Neutrinos from Stored Muons
nSTORM

n physics with a μ storage ring

Fermilab

Outline

- Introduction/Motivation
- Facility
- SBL oscillation physics
- Neutrino interaction physics possibilities
  - Jorge covered this very nicely on Wednesday, so I will be brief
- Project Considerations

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
- nuSTORM can:
  - Address the large Dm^2 oscillation regime and make a major contribution to the study of sterile neutrinos
    - Either allow for precision study (in many channels), if they exist in this regime
    - Or greatly expand the dis-allowed region
  - Make precision n_e and n_e-bar cross-section measurements
    - In general, possibly offer a paradigm shift in the study of neutrino interactions
  - Provide a technology test demonstration (mdecay ring) and m beam diagnostics test bed for future facilities (NF and/or MC)
  - Provide a precisely understood n beam for detector studies

m-based n beams

Well-understood neutrino source:

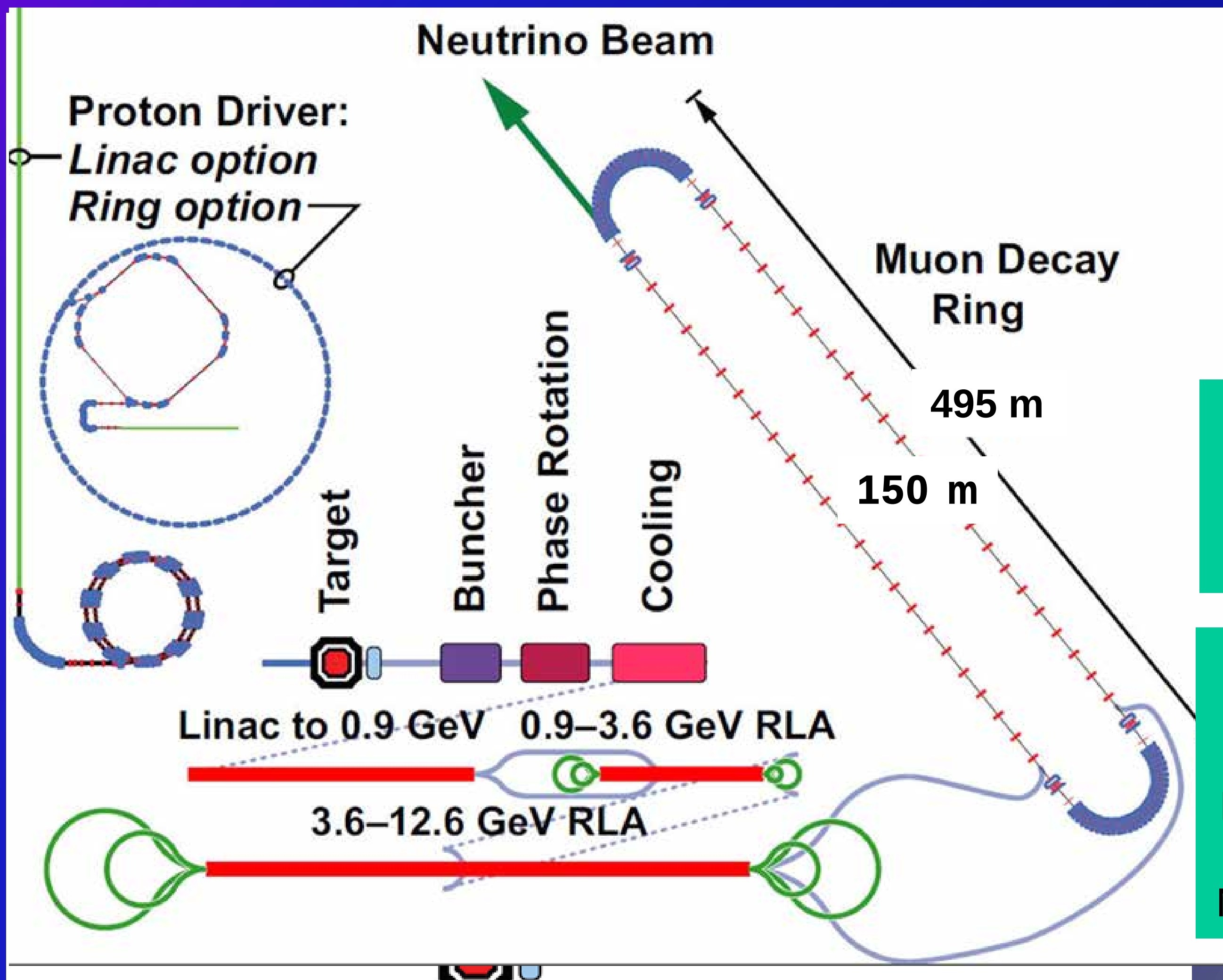
μ Decay Ring:

$$m^{+} ® e^{+}\bar{n}_{m}n_{e}$$

$$m^{-} ® e^{-}n_{m}\bar{n}_{e}$$

- Ø Flavor content fully known
- Ø "*Near Absolute*" (1% ® 0.1%) Flux Determination is possible in a storage ring
  - ø Beam current, m_p spectrometer & beam divergence monitor,
  - ø Overall, there is tremendous control of systematic uncertainties with a well designed system

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

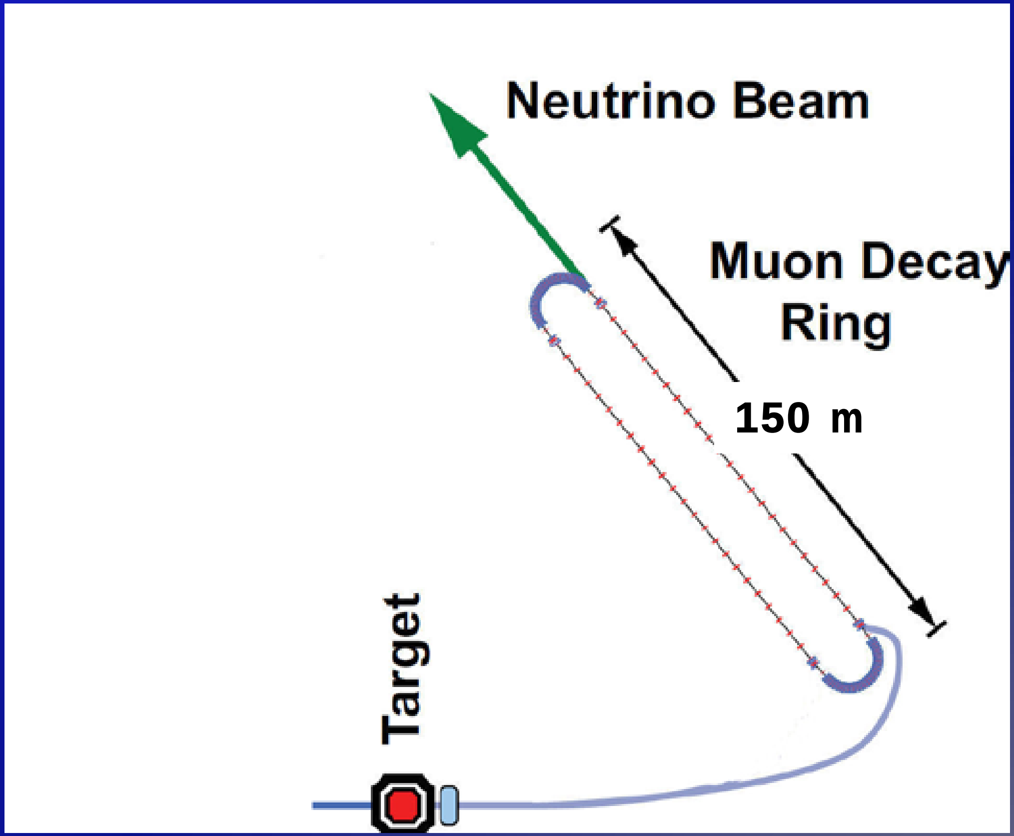


This is the simplest implementation of the NF

And DOES NOT Require the Development of ANY New Technology

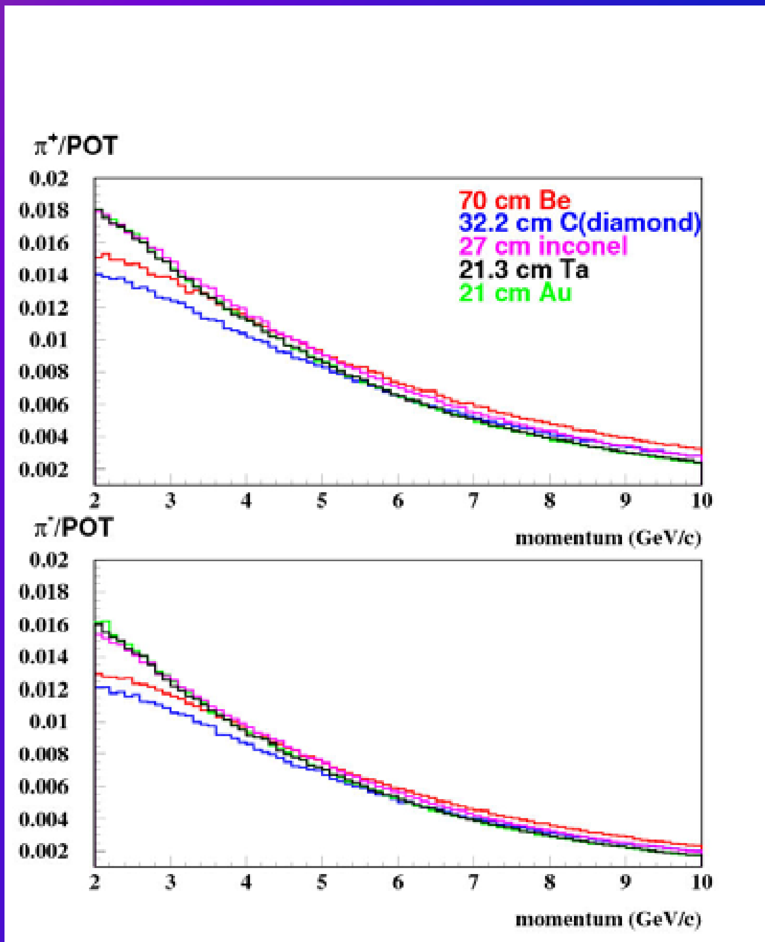
Baseline(s)

