Neutrinos from Stored Muons
nSTORM

n physics with a μ storage ring

νSTORM

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, 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 (m decay ring) and m beam diagnostics test bed
  - Provide a precisely understood n beam for detector studies

μ-based ν beams

Well-understood neutrino source:

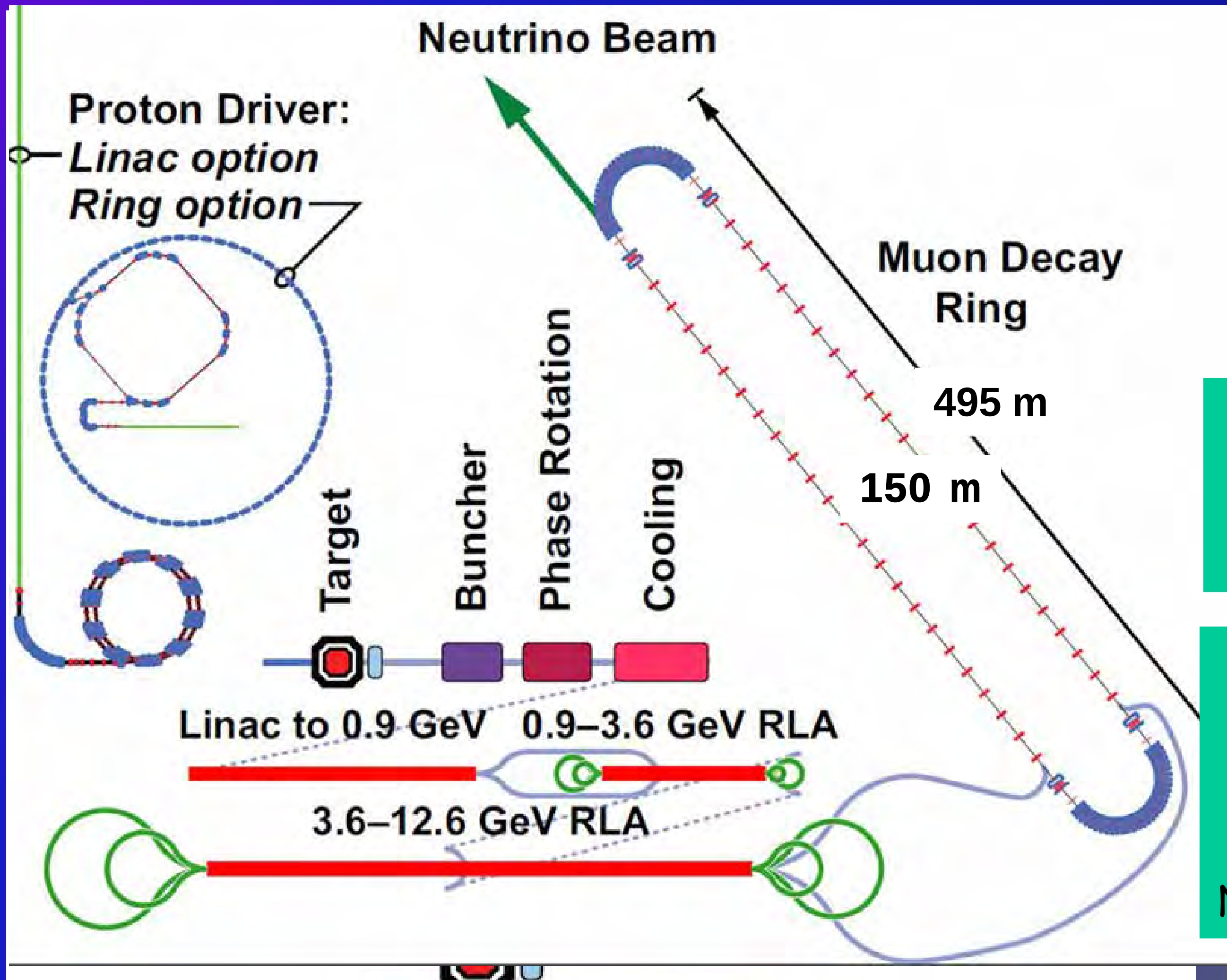
μ Decay Ring:

