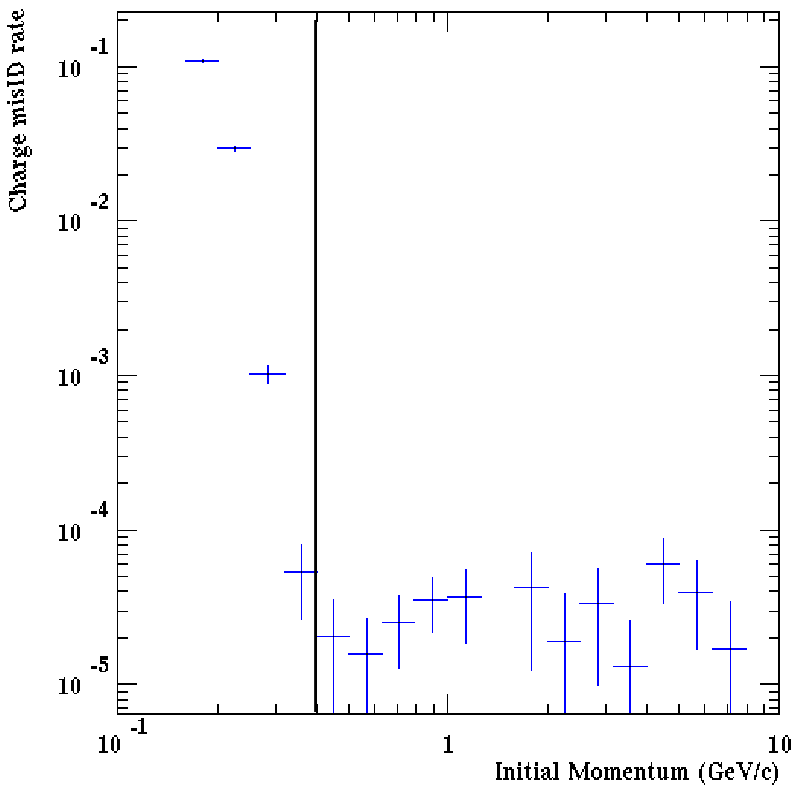
TASD Performance

n Event Reconstruction e



Excellent s$_E$

Muon charge mis-ID rate



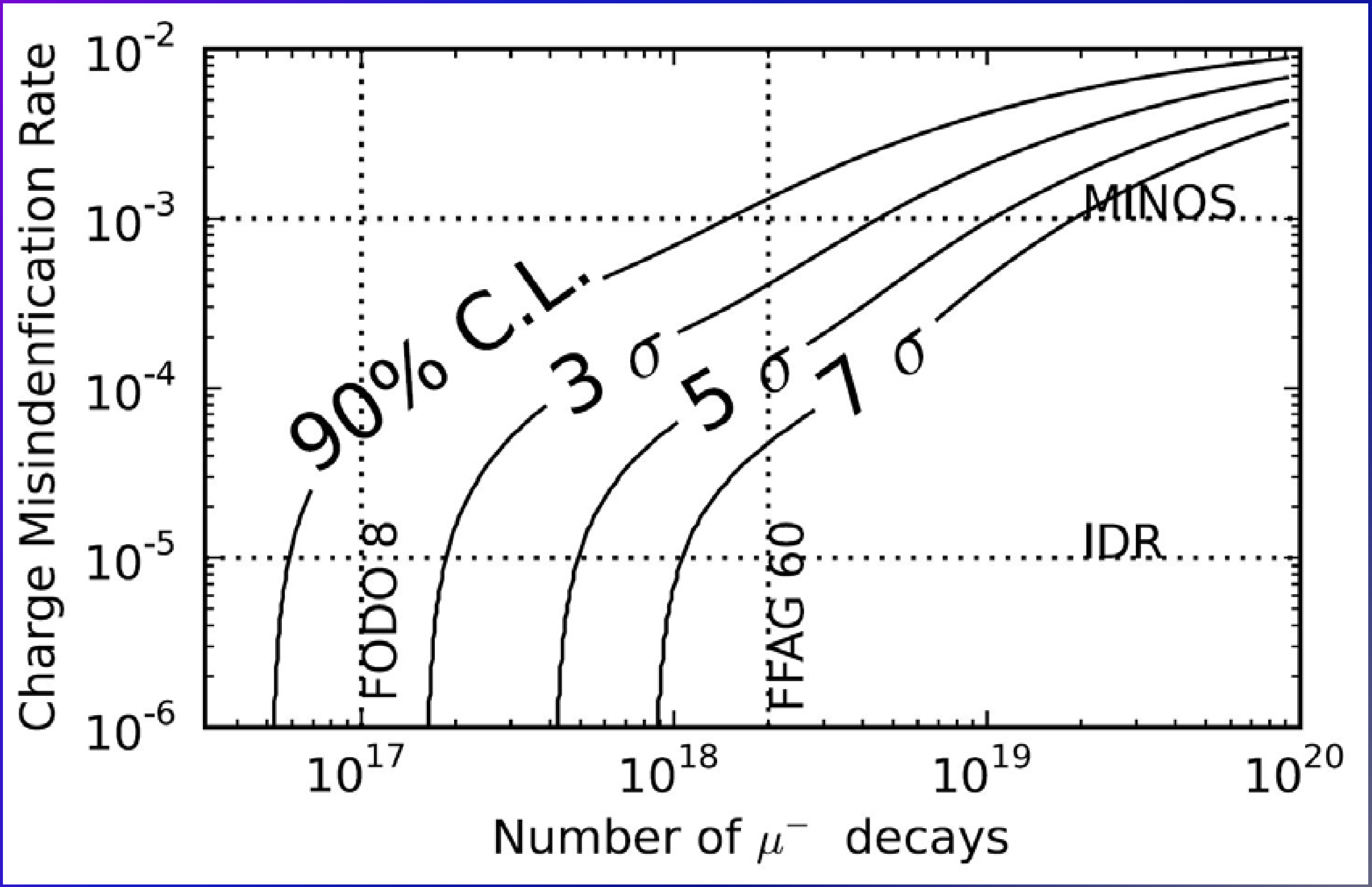
Detector Options

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

Sensitivity in m charge mis-ID rate - # m plane