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



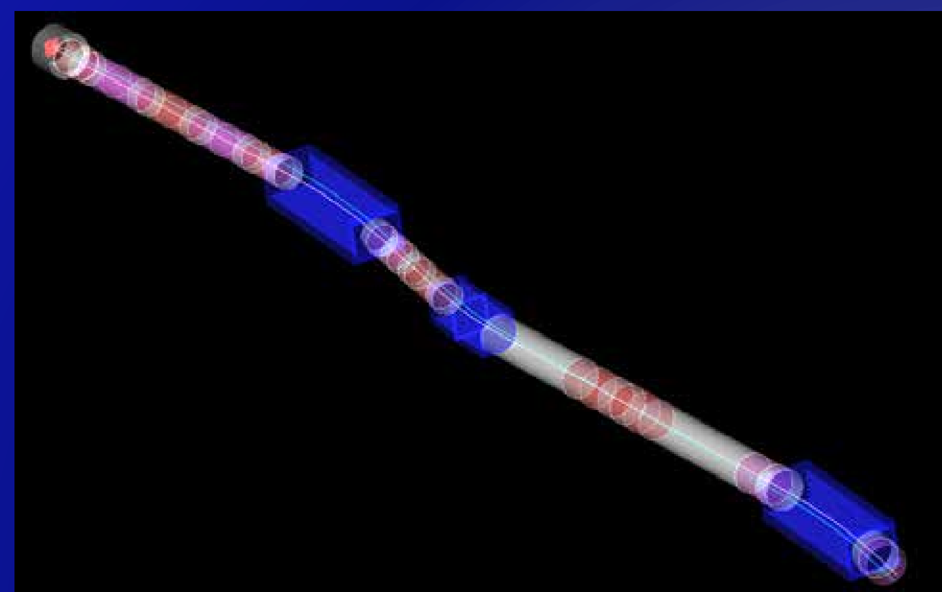
p production

Sergei Striganov
Ao Liu
Fermilab



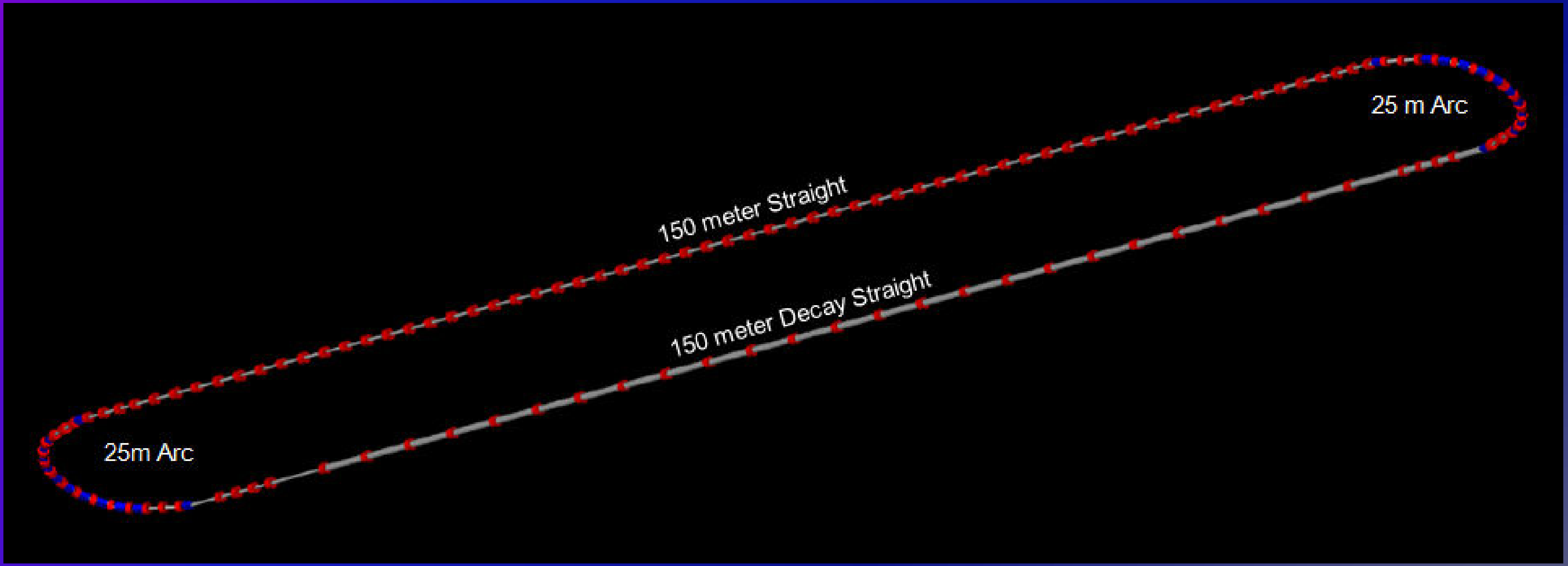
In momentum range
4.5 < 5.0 < 5.5
Obtain
» 0.11 p±/pot
with 60 GeV p