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

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

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

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

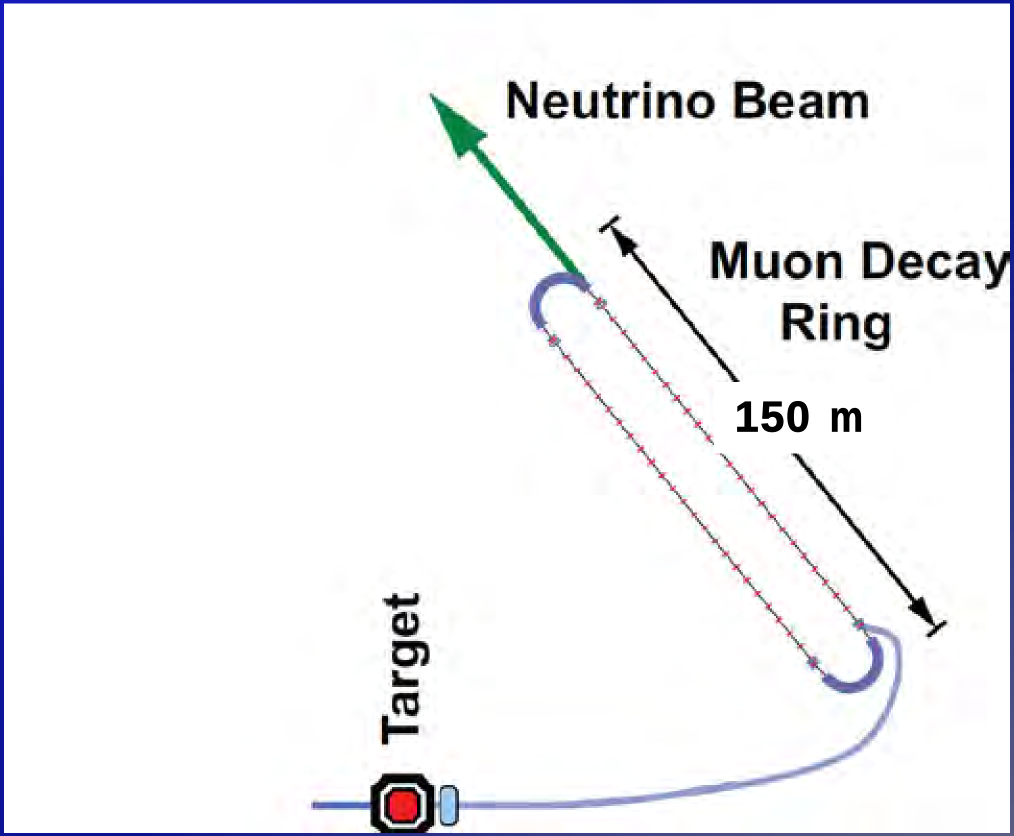


This
is the simplest
implementation
of the NF

And
DOES NOT
Require the
Development of
ANY
New Technology

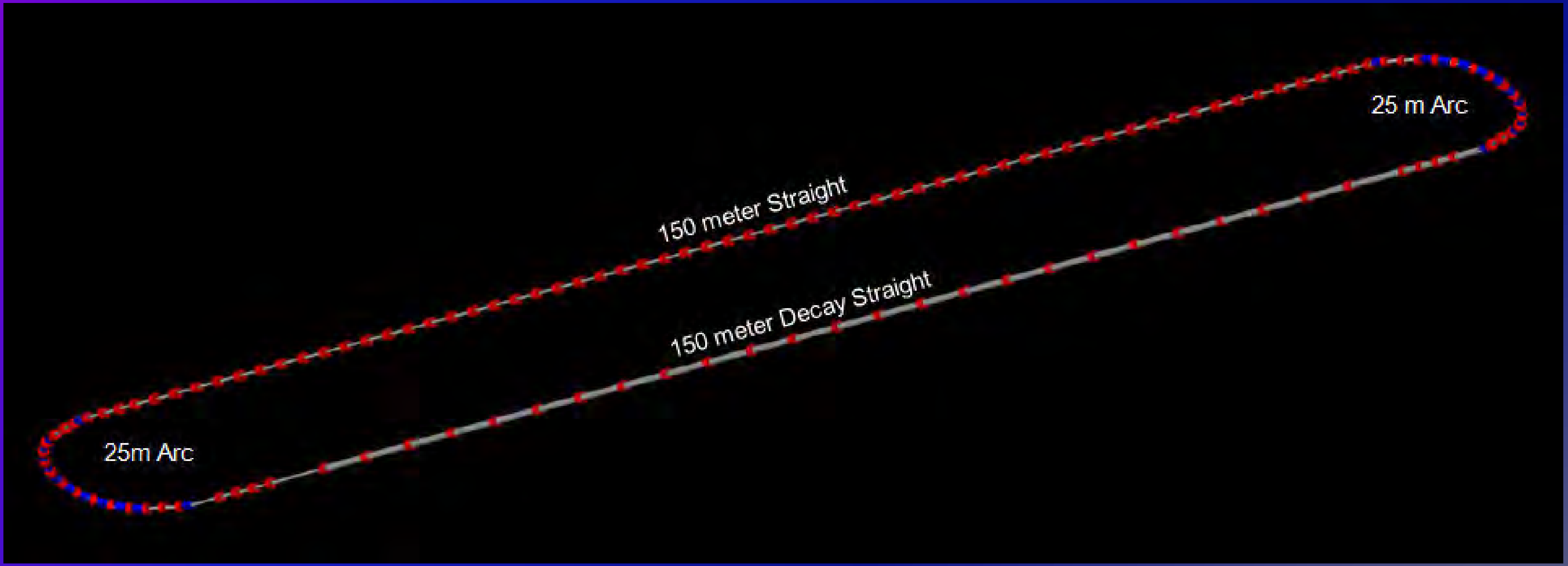
Baseline(s)