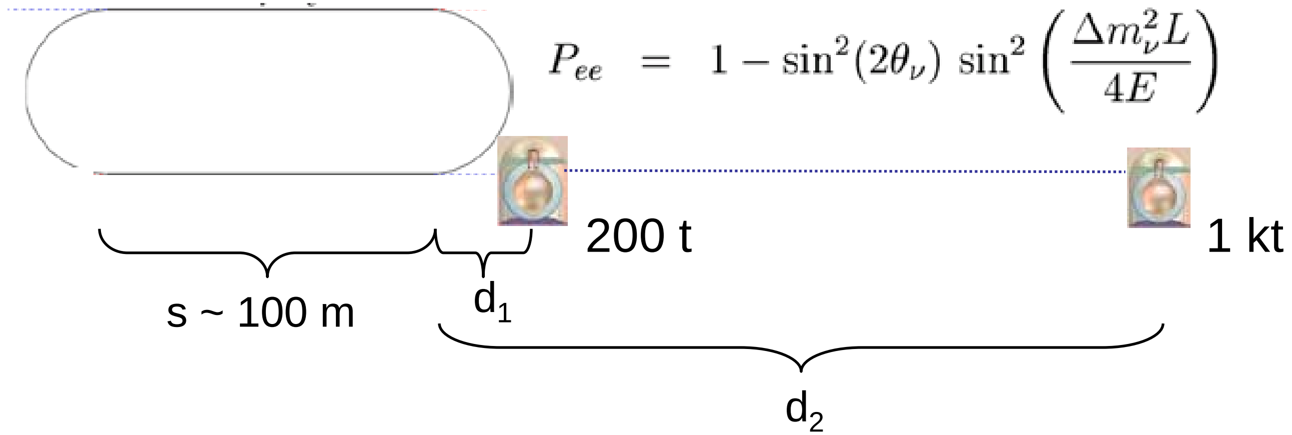


Disappearance Experiments

Disappearance @ VLENF

- Lesson from reactor experiments:
  Near detectors to measure **flux x cross sections**

$$P_{ee} = 1 - \sin^2(2\theta_\nu)\, \sin^2\left(\frac{\Delta m_\nu^2 L}{4E}\right)$$