Target/capture optimization ongoing



FODO Decay ring

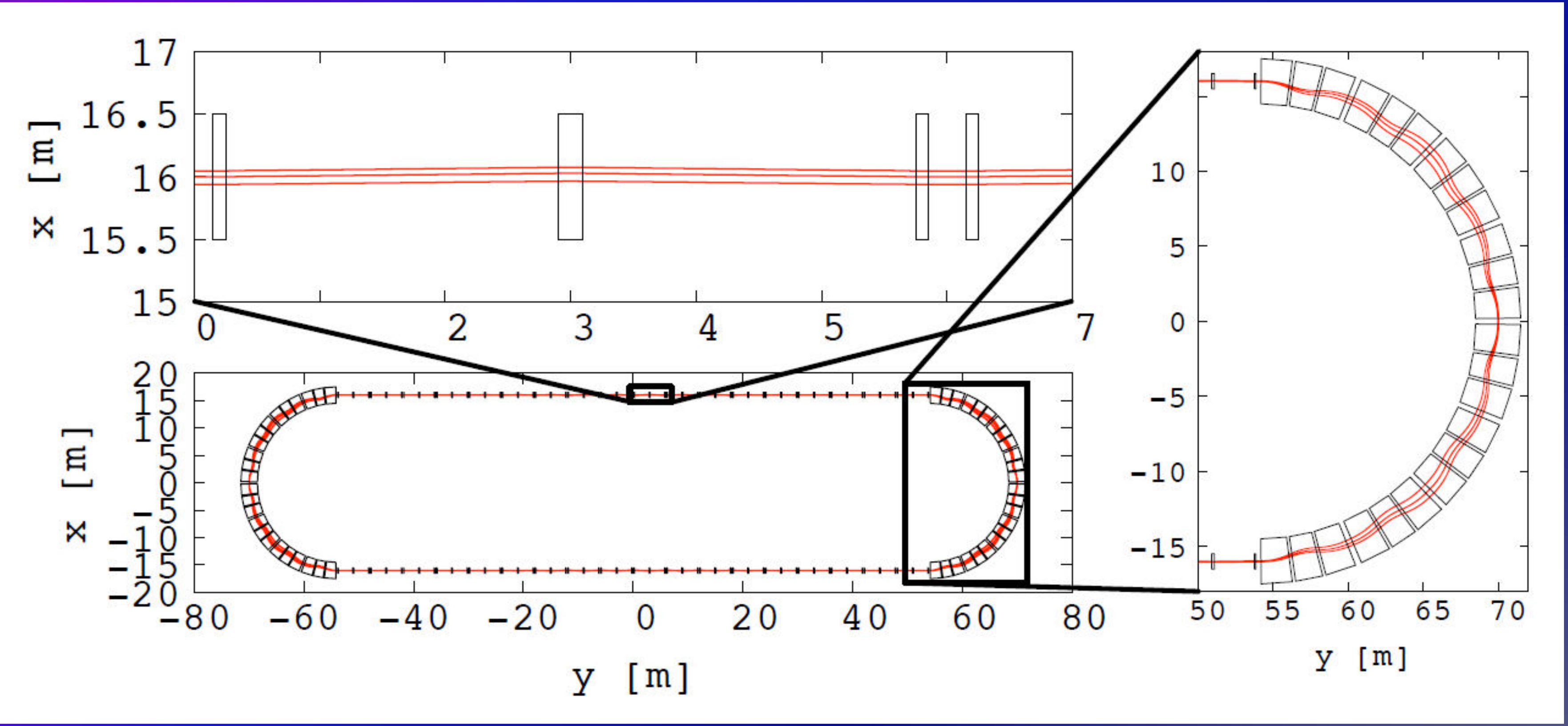
Alex Bogacz
JLAB



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

Y. Mori, JB Lagrange
Kyoto

FFAG Racetrack



dp/p » 15-20%

Low dispersion in straight

3.8 GeV/c

The Physics Reach

Short-baseline oscillation physics

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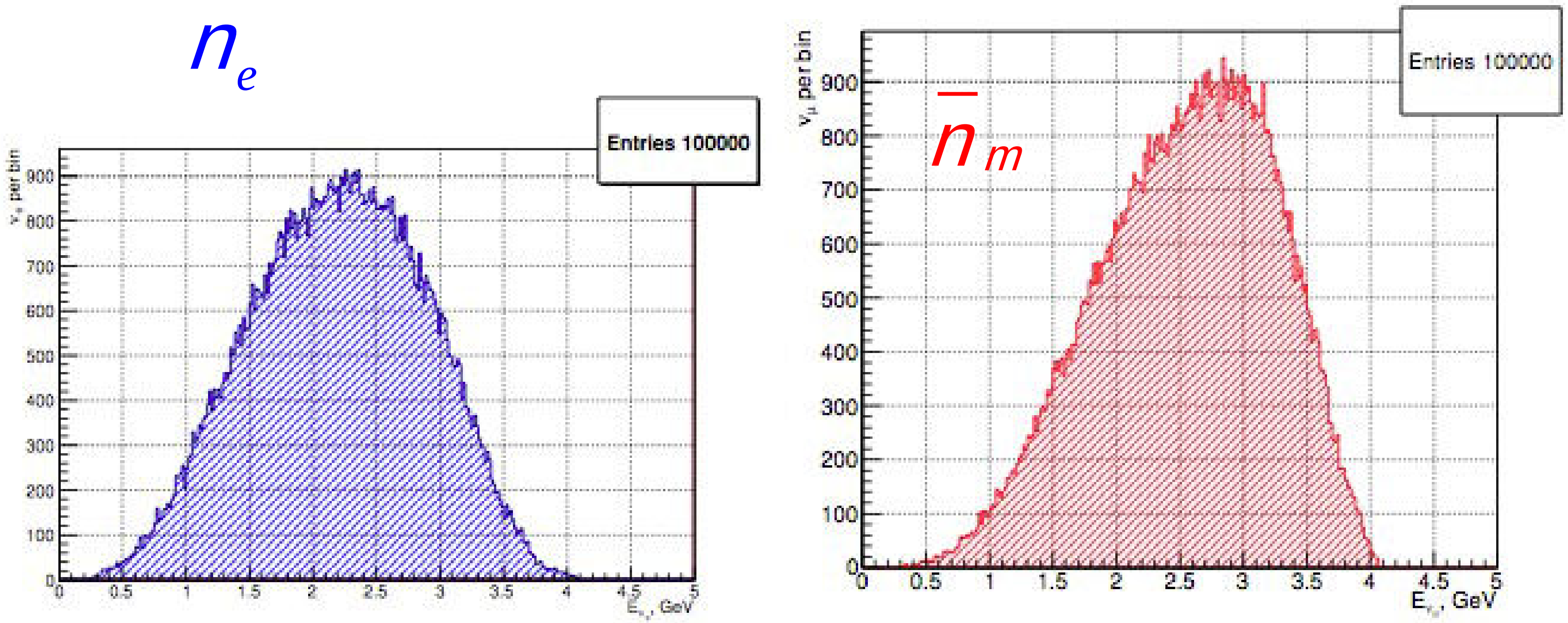
νSTORM

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 (FODO)
  - Ø $e_{collection}$ = 0.8 þ
  - Ø e_{inj} = 0.8 þ
  - Ø m/p = 0.08 (gct X mcapture in p ® mdecay) [p decay in straight]
  - Ø $A_{dynamic}$ = 0.75 (FODO)
  - Ø W= Straight/circumference ratio (0.43) (FODO)
- Ø This yields » 1.7 X 10^{18} useful mdecays

Ao Liu
Fermilab/UI

E_ν spectra (μ^+ stored)

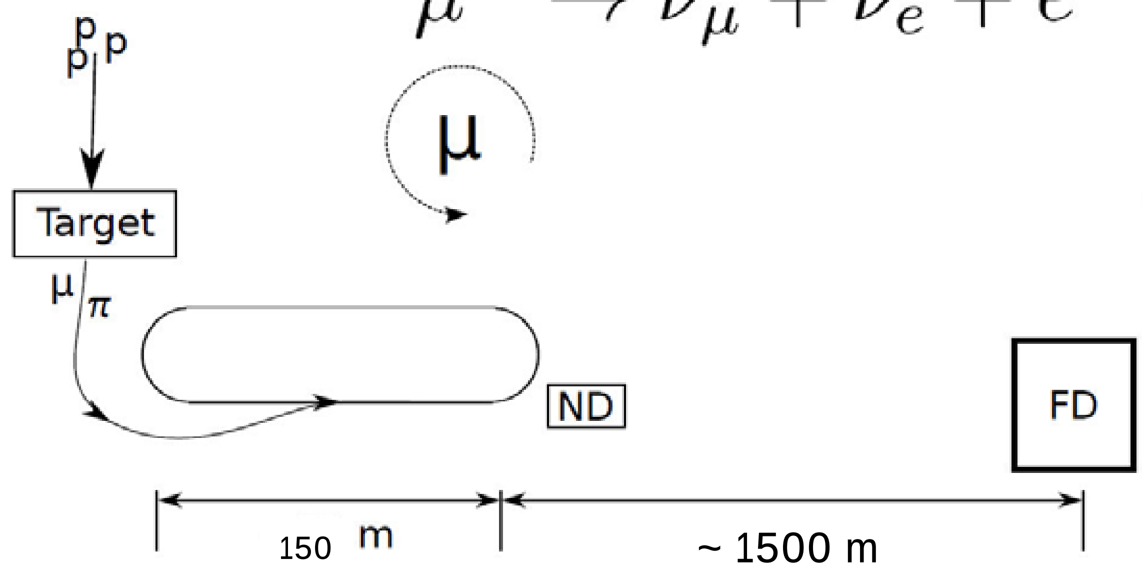


Integrated over the 150 m straight at a position 50m from the end of the straight with 3m diameter detector

NOTE: The transport line and ring could be re-tuned for 2 GeV/c μ and move these spectra lower by $\approx$ a factor of two with some drop in μ production efficiency

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

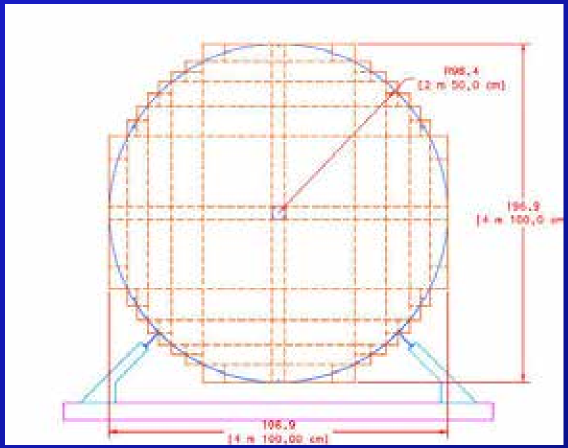
Must reject the "wrong" sign mwith great efficiency

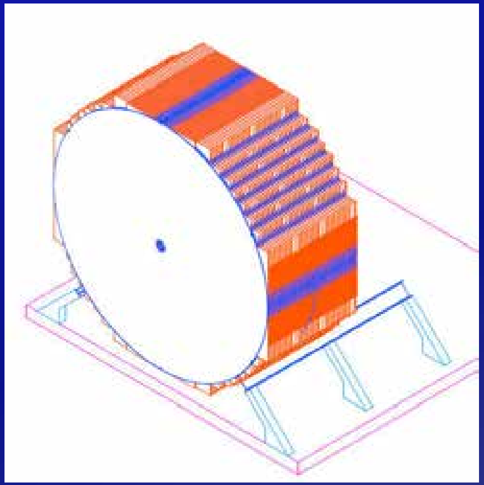
Why n_m® n_e Appearance Ch. *"not"* possible