- 100 kW Target Station
  - Assume 60 GeV proton
    - Fermilab PIP era
  - Ta target
    - Optimization on-going
  - Horn collection after target
    - 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



FODO Decay ring

Alex Bogacz
JLAB



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

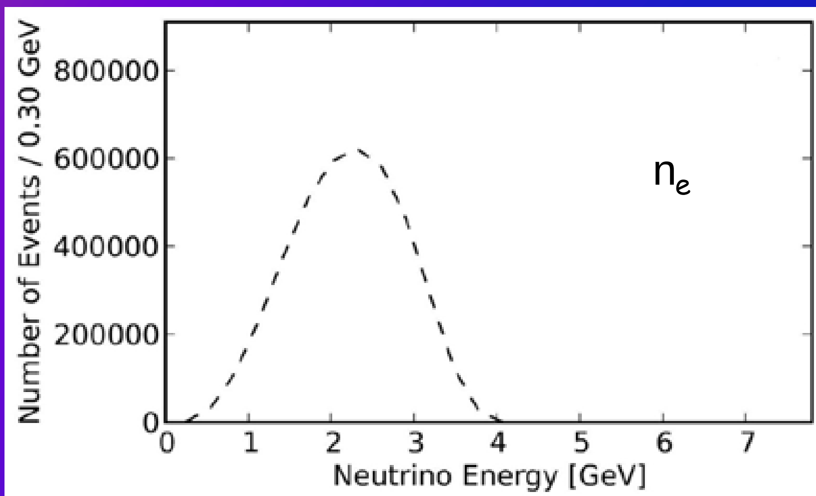
The Physics Reach

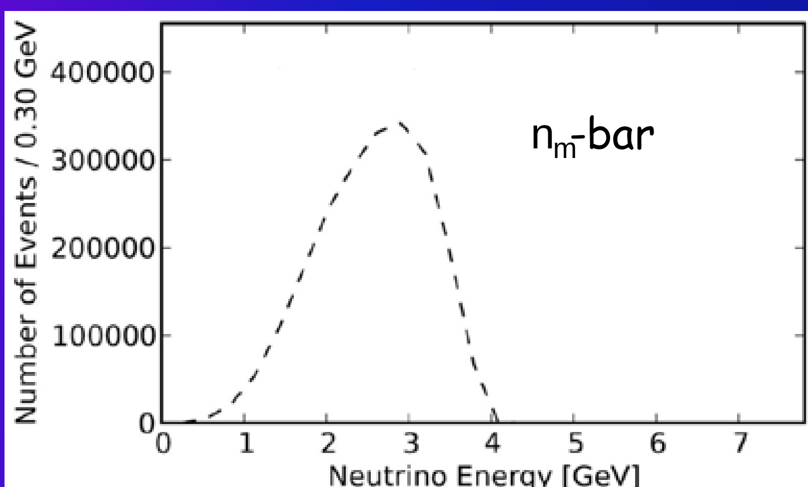
Assumptions

- 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 (FODO)
  - ø $e_{collection}$ = 0.8 b
  - ø e_{inj} = 0.8 b
  - 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

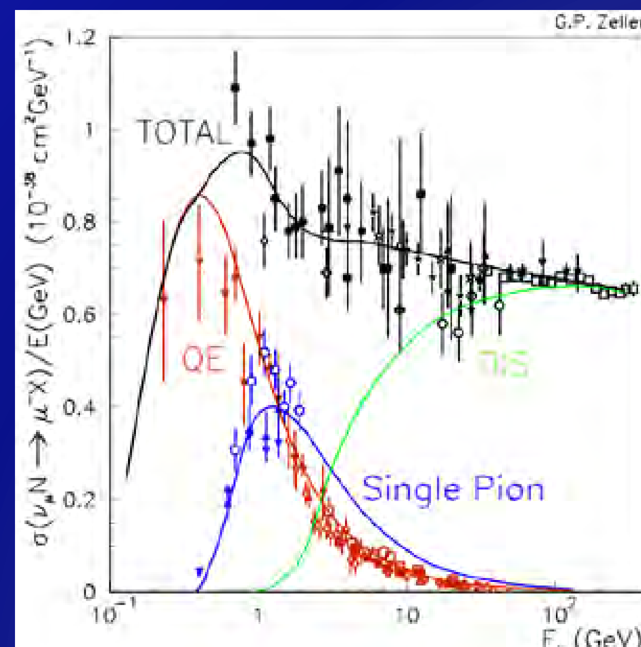
E_n spectra (m^+ stored)