Detectors:
D ~ 6 m
100% eff.
E_{res} ~ $0.1\sqrt{E}$

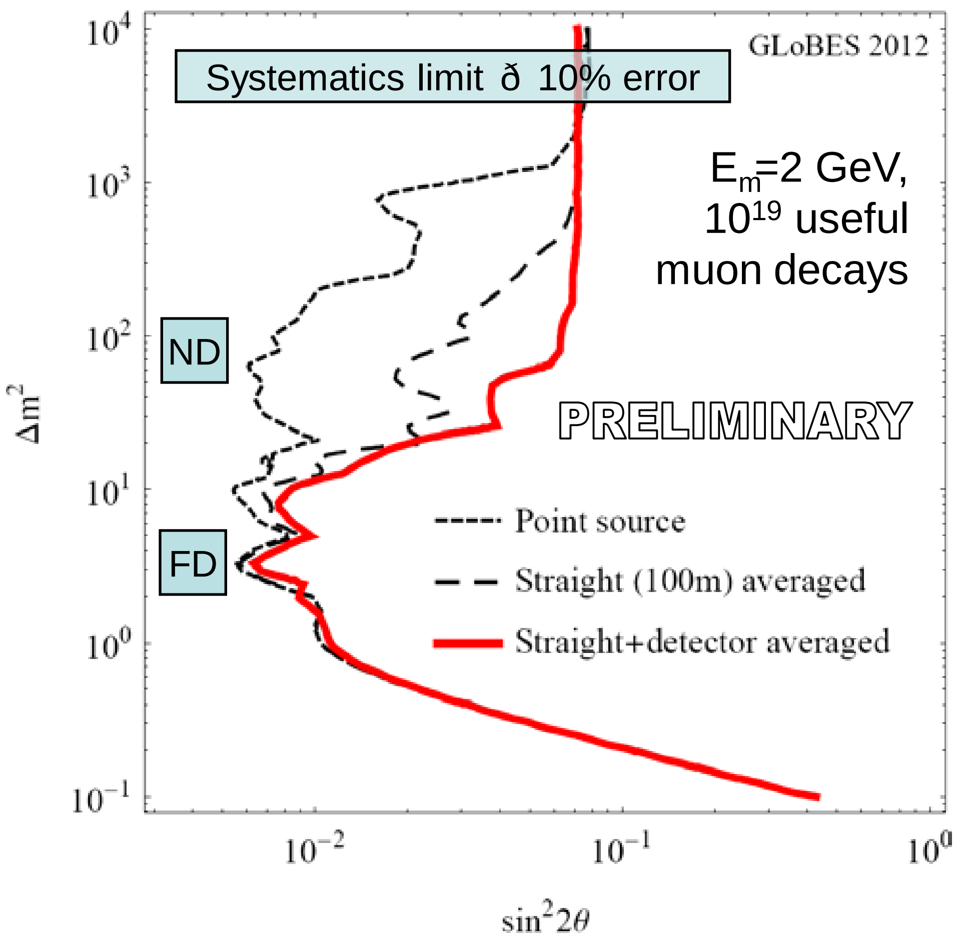
- The challenge: there may be oscillations already in near detectors

Ø Self-consistent two-detector simulation including (bin-to-bin) uncorrelated shape error ~ 10%

(Concepts: Tang, Winter, arXiv:0903.3039; Giunti, Laveder, Winter, arXiv:0907.5487)

Geometry, optimization

20m+500m (Point A)