Baseline Detector

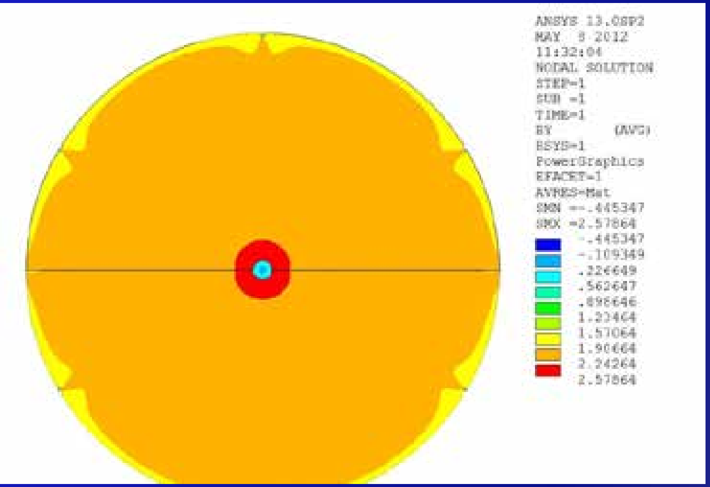
Super B Iron Neutrino Detector: SuperBIND

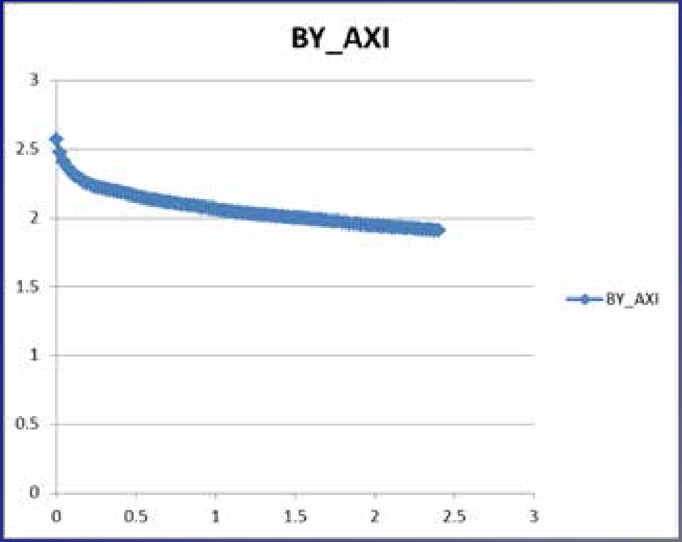
- Magnetized Iron
  - 1.3 kT
    - Following MINOS ND ME design
    - 1-2 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM





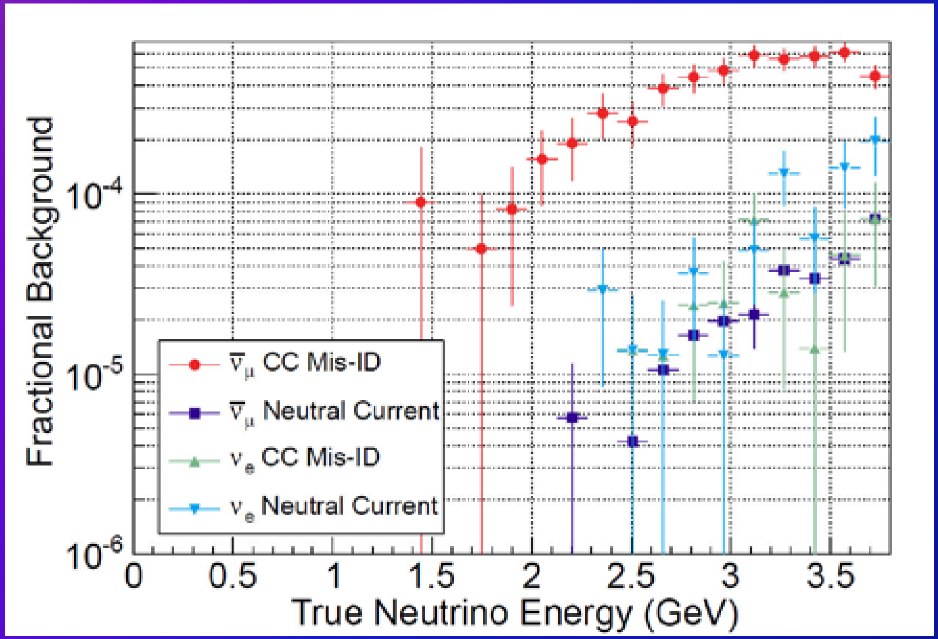
20 cm hole
For 6-8 turns
of STL

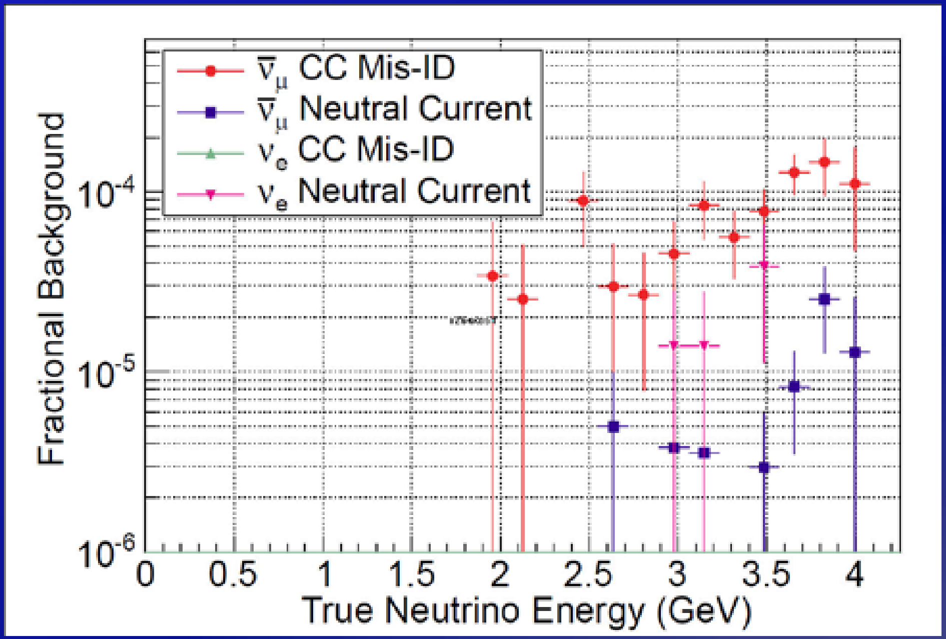




Backgrounds

Ryan Bayes
Glasgow

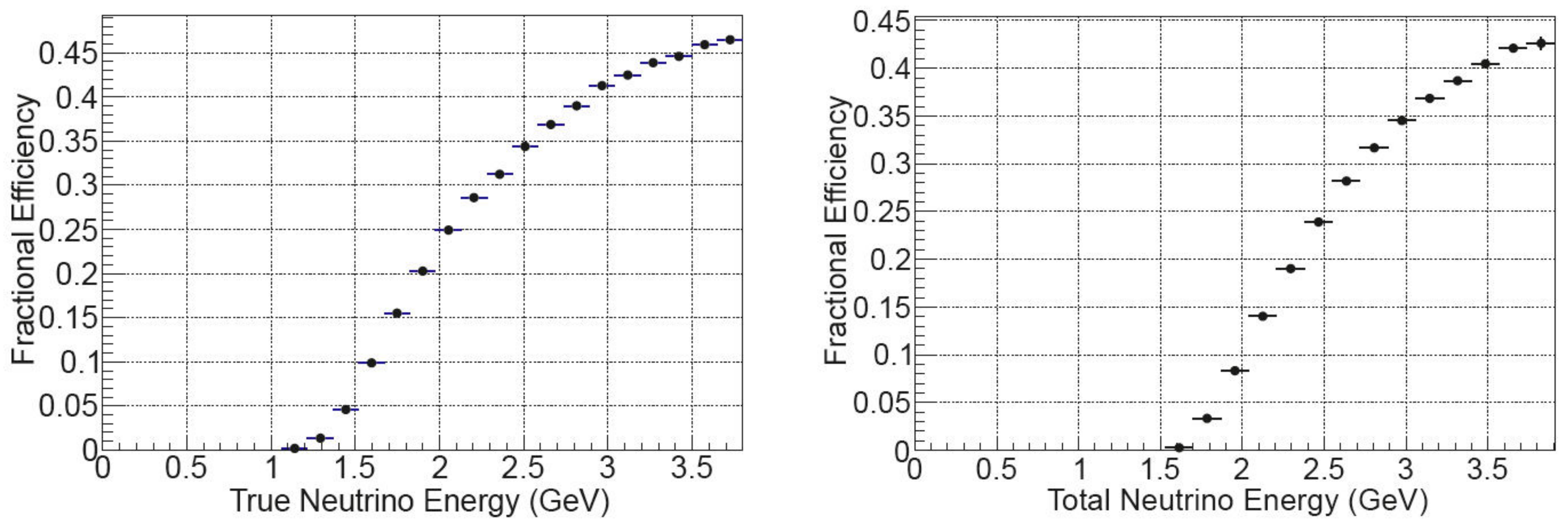




Left: 1 cm plates

Right: 2 cm plates

Event reconstruction efficiency



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

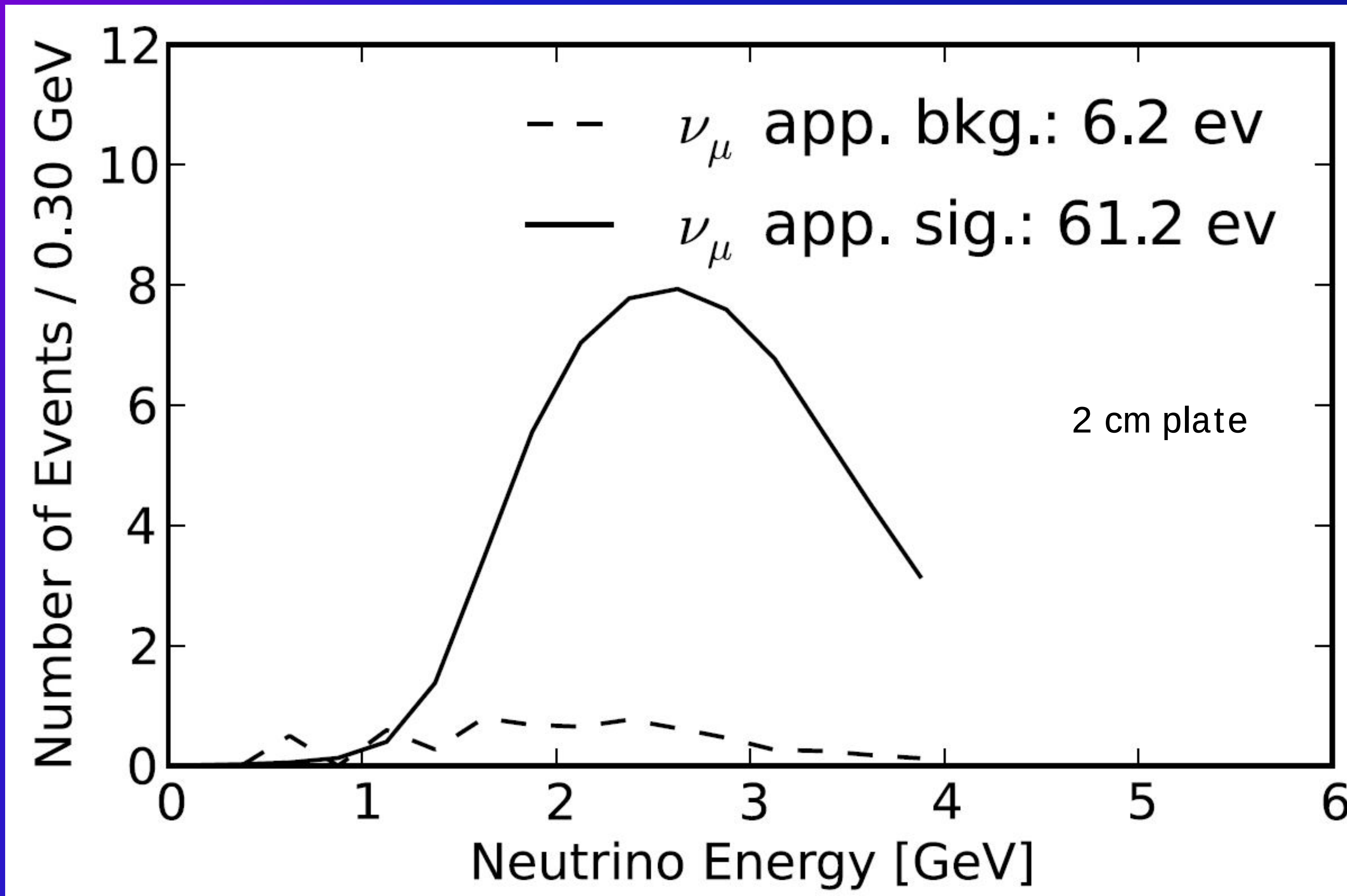
Anti-neutrino mode with stored μ^-.