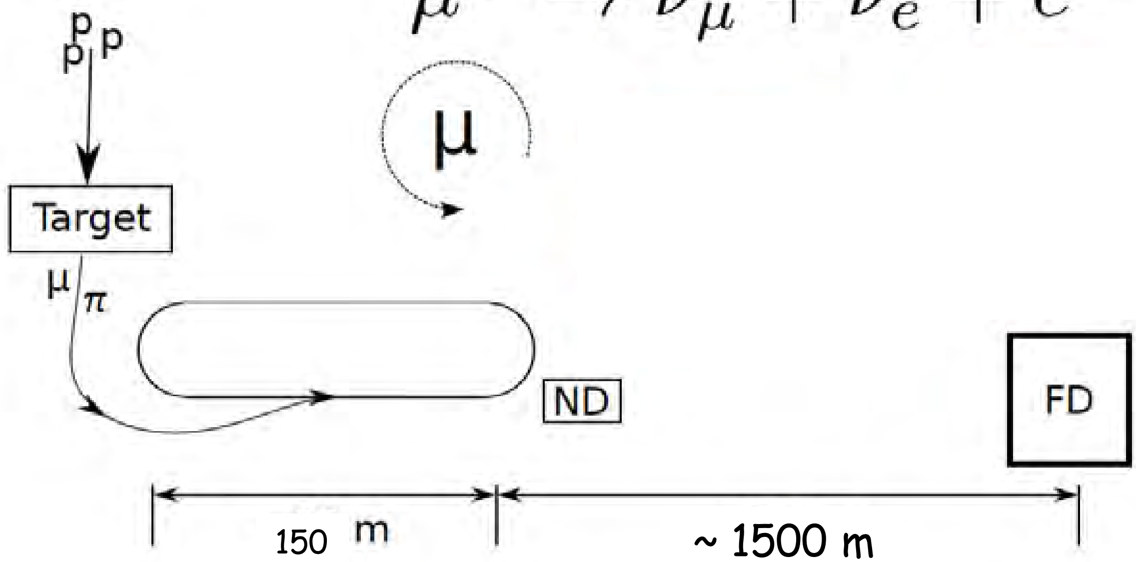
Event rates/100T
at ND hall 50m
from straight with
m^+ stored

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



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

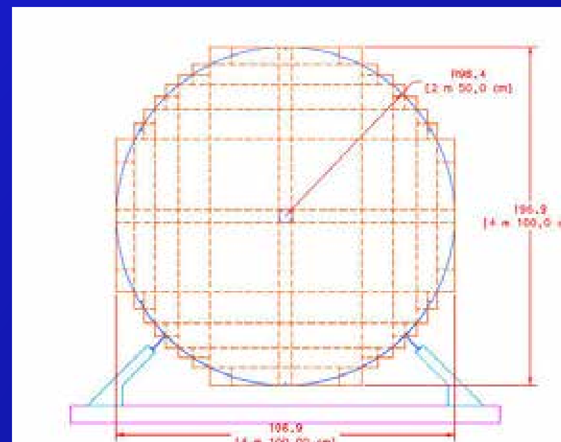
Must reject the "wrong" sign mwith great efficiency

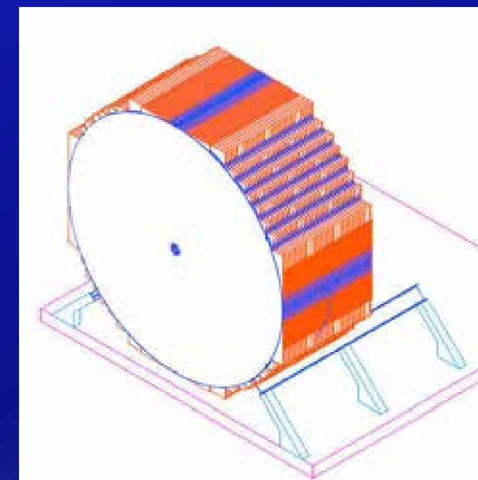
Why n_m® n_e Appearance Ch. *"not"* possible