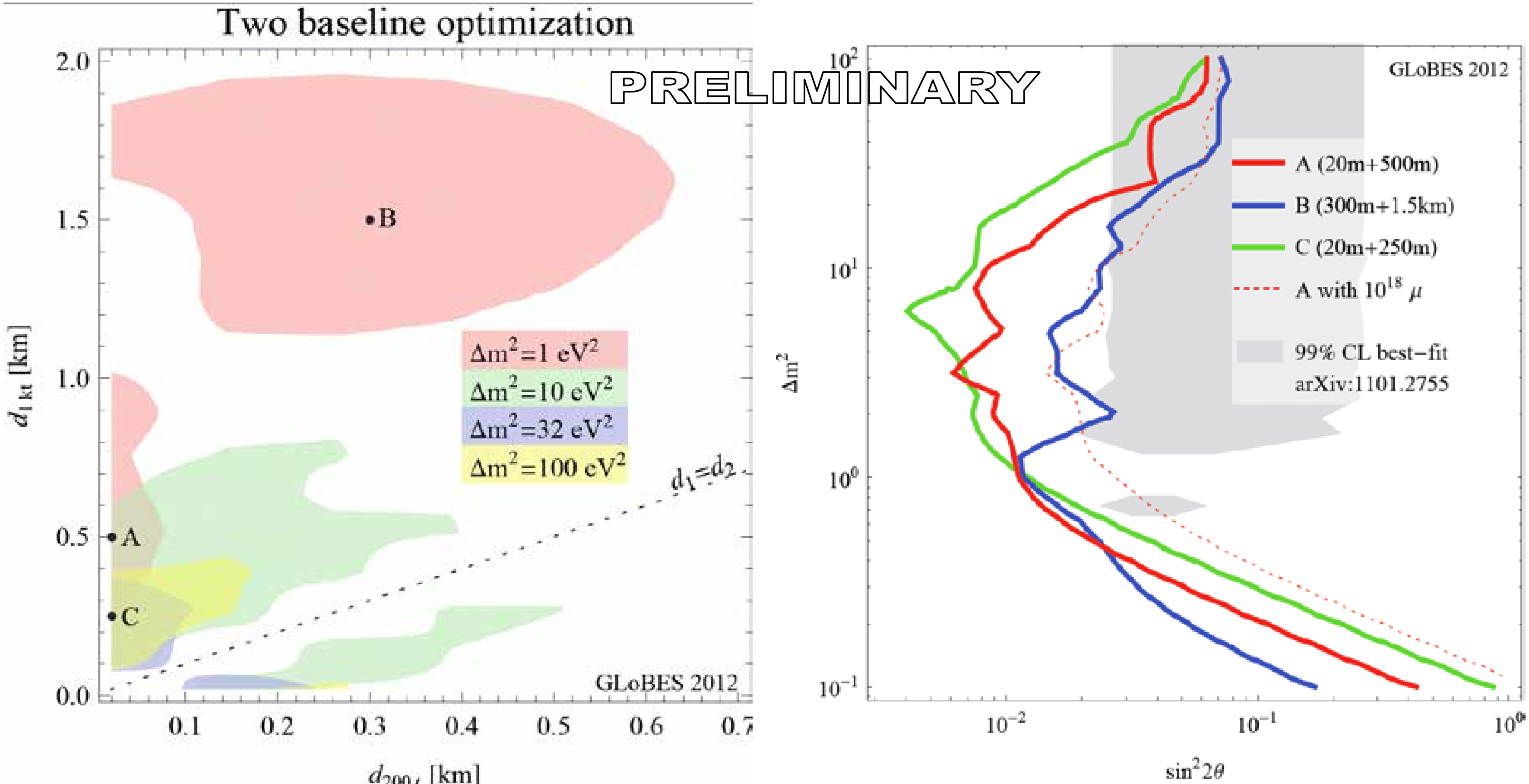


(Winter, work in progress)

- § Geometry important for Dm^2 ~ 10^1 – 10^3 eV^2
  (here: ideally collimated beam, muon decay kinematics only!)
- § Systematics (flux x cross secs) limits measurement for Dm^2 >> 10^2 eV^2
  - Ø How can one improve that?
    (NB: oscillation in ND!?)

Conclusions

(Winter, work in progress)



- Optimal setup: ND as close as possible to source, FD ~ 250-500m **(20+500m OK for appearance; Cobb, Tunnell, Bross, arXiv:1111.6550)**
- Need >> 10^{18} useful muon decays to fully exclude best-fit
- Muon neutrino disappearance: conclusions similar