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

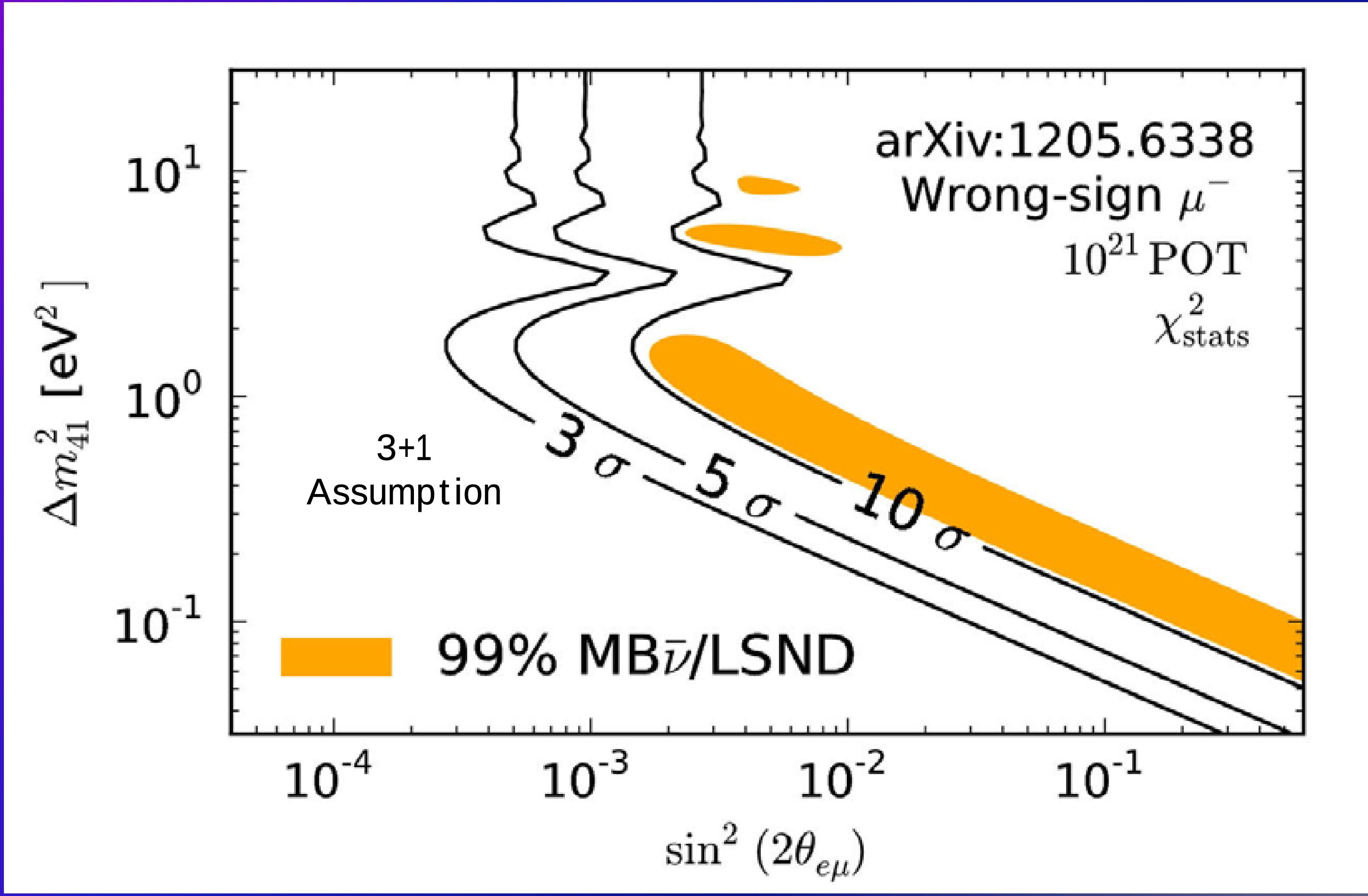
Appearance channels

n_e ® n_m appearance
CPT invariant channel to MiniBooNE

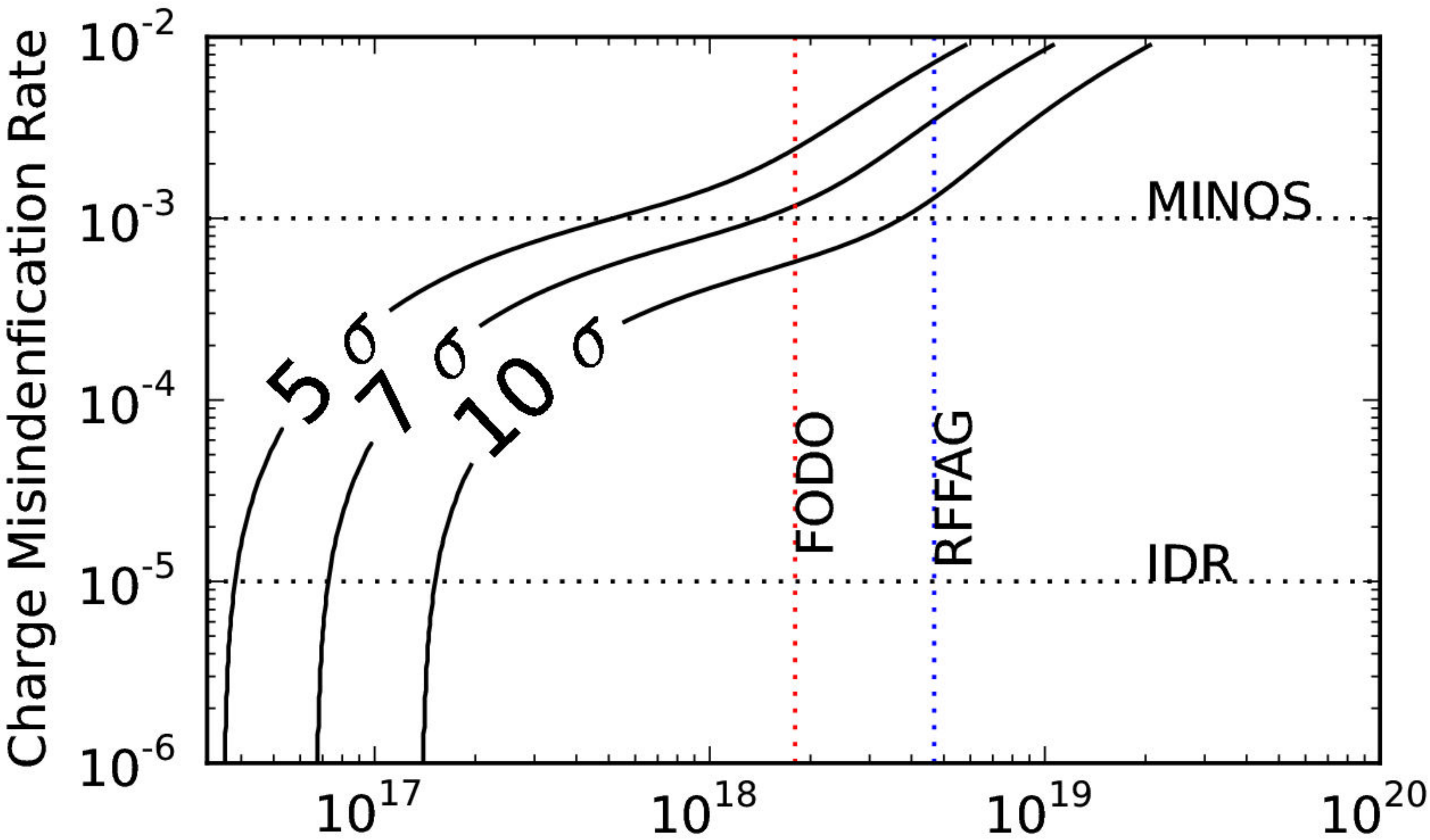


n_e ® n_m appearance
CPT invariant channel to LSND/MiniBooNE

Chris Tunnell
Oxford



Required mcharge mis-ID rate needed for given sensitivity



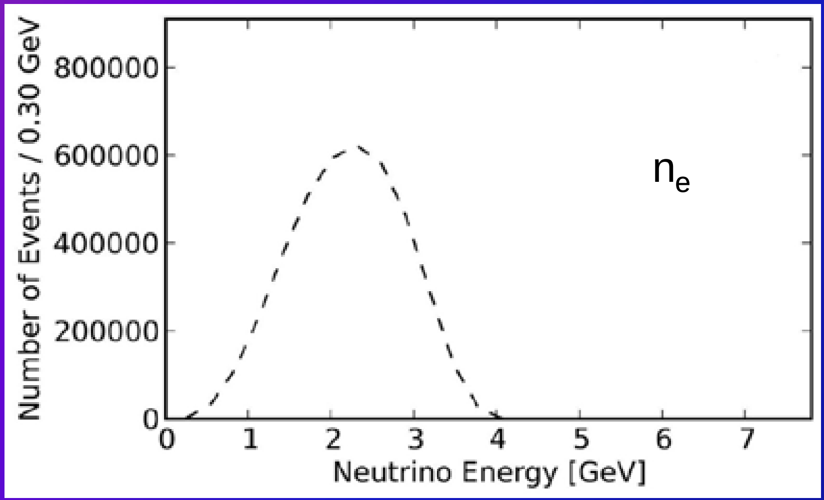
Comments on n beam

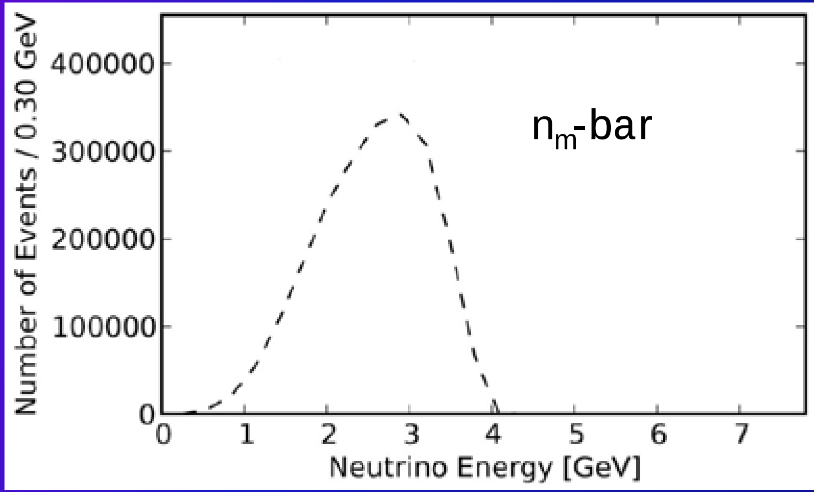
- Although the primary beam is from m decay, at the beginning of p injection into the first straight, p ® mn_m may offer the opportunity to study n_m ® n_e appearance
  - Capture transport line reduces n_e background from K decay by factor of roughly 100
    - Left only with n_e from mdecay

ν Interaction Physics

Possibilities at a Near Detector Hall

E_n spectra (m+ stored)