Baseline Detector

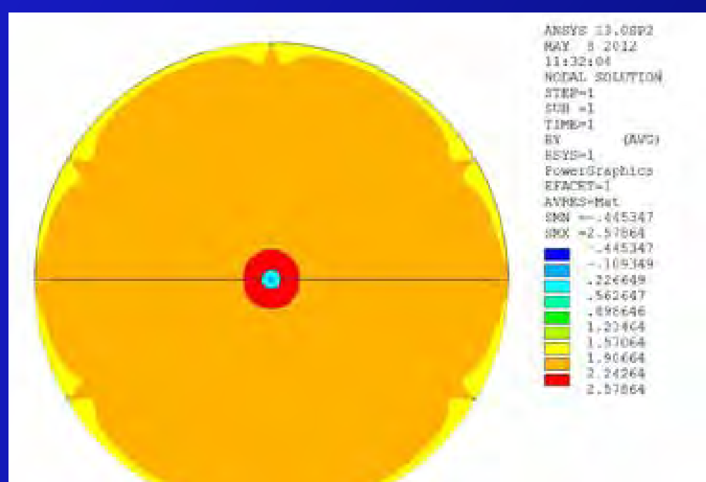
Super B Iron Neutrino Detector: SuperBIND

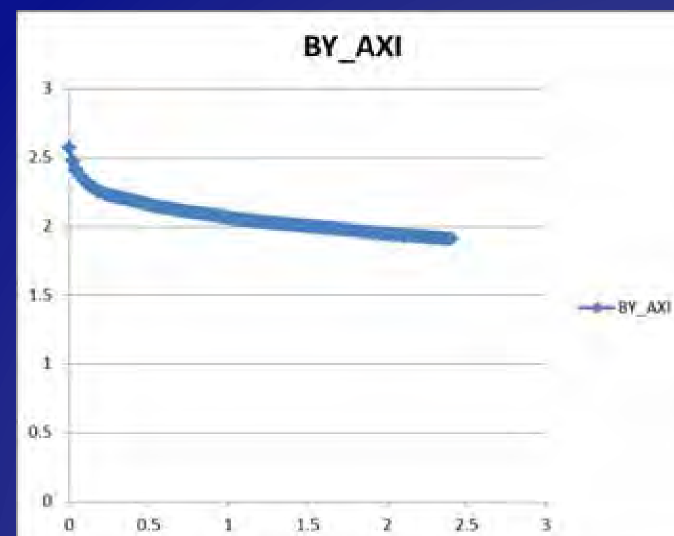
- Magnetized Iron
  - 1.3 kT
    - Following MINOS ND ME design
    - 1-2 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM



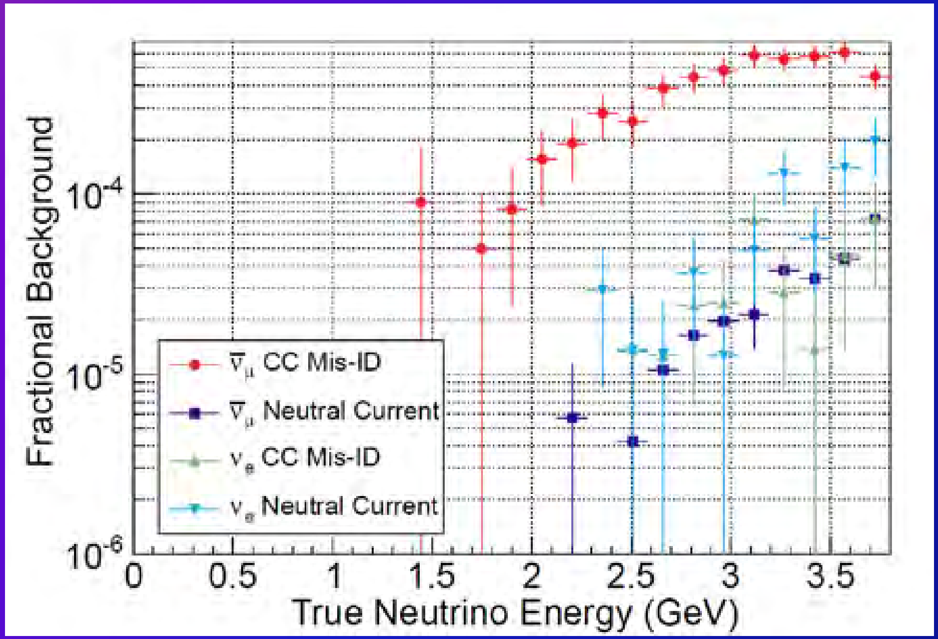


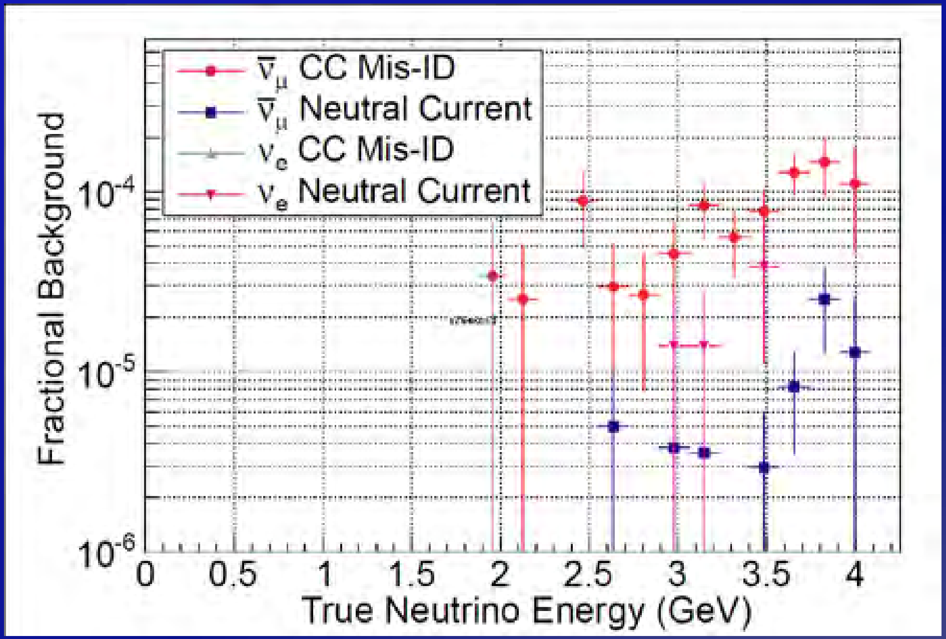
20 cm hole
For 3 turns
of STL





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

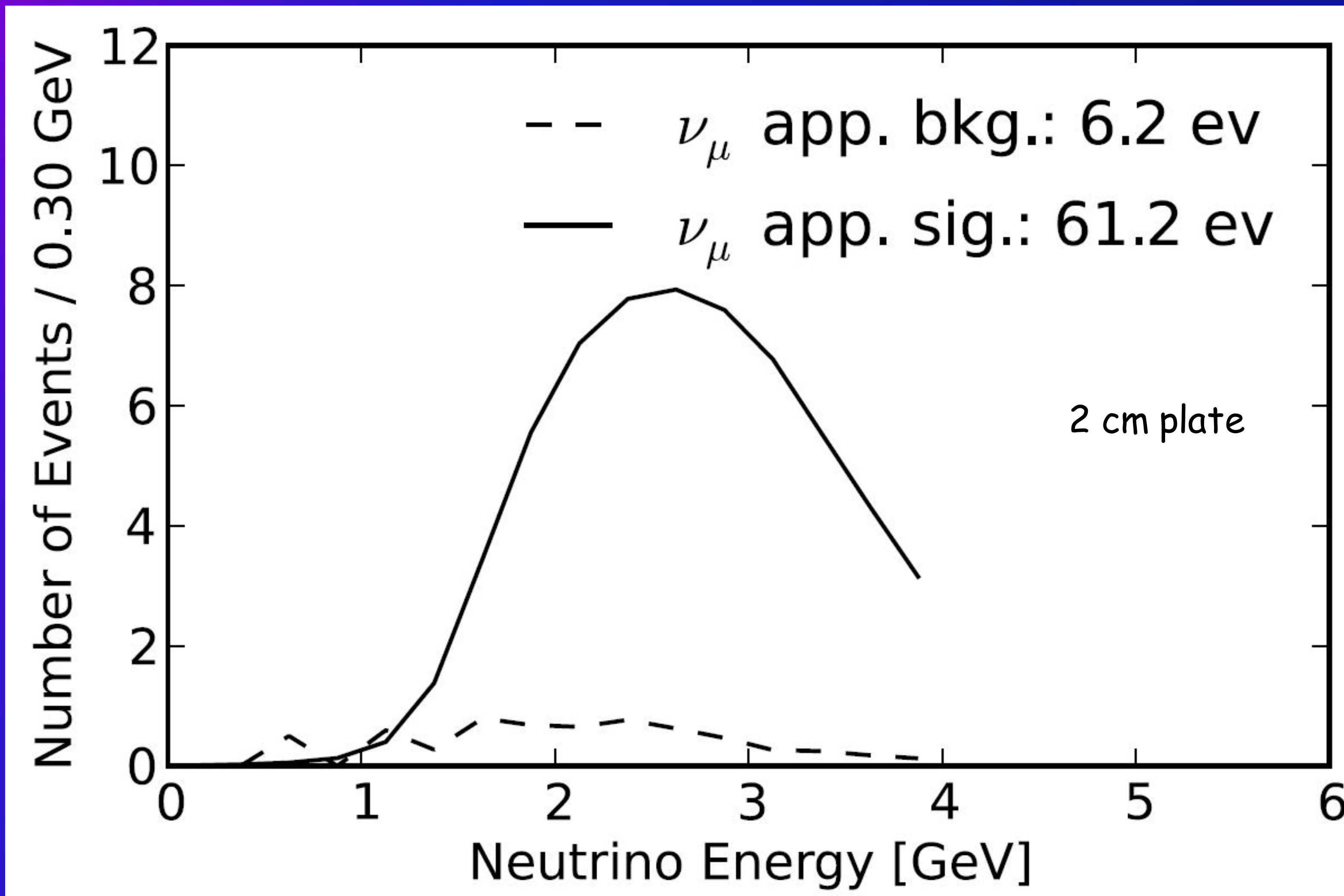
Anti-neutrino mode with stored μ^-.

