Neutrinos from Stored Muons
nuSTORM

ν physics with a μ storage ring

Documentation

- Proposal to Fermilab PAC, June 2013
  - arXiv: 1308.6822
- nuSTORM Project Definition Report
  - arXiv: 1309.1389
- nuSTORM Costing document
  - FERMILAB-TM-2569-APC https://inspirehep.net/record/1263003

νSTORM

Requests, Questions

1. Give a brief summary of the physics case coupled with the explicit scope of the experiment, and a notional timeline for construction start, data taking, and specific anticipated results.
    1. What makes this experiment unique, and how does fit in the overall picture of this area?
2. What scope of international participation is required, and what is the status of these arrangements?
    1. How do you anticipate this will develop over time?
3. At a top level, what is your current estimate of U.S. construction costs, including notional technically-driven and realistic cost profiles (to the extent you can), and what is the basis of estimate?
    1. What contingency are you carrying in these estimates?
    2. What R&D is still required, and what is the scope?
    3. If this is a multi-agency project, what are the envisioned roles and division of scope?
4. Estimate of the number of physicists (in FTEs) needed by project phase, including operations and data analysis.

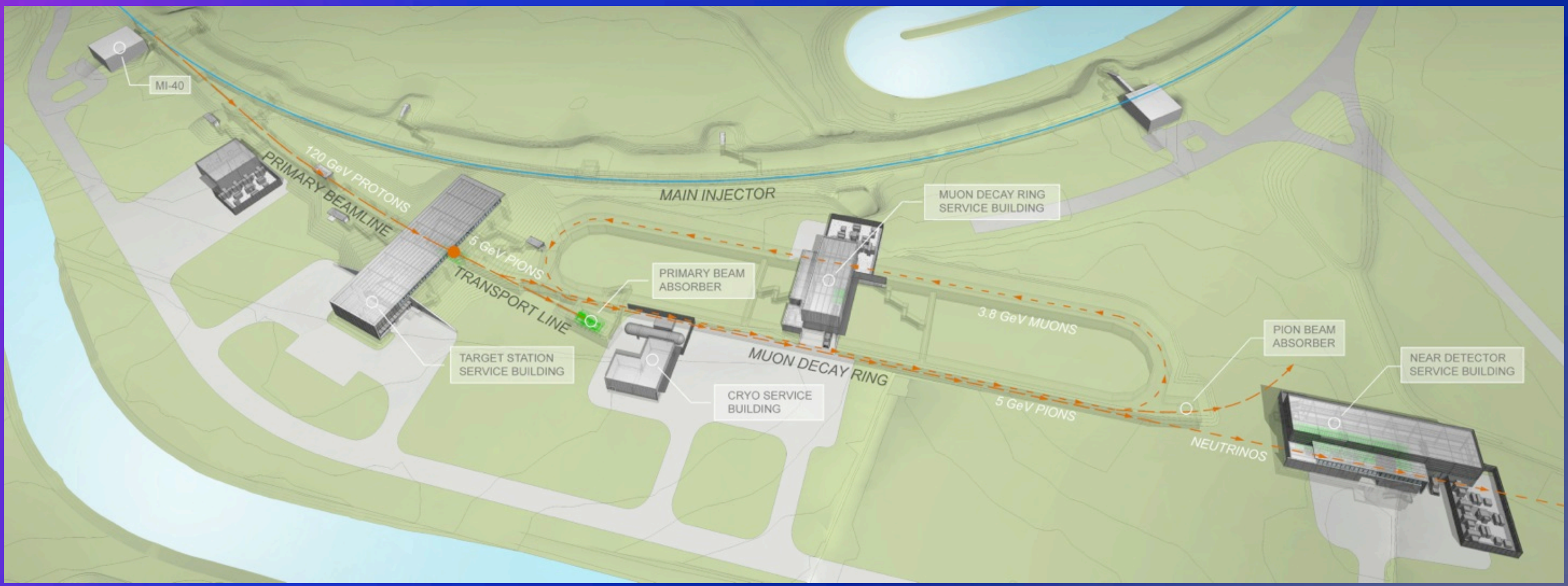
νSTORM

Request/Question 1

- Give a brief summary of the physics case coupled with the explicit scope of the experiment, and a notional timeline for construction start, data taking, and specific anticipated results.
  - *What makes this experiment unique, and how does it fit in the overall picture of this area? (Will get back to this at the end)*