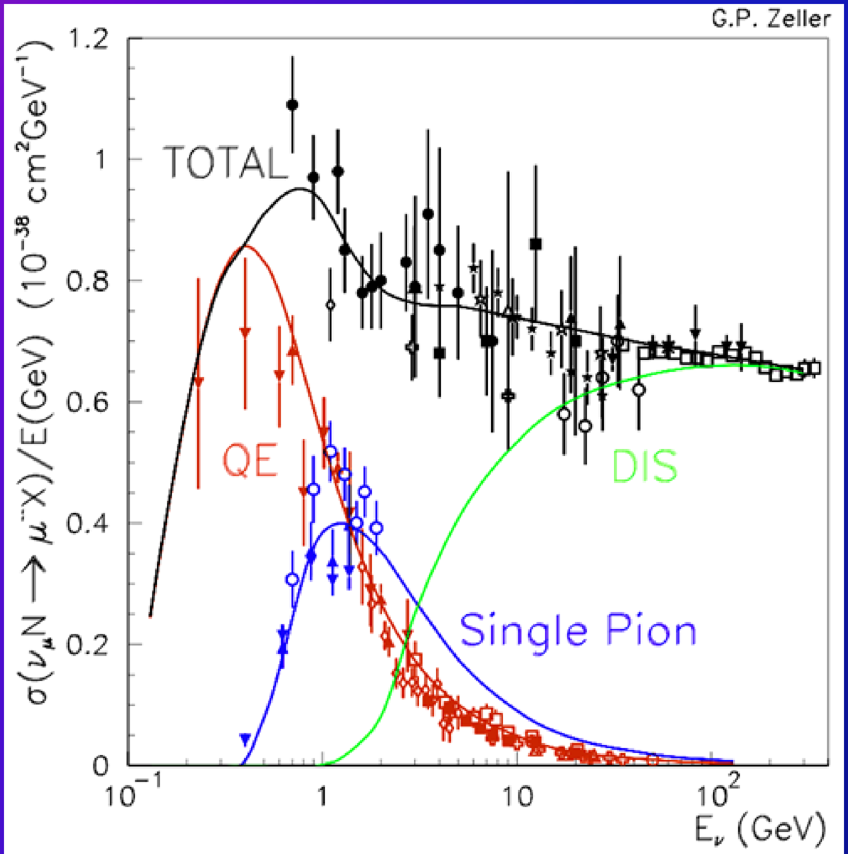


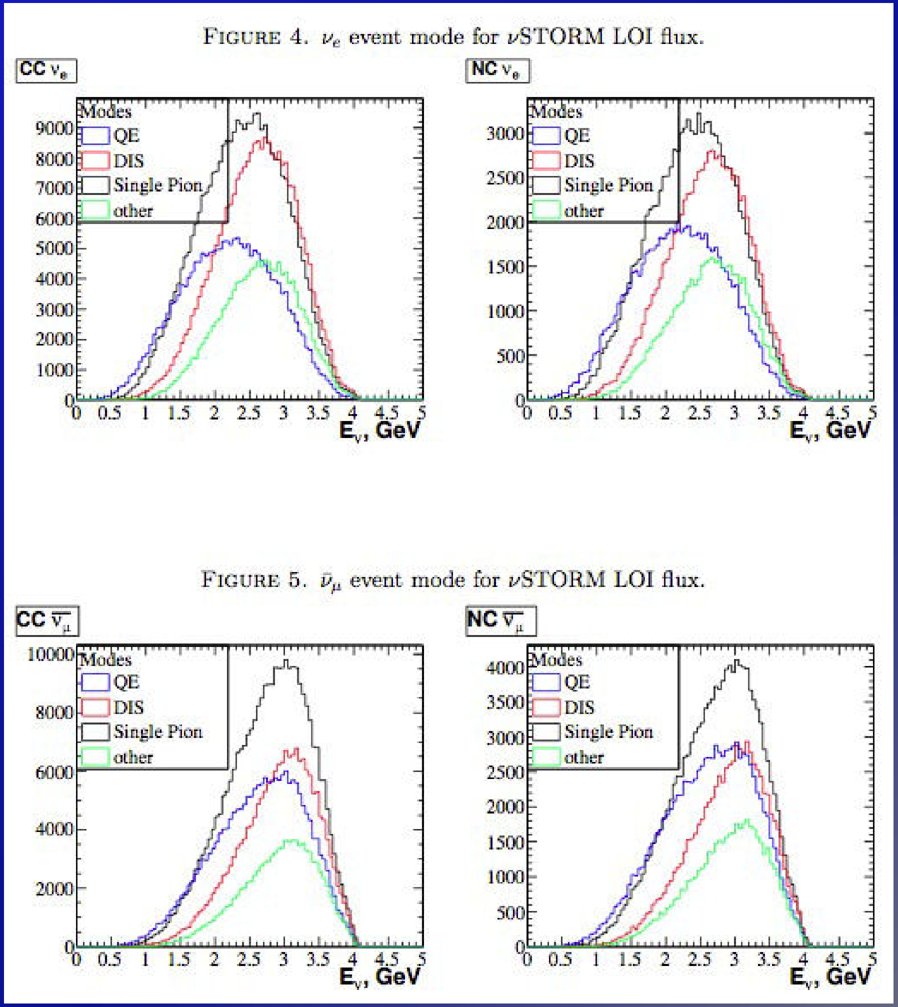
Event rates/100T at ND hall 50m from straight with m+ stored

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

Final States

Edward Santos
Imperial





n interaction physics with nuSTORM

Ø nuSTORM can deliver a n beam with unprecedented control over systematics

Ø The strength of the physics will depend on the detector(s) and their design

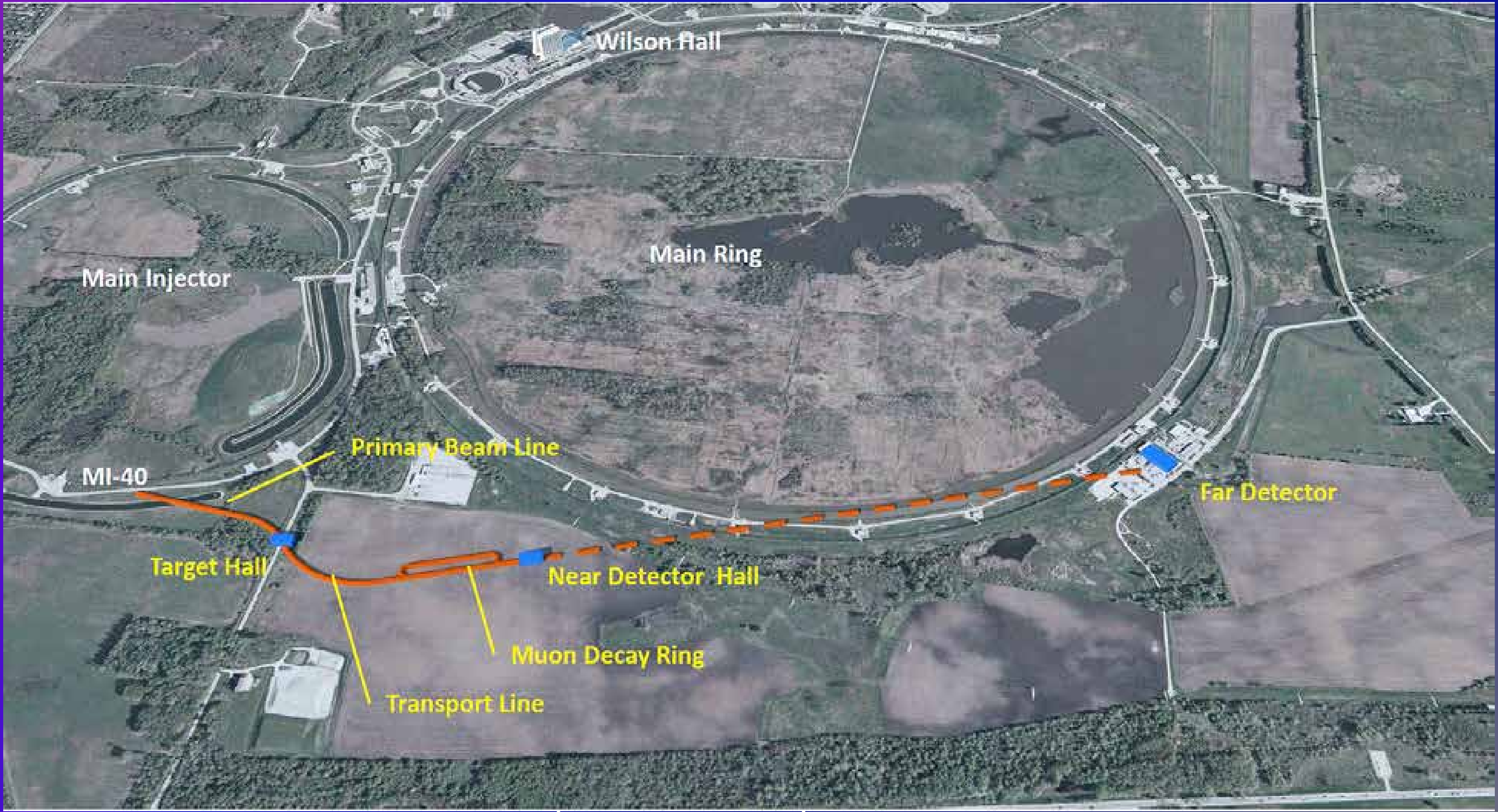
Ø Near detector studies for the IDS-NF and LBNE already point to some very powerful options

  - Ø LAr
  - Ø HighRes

Ø Detailed simulation studies are just beginning

Project Considerations

Siting Concept



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Preliminary Cost Estimate

- Major Components

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, NuMI 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.

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Moving Forward

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Moving Forward

ØOptimize the 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, 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 II

- Ø 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.
  - n interaction physics need detector baseline design
    - Learn much from detector work for LBNE & IDS-NF
      - Increased emphasis on n_e interactions, however
- Ø Produce Full Proposal for June 2013 PAC Mtg.

nuSTORM: 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_m and (n_e) 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 n physics studies with near detector(s) offer a unique opportunity & can be extended to cover 0.2<GeV< E_n< 4 GeV
  - Ø Could be *"transformational"* w/r to n interaction physics

Conclusions II

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

Advertisement

- Interested ® subscribe to NUSTORM mailing list on listserv.fnal.gov

- In the end, nuSTORM will only succeed if there is a large non-US component to the collaboration with commensurate resources
  - ½ the names on the LOI are from non-US institutions: A Good Start!