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

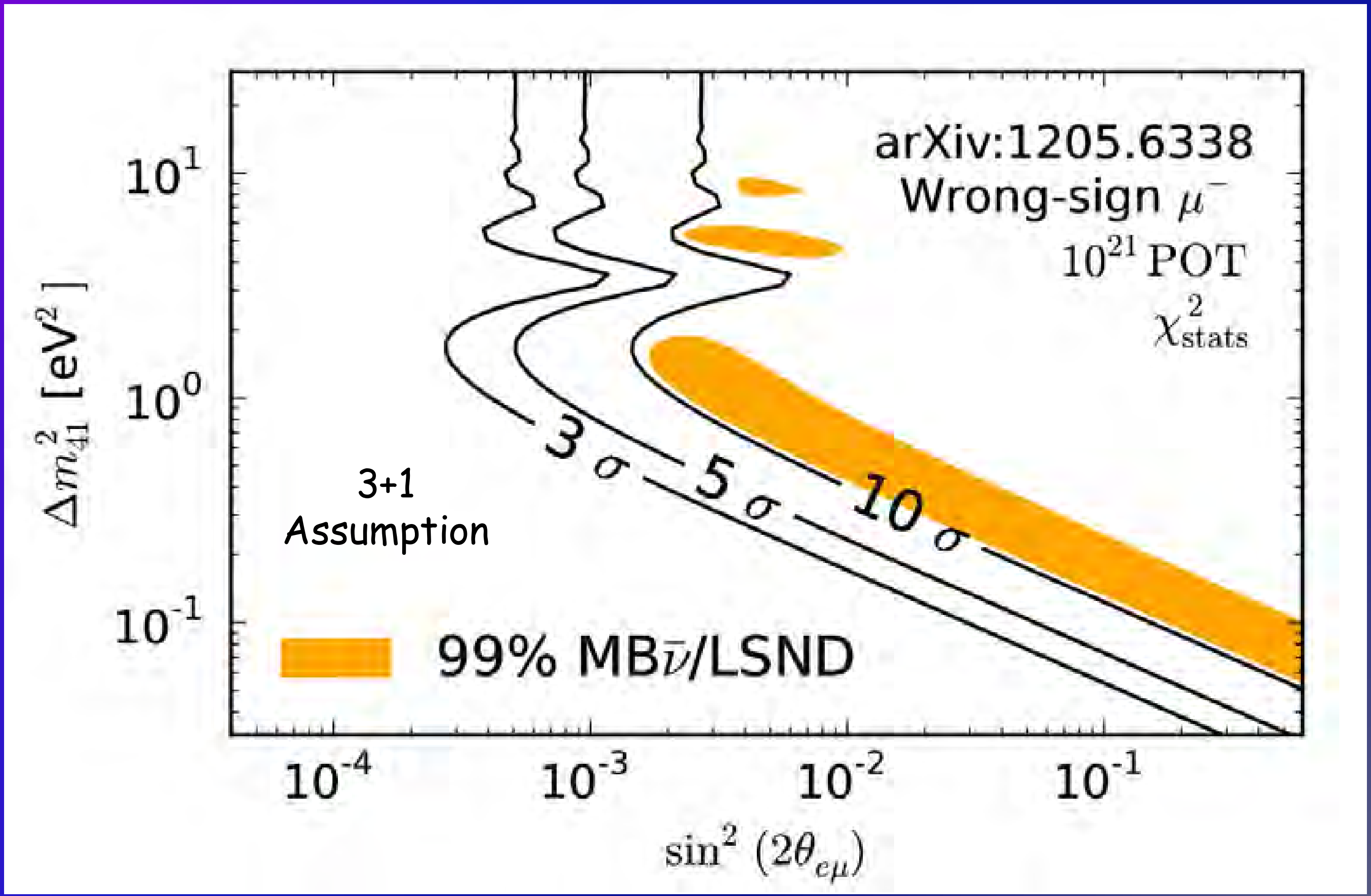
3+1
Assumption

Appearance channels

n_e ® n_m appearance
CPT invariant channel to MiniBooNE



n_e ® n_m appearance
CPT invariant channel to MiniBooNE



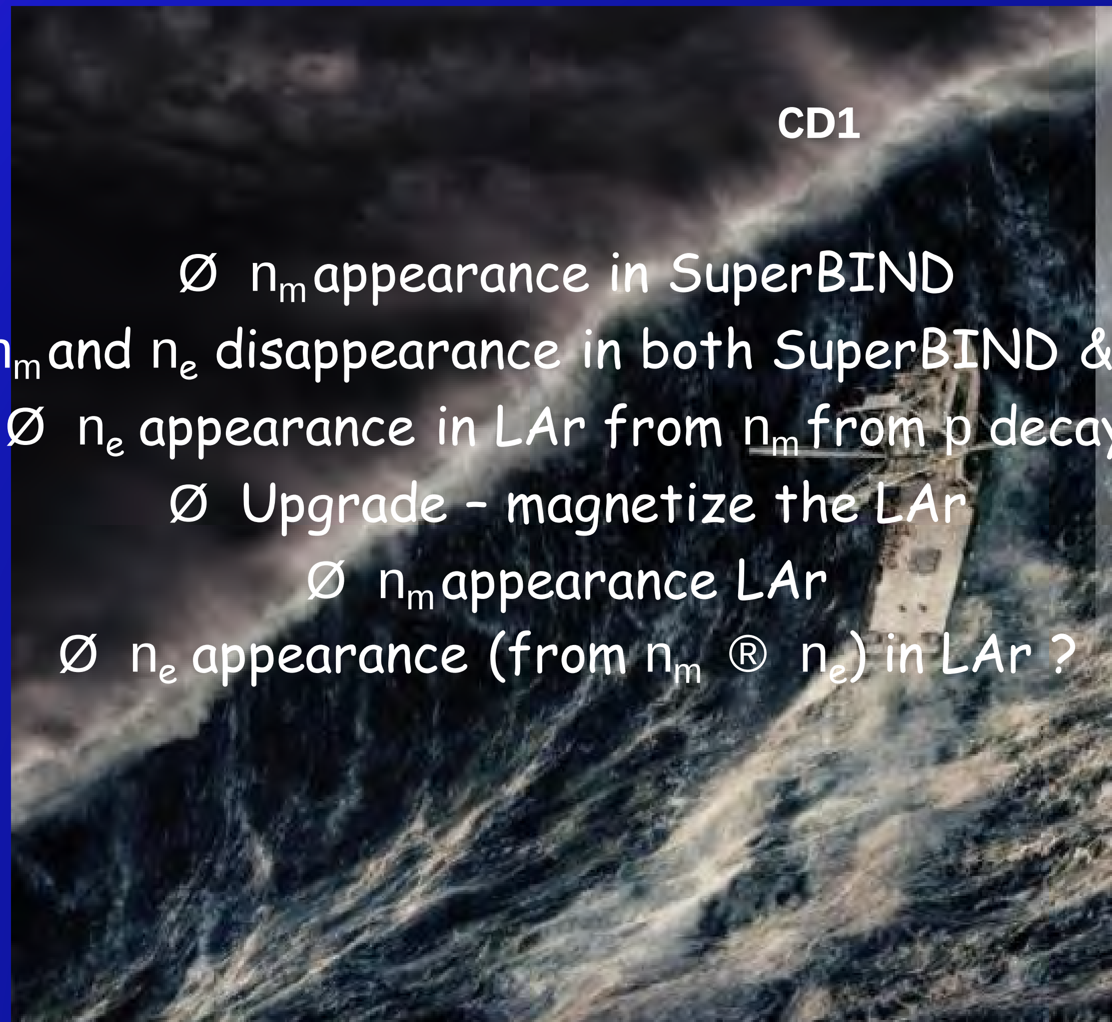
Detailed talks by Ryan Byes, Chris Tunnel and Sanjib Mishra νSTORM

A Perfect nuSTORM?

- SuperBIND & a large LAr detector can fit in the D0 Bldg.
- n_m beam (fr. p decay, Turn 1)
- mdecay n beam

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

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



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

Project Considerations

Back to Earth

Siting Concept

Steve Dixon (Fermilab FESS) will discuss tomorrow

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, 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

Why we are here

Moving forward:

Ø Facility

- Targeting, capture/transport & Injection (Striganov, Liu)
  - Need to complete detailed design and simulation
- Decay Ring optimization (Neuffer, Mori, Sato)
  - Continued study of both RFFAG & FODO decay rings
- Decay Ring Instrumentation (Tassotto)
  - 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:

- 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 for June 2013 PAC Mtg.

® Full Proposal

- June 2012 PAC response to nuSTORM presentation
  - The combination of a clear resolution of the short-baseline neutrino anomalies, the precise measurements of the neutrino cross sections, and the synergy with neutrino-factory technology makes this a potentially attractive project.
- From Pier
  - As you see, the Committee was quite intrigued by the possibility of the nuSTORM approach to resolving the short-baseline neutrino anomalies and its being a stepping stone toward use of neutrino-factory technology.
- So,
  - Although we do not have a mandate ($$$), there is recognition of the power of the concept and encouragement to proceed to a full proposal.

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 for n_e?
- 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

Back Ups

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	Quantity	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

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**