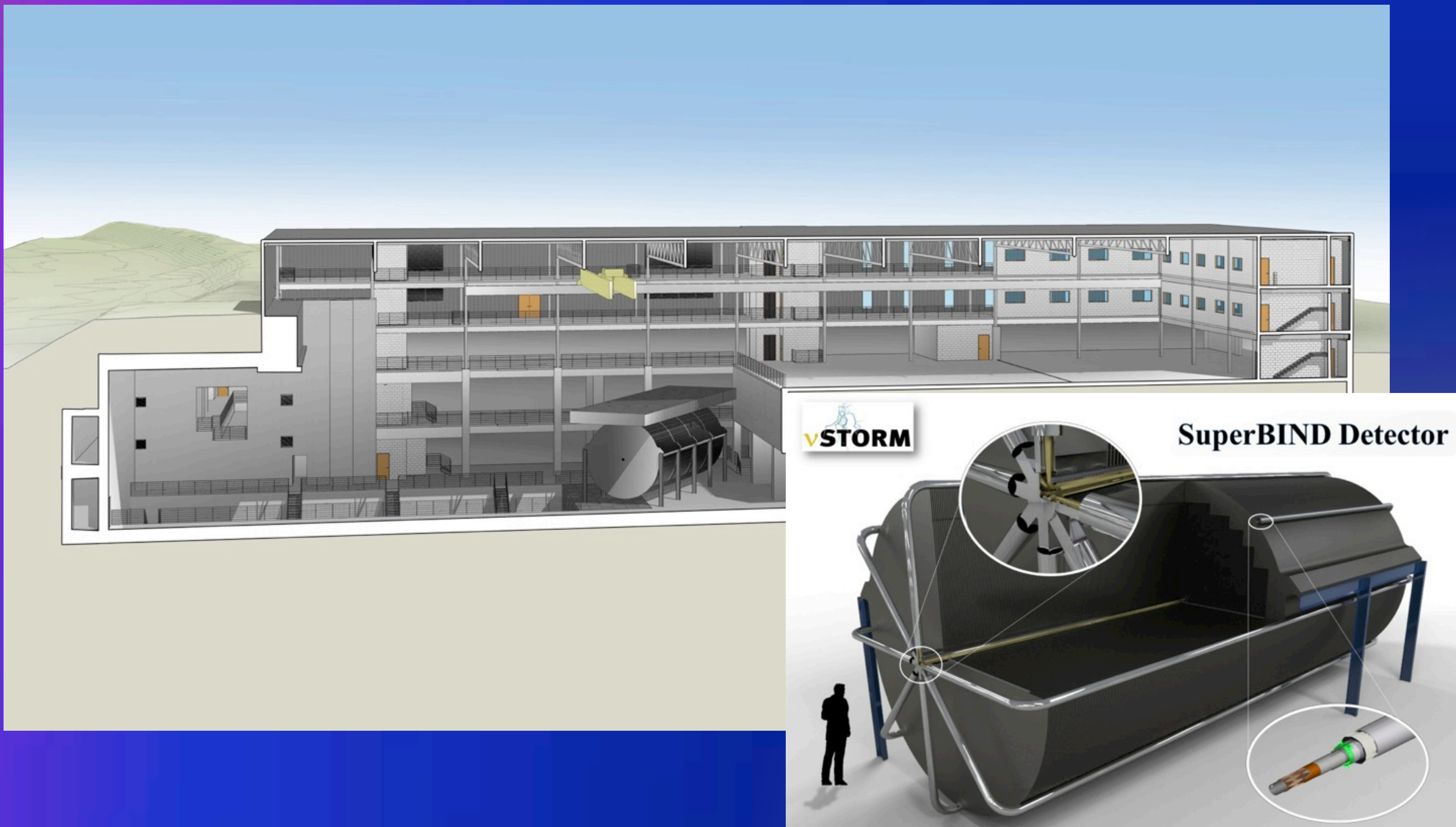
nuSTORM: Siting

Scope: nuSTORM Facility near site



μ decay ring: P = 3.8 GeV/c ± 10%

Scope:
Far site – D0 Assembly Building



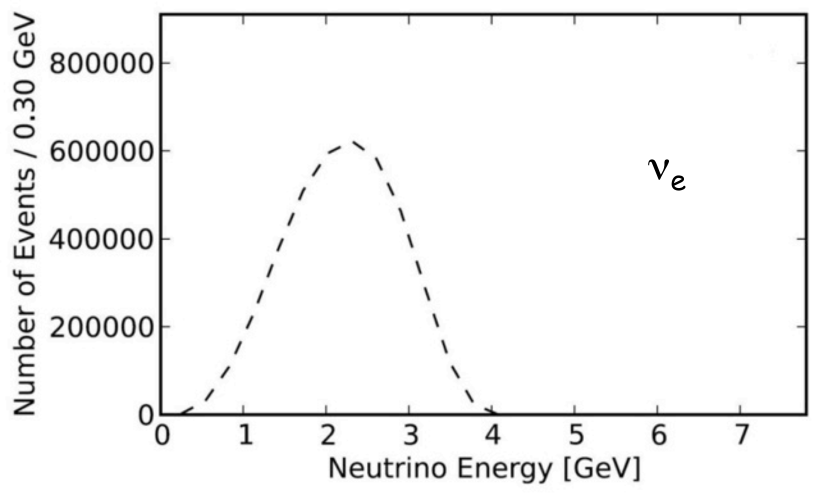
nuSTORM Physics program

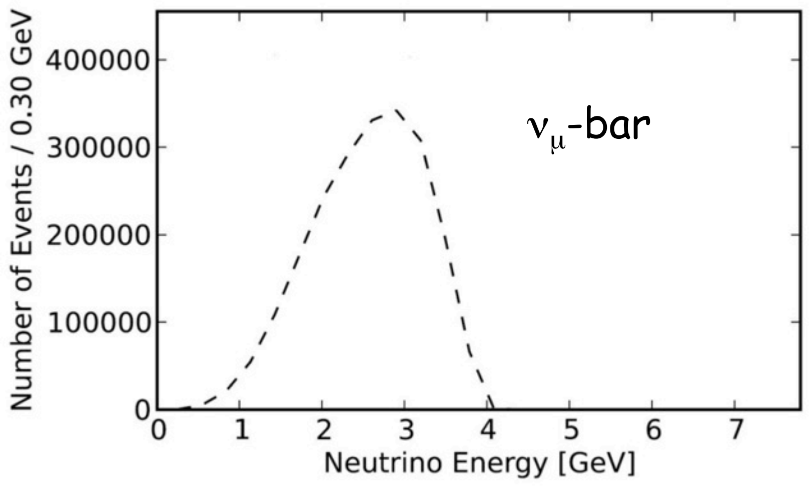
- Addresses the SBL, large δm^2 ν-oscillation regime
- Provides a beam for precision ν interaction physics (GeV-scale high-statistics ν_e & anti-ν_e data for the First Time)
  - Approach 0.1% uncertainty on flux & spectrum
- Accelerator & Detector technology test bed
  - Potential for intense low energy muon beam
  - Provides for μ decay ring R&D (instrumentation) & technology demonstration platform
  - Provides a ν Detector Test Facility

ν flux

- Based on 10^{21} 120 GeV POT, we obtain $\approx 1.9 \times 10^{18}$ useful μ decays
  - In PIP era, extract one Booster batch/cycle (10^{20} POT/yr → 10 year run)
  - Baseline FODO ring, C target, NUMI style 1 horn
- Inconel target + horn optimization + RFFAG → X5 (2 year run)

E_ν spectra (3.8 GeV/c μ^+ stored)





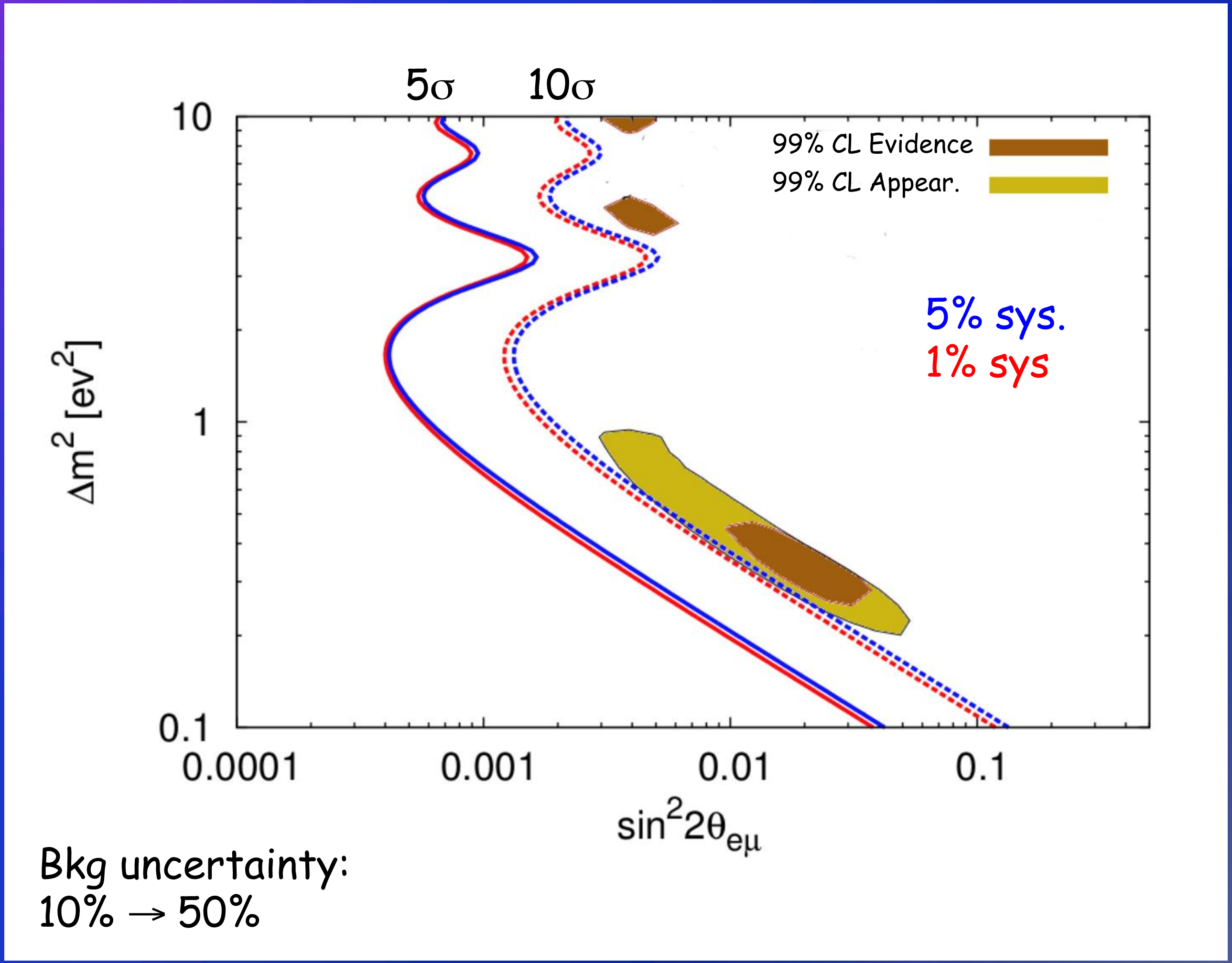
Event rates/100T at ND hall 50m from straight with μ^+ stored for 10^{21} POT exposure

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 at Far detector

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

Appearance: Exclusion contours $\nu_e \rightarrow \nu_\mu$ (CPT invariant mode of LSND)



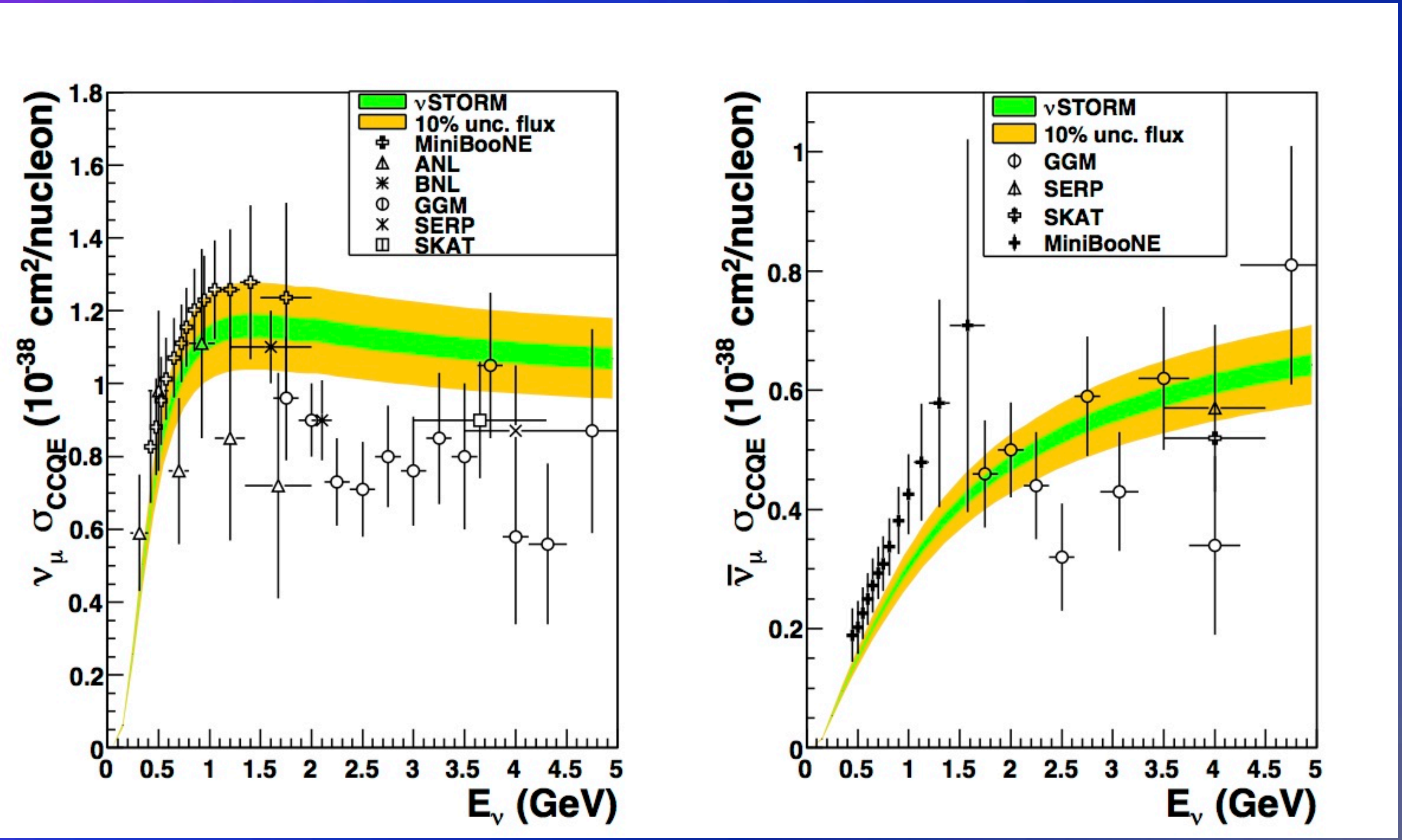
Global fit from: J. Kopp, P. A. N. Machado, M. Maltoni, and T. Schwetz, 392 JHEP 1305, 050 (2013)

Cross section measurements - ν_μ

HIRESMnu straw-tube-based near detector same as proposed for LBNE

Figures show systematics of HIRESMnu + nuSTORM Beam (1%)added in quadrature

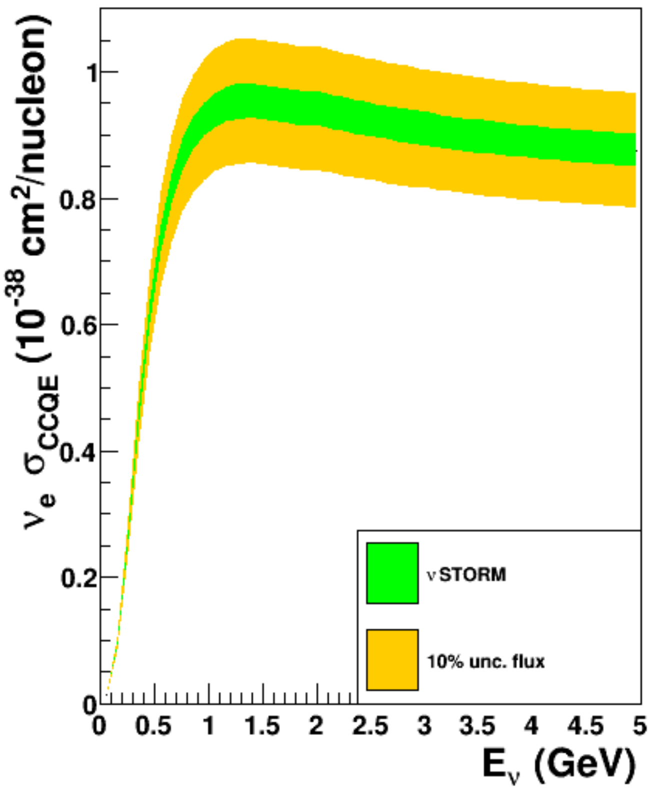
μ^-

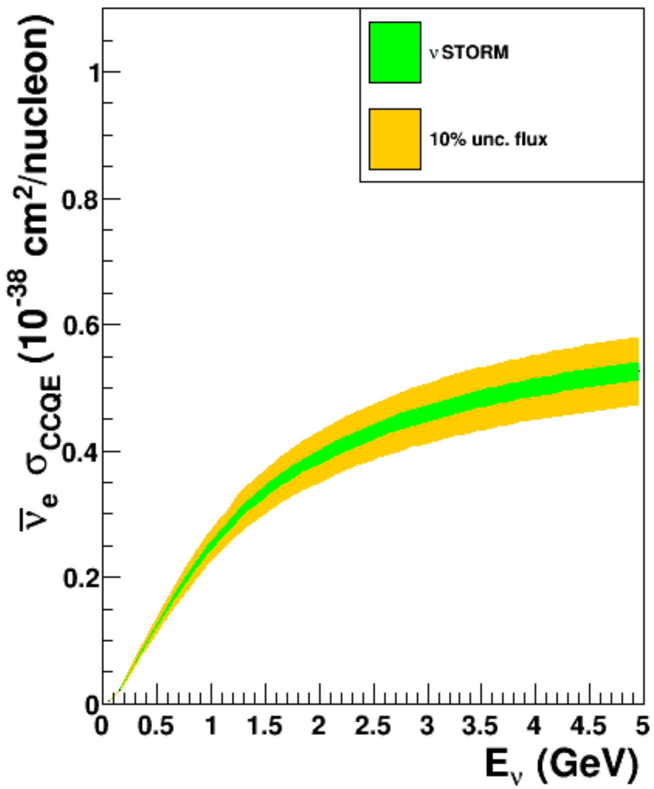


μ^+

Cross section measurements - ν_e

μ^-





μ^+

The search for CP in LBL expts. counts ν_e and anti-ν_e events (flux X xsection)

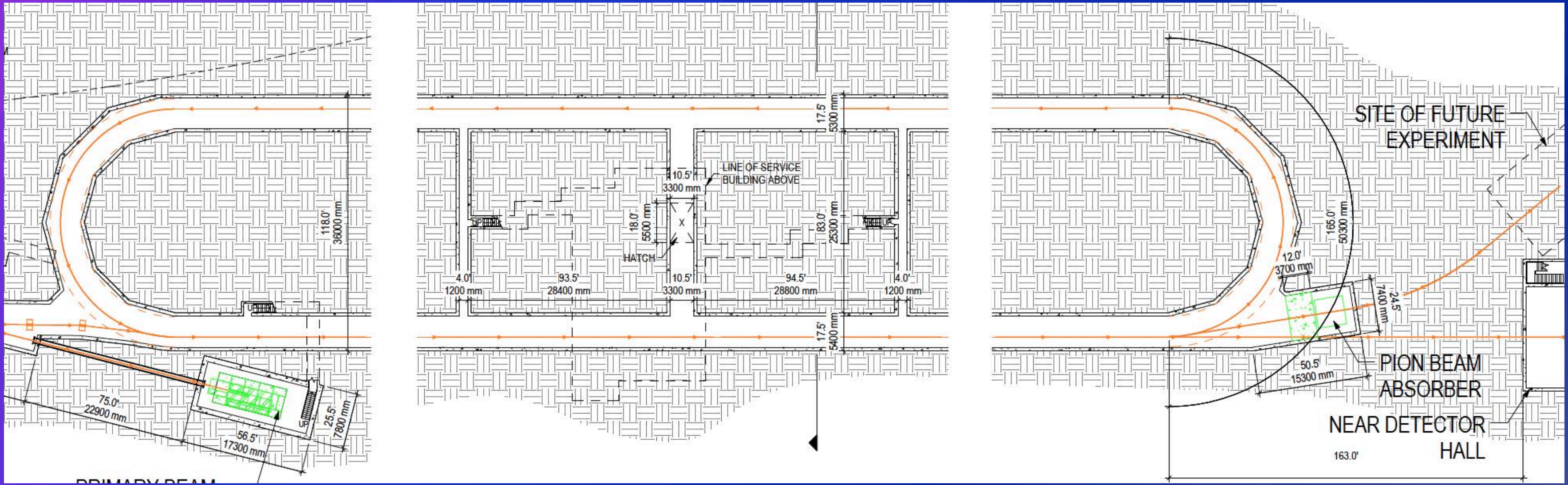
Note: not shown here ν_e (200 evts) and ν_e-bar (60 evts) inclusive xsection data (1978)

Accelerator R&D

Looking Forward

nuSTORM

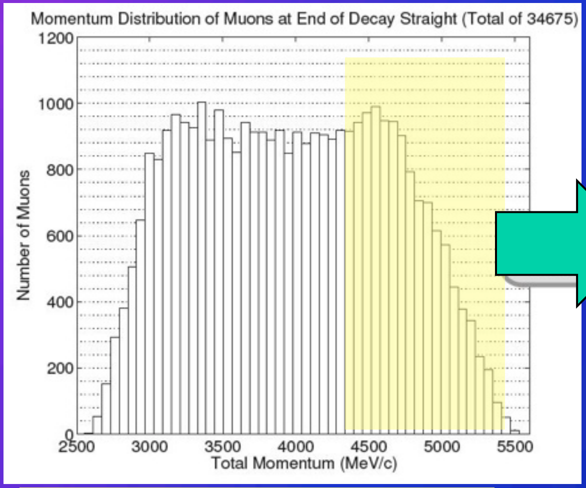
Setting the stage for the next step

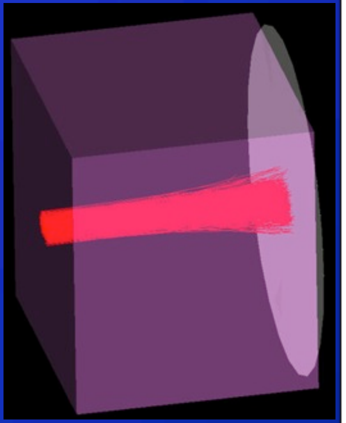


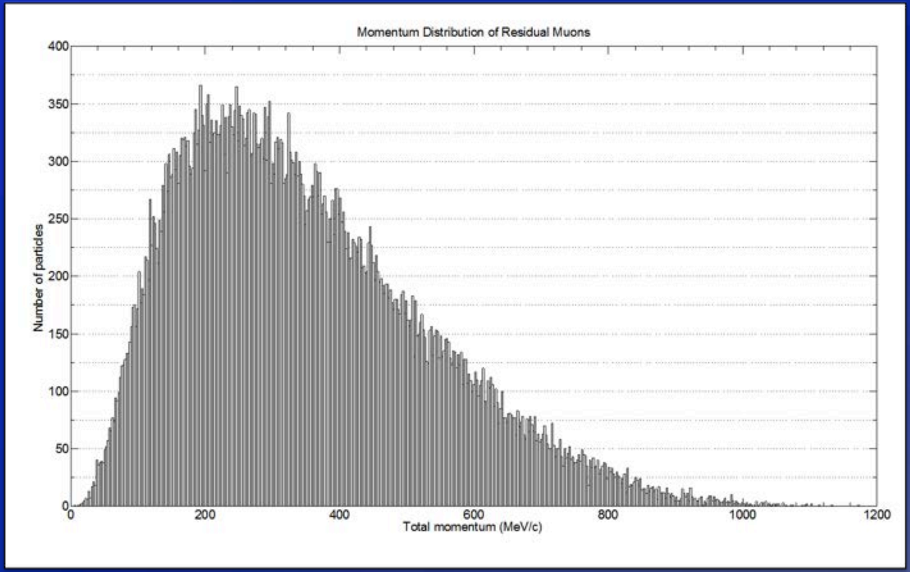
Capture and inject πs with P=5 GeV/c ± 10%
Only ~50% of πs decay in straight
Need π absorber

Note: injection produces a ν_μ "flash" from $\pi \rightarrow \mu\nu_\mu$ decay
= integrated flux of the neutrinos from μ decay

Low Energy μ beam







At end of straight we have a lot of πs, but also a lot of μs with 4.5 < P(GeV/c) < 5.5

After 3.48m Fe, we have ≈ 10^{10} μ/pulse in 100 < P(MeV/c) < 300

Question 2

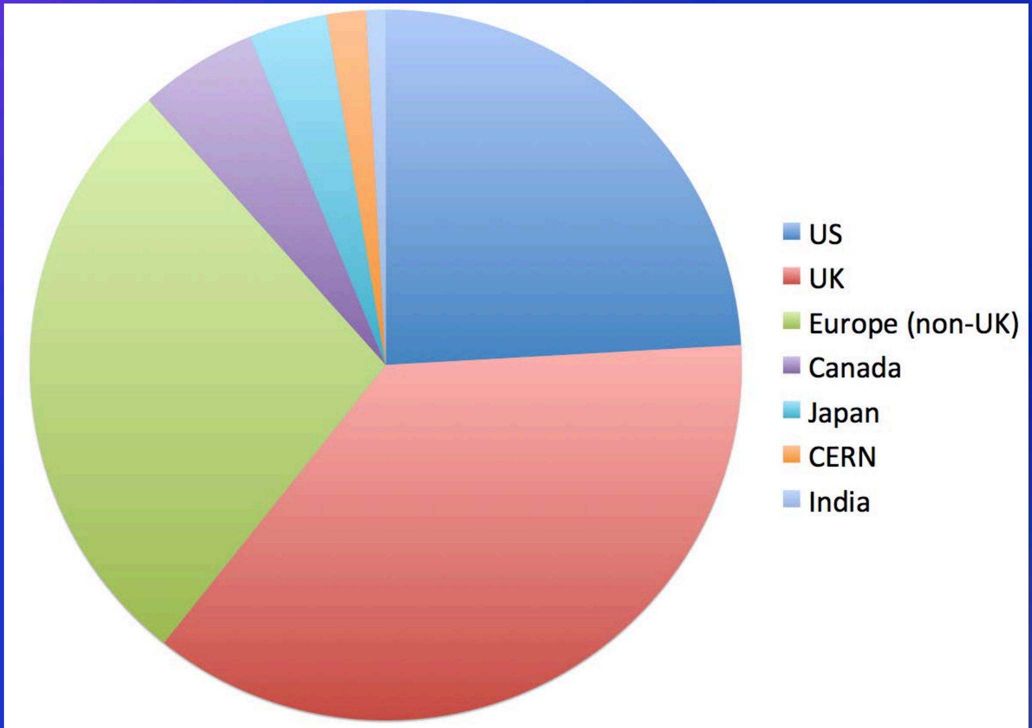
- What scope of international participation is required, and what is the status of these arrangements? How do you anticipate this will develop over time?

International participation

What is required?

- Host laboratory must carry burden of conventional facilities
  - Roughly ½ TPC (next question)
- Magnets, power supplies, horn/ target, detector can all be supplied off-shore

nuSTORM Collaboration



110 members

- The scope of International involvement is already large
- With encouragement, would aim for X2 increase in collaboration with international fraction 40-50%

nuSTORM EOI to CERN

- Twin-Track Approach
  - Develop International support at the Laboratory level for the concept
    - Bottom-up (grass roots) & Top-down
- Has produced significant increase in the size of the collaboration
  - From 38 at time of Fermilab LOI to 110 now (single collaboration)
- CERN EOI has requested support to:
  - Investigate in detail how nuSTORM could be implemented at CERN; and
  - Develop options for decisive European contributions to the nuSTORM facility and experimental program wherever the facility is sited.
- It defines a roughly two-year program which culminates in the delivery of a Technical Design Report.
- Submitted in April of this year:
  - SPSC review of EOI 25 June 13:
    - Recognition of importance of nuSTORM and the opportunities for excellent contributions to searches for sterile neutrinos and cross-section measurements
    - Encouragement for collaboration to carry out program defined in EOI
- Negotiations for the necessary support at CERN are now at an advanced stage

Costing

Question 3

- At a top level, what is your current estimate of U.S. construction costs, including notional technically-driven and realistic cost profiles (to the extent you can), and what is the basis of estimate?
  - What contingency are you carrying in these estimates?
  - What R&D is still required, and what is the scope?
  - If this is a multi-agency project, what are the envisioned roles and division of scope?

BTW, one definition of notional: not evident in reality; hypothetical or imaginary

νSTORM

Costing model

Basis of Estimation

- Conventional facilities
  - PDR
- Cost estimates from AD for
  - Primary beam line
  - Target Station
- Cross-checks to LBNE
- Magnet Costs based on construction analysis for room temperature magnets and on Strauss & Green model for SC magnets (TD)
- Detector costs
  - Euronu, MINOS + Nova

See FERMILAB-TM-2569-APC for details

https://inspirehep.net/record/1263003

nuSTORM: Total Project Cost

Subsystem	Base cost	Contingency	Cost
Proton beam line	21,143,940	7,356,253	28,500,193
Target Station	26,674,694	11,225,150	37,899,844
Capture/transport	10,811,010	5,681,943	16,492,953
Decay ring	89,248,924	45,956,474	135,205,398
Near detector hall	16,778,572	6,711,429	23,490,001
Far detector hall	1,182,581	650,420	1,833,001
SuperBIND	21,057,070	4,190,528	25,247,598
Site work	17,429,678	9,586,323	27,526,000
CF other	1,804,286	721,714	2,526,000
TOTAL	**206,130,755**	**92,080,233**	**298,210,988**
Management			37,080,186
TPC		**45% contingency**	**335,291,175**

Total contingency – 45%

[1]Near Hall sized for multiple experiments & ND for SBL oscillation physics
[2]1.3kT Far + .2kT Near & include DAB work
[3]Assumes LBNE estimates: Proj. Office (10%), L2 (9.4%), L3 (4%)

Conventional Facilities

		EDIA	Contingency				
WBS	**Functional Area**	**Base Cost**	**30%**	**%**	**$**	**Indirects**	**Totals**
1.0	Primary Beamline Enclosure	$7,013,000	$2,104,000	40%	$3,647,000	$1,266,000	$14,030,000
2.0	Target Station	$8,993,000	$2,698,000	55%	$6,430,000	$1,662,000	$19,783,000
3.0	Transport Line Enclosure	$1,883,000	$565,000	60%	$1,469,000	$504,000	$4,421,000
4.0	Muon Decay Ring Enclosure	$26,002,000	$7,801,000	60%	$20,282,000	$4,215,000	$58,300,000
5.0	Near Detector	$11,750,000	$3,525,000	40%	$6,110,000	$1,882,000	$23,267,000
6.0	Far Detector	$720,000	$216,000	55%	$515,000	$333,000	$1,784,000
8.0	Site Work	$12,233,000	$3,670,000	55%	$8,747,000	$2,115,000	$26,765,000
	TOTALS	**$68,594,000**	**$20,579,000**		**$47,200,000**	**$11,977,000**	**$148,350,000**

Overall contingency on Base Cost + EDIA – 53%

Schedule from Project Definition Report

➢ CD-0 Approval	Month 0
➢ CD-1 Approval	Month 12
➢ CD-2 Approval	Month 24
➢ CD-3 Approval	Month 36
➢ Start Conventional Facilities Construction	Month 39
➢ Complete Conventional Facilities Construction	Month 57

- The schedule is based on technically driven parameters and does not incorporate lags for DOE approvals or funding restrictions.
- A "realistic" schedule is 5-7 years from CD1 ($50M/yr)

Question 3(b)(c)

- What R&D is still required, and what is the scope?
  - Decay ring instrumentation
    - Captured in DRI costs of $3.4M
  - Magnet prototyping
    - $3-5M
- If this is a multi-agency project, what are the envisioned roles and division of scope?
  - None has been studied.
  - Near detector for ν interaction studies could fall within NSF MREFC

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Question 4

- Estimate of the number of physicists (in FTEs) needed by project phase, including operations and data analysis.
  - Project phase (based on $37M) -5 years
    - 15-20
  - Operations and data analysis (for SBL osc only)
    - 8 + 3
      - Based on MINOS ND

Back to Question 1

- *What makes this experiment unique, and how does fit in the overall picture of this area?*

What makes nuSTORM unique

The Physics:

- Can confirm/exclude at 10σ (CPT invariant channel) the LSND/ MiniBooNE result
  - Only experiment that has access to appearance & disappearance for both ν_μ and ν_e, neutrino and anti-neutrino
- ν interaction physics studies with near detector(s) offer a unique opportunity & can be extended to cover $0.2 < E_\nu(\text{GeV}) < 4$
  - Could be "*transformational*" w/r to ν interaction physics
    - Unique opportunities for ν_e interaction studies
  - For this physics, nuSTORM should really be thought of as a facility: A ν "*light-source*" is a good analogy
    - nuSTORM provides the beam & users will bring their detector to the near hall

What makes nuSTORM unique II

The Facility:

- Although it only needs very manageable extrapolations from existing technology
  - It 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

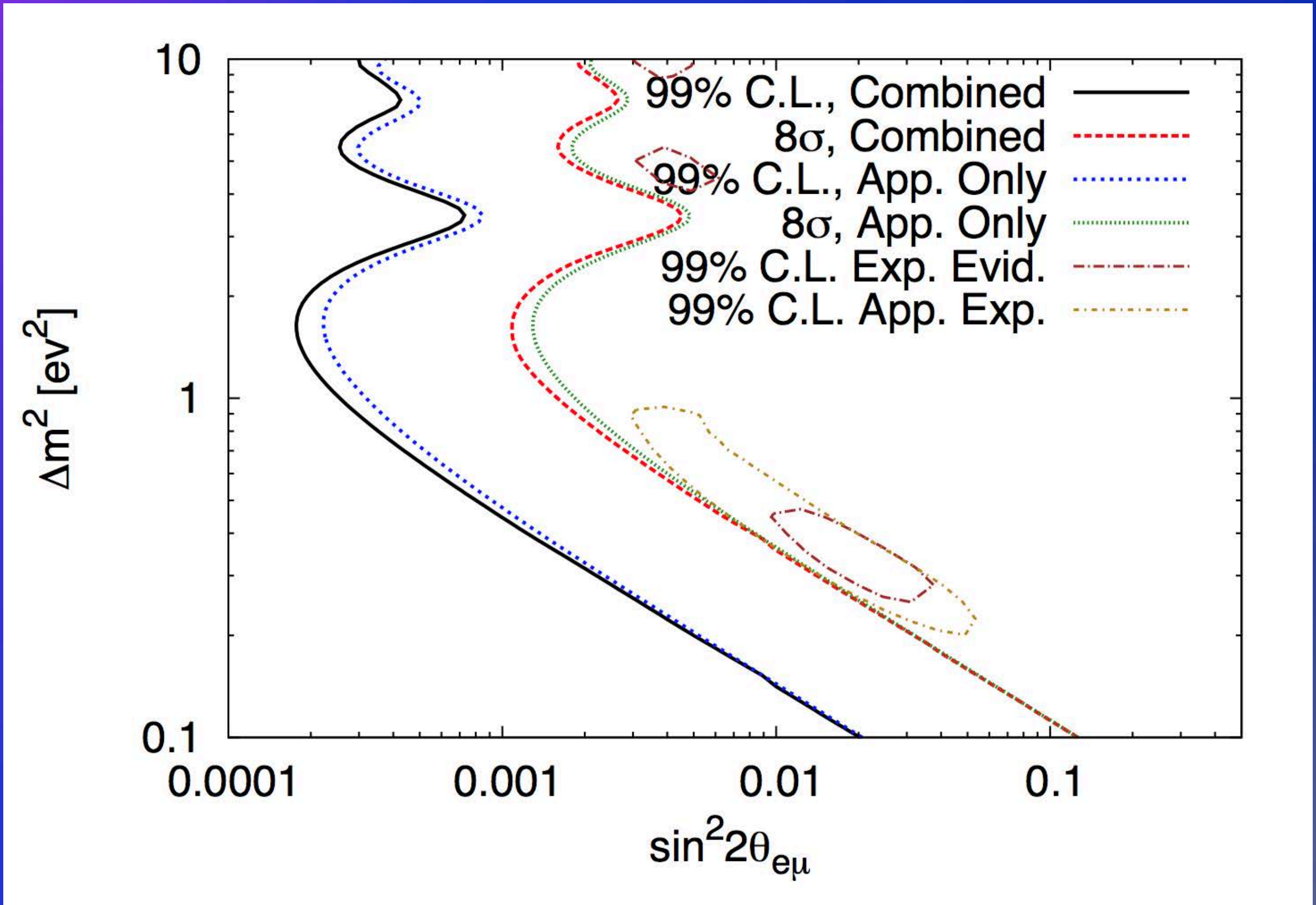
Three Pillars of nuSTORM

- Delivers on the physics for the study of sterile ν
  - As MP said yesterday: *"Prepare for discovery, have a plan for machines that can exploit it."* nuSTORM is preeminent in this regard w/r to sterile neutrinos
  - Offers a new approach to the production of ν beams setting a 10σ benchmark to make definitive statement w/r LSND/ MiniBooNE
    - Only facility that can do appearance & disappearance for ν and anti-ν
- Can add significantly to our knowledge of ν interactions, particularly for ν_e
  - ν *"Light Source"*
- Provides an accelerator science test facility

Thank you

Back Ups

5 X 10^{21} POT exposure



Assuming 10^{20} POT/yr. for 5 years, 10σ contour becomes 8σ

Systematics for Golden Channel in nuSTORM

- Magnetic field uncertainties
  - If we do as well as MINOS (3%), no impact
  - Need high field, however. STL must work
- Cross sections and nuclear effects
  - Needs some more work
    - ND for disappearance ch (100T of SuperBIND) should minimize contribution to the uncertainties
- Cosmic rays
  - Not an issue (But, we do need to distinguish between upward and downward going muons via timing).
- Detector modeling (EM & Hadronic showering)
  - Experience from MINOS indicates we are OK, but this needs more work for SuperBIND
- Atmospheric neutrinos
  - Negligible
- Beam and rock muons
  - Active veto – no problem

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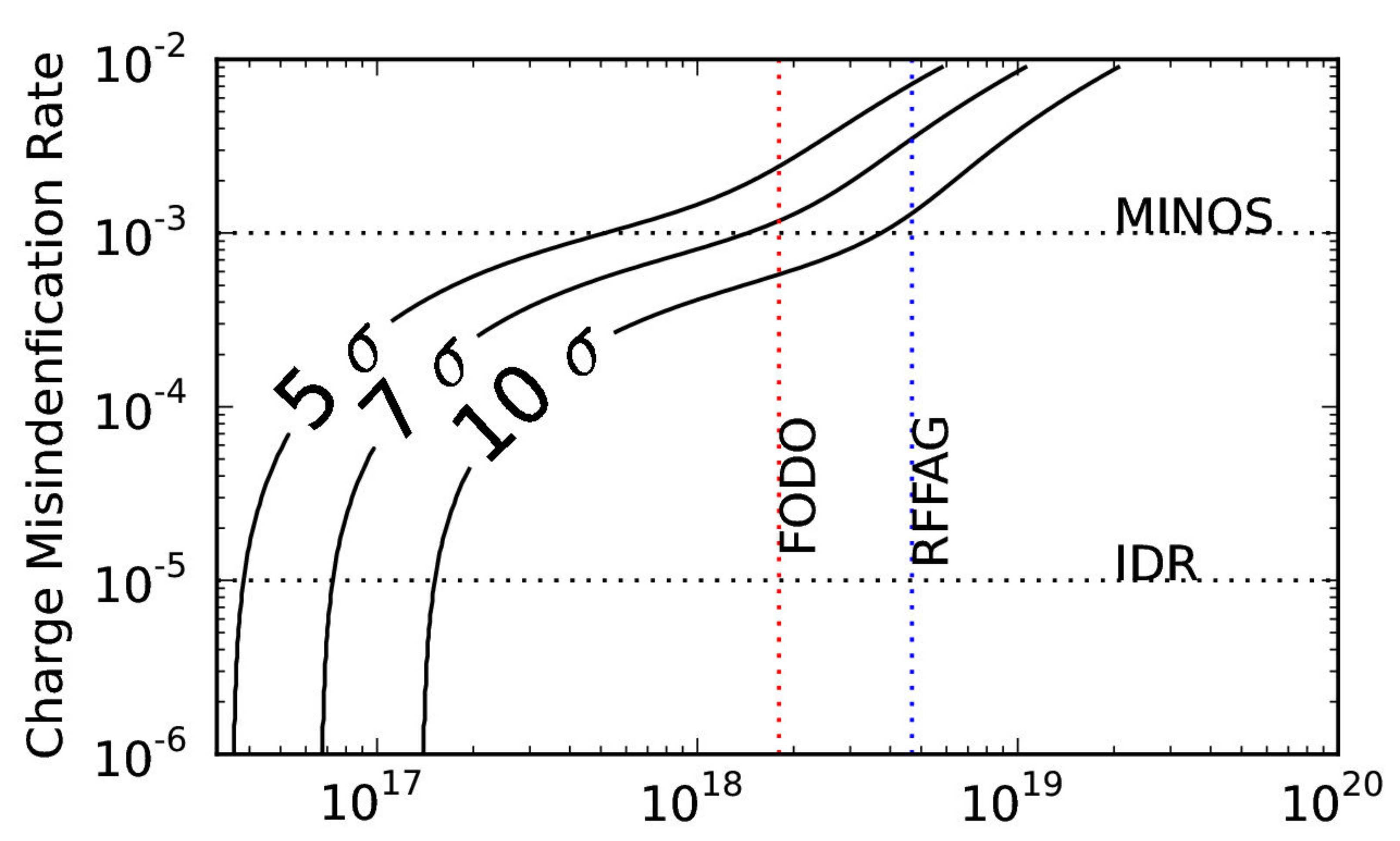
Systematics II

Uncertainty	Known Measures			Expected Contribution	
	Signal	Background	Reference	Signal	Background
Source luminosity	1%	1%	[229]	1%	1%
Cross section	4%	40%	[232]	0.5%	5%
Hadronic Model	0	15%	[233]	0	8%
Electromagnetic Model	2%	0	[233]	0.5%	0
Magnetic Field	<1%	<1%	[229]	<1%	<1%
Steel	0.2%	0.2%	[229]	0.2%	0.2%
Total	5%	43%		1%	10%

[232], [233] - MINOS

Required μ charge mis-ID rate needed for given sensitivity