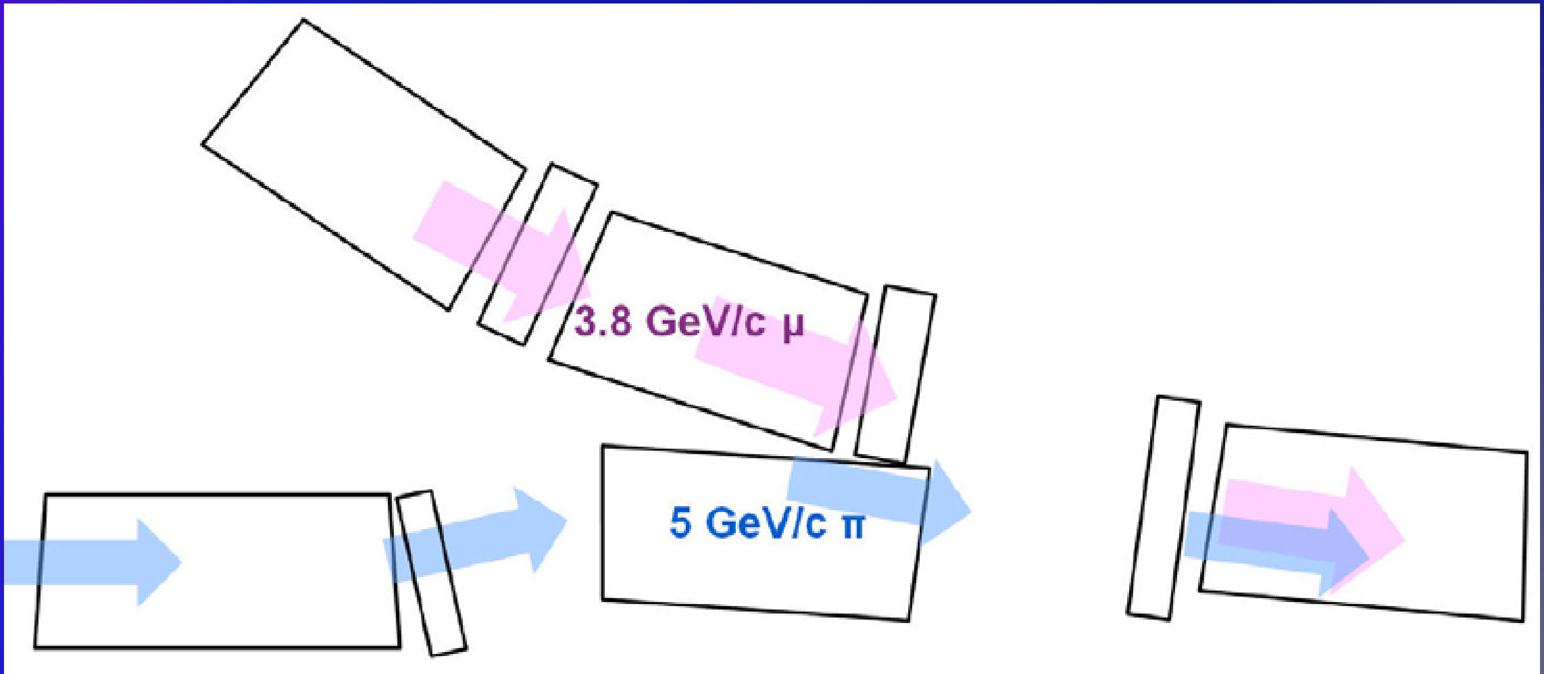
Obrigado

Back Ups

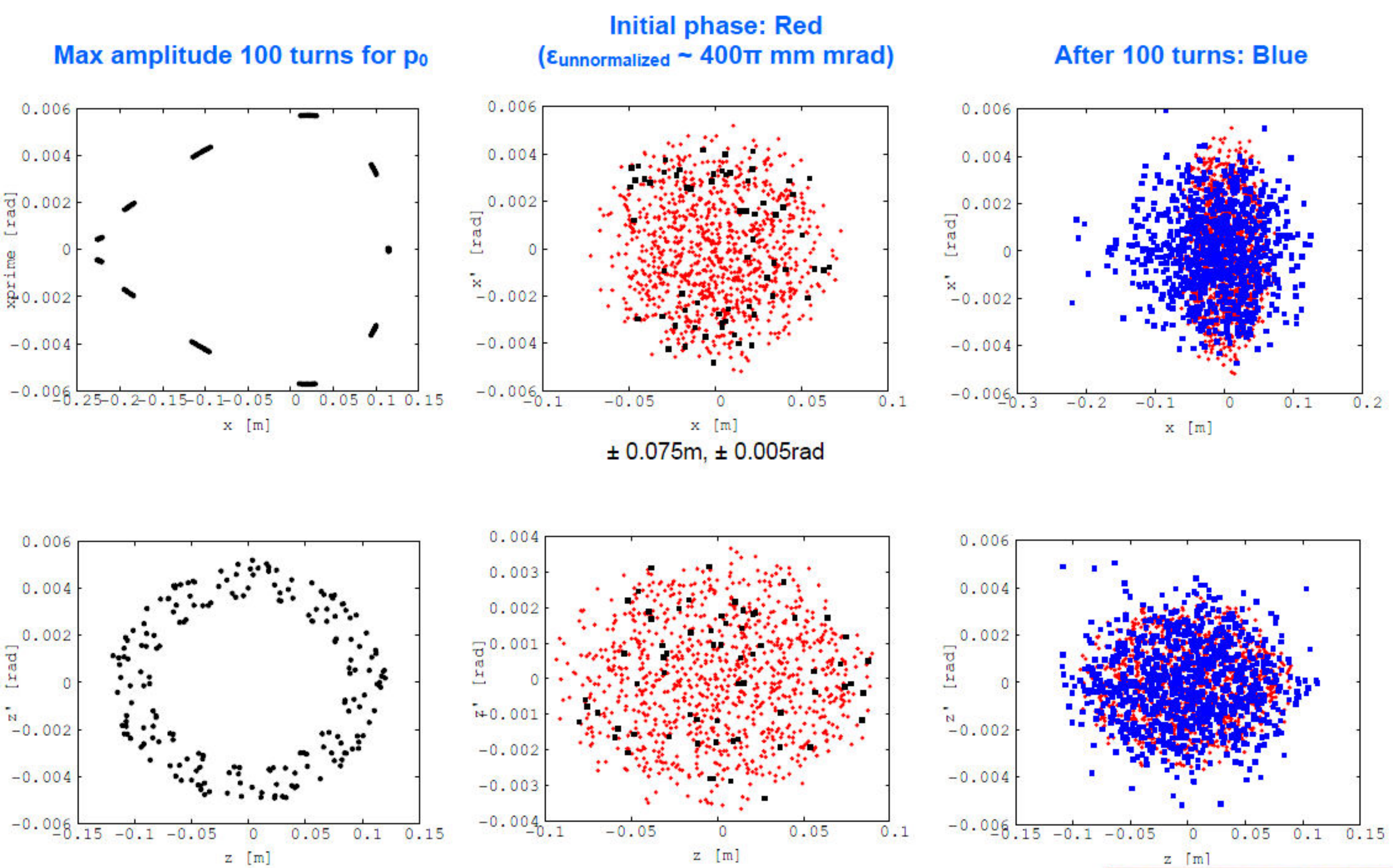
Injection Concept

- 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



FFAG Tracking



± 0.075m, ± 0.005rad

± 0.090m, ± 0.035rad

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

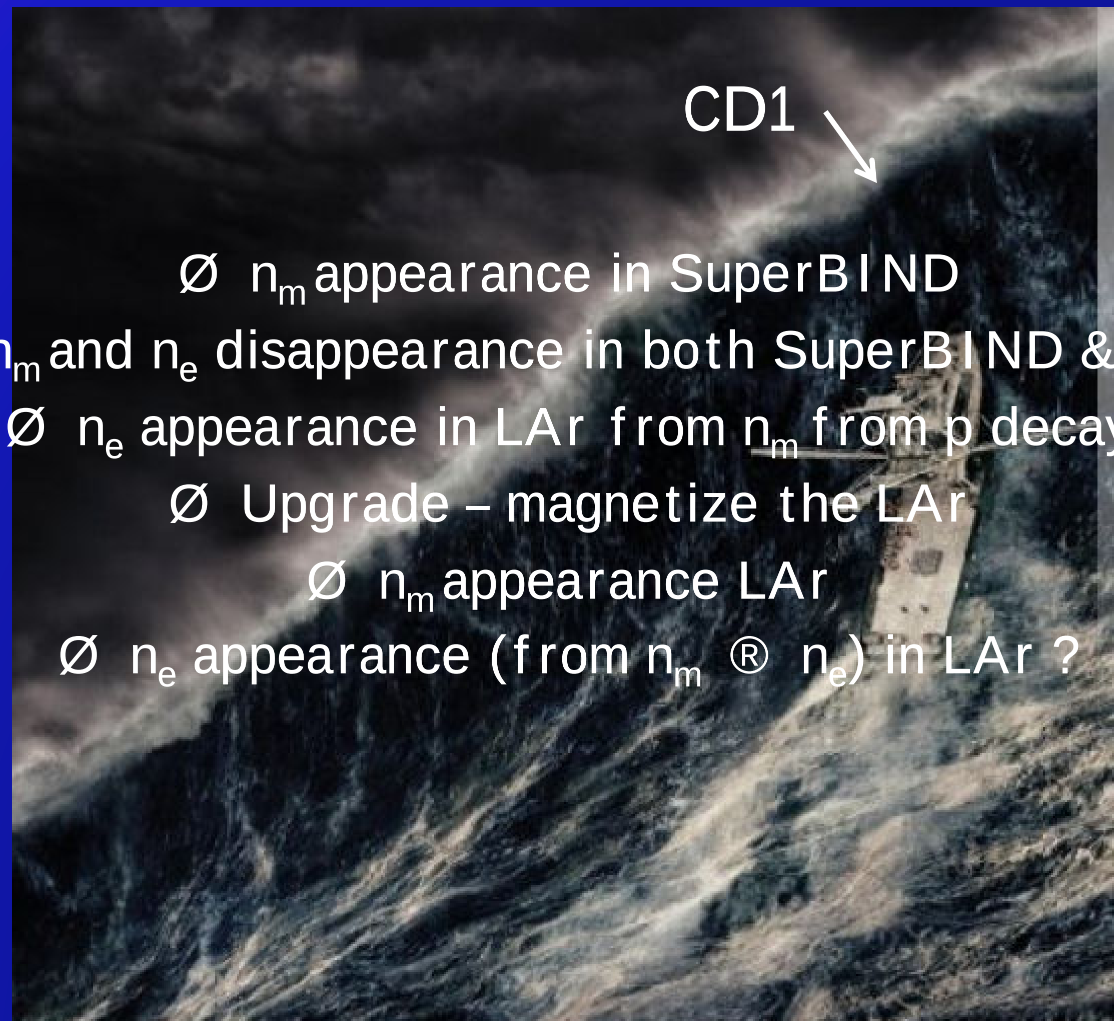
>90% dynamic aperture

A Perfect nuSTORM?

- Ø SuperBIND & a large LAr detector can fit in D0 pit
  - Ø kT-scale each
- 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



CD1

- 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 ?

p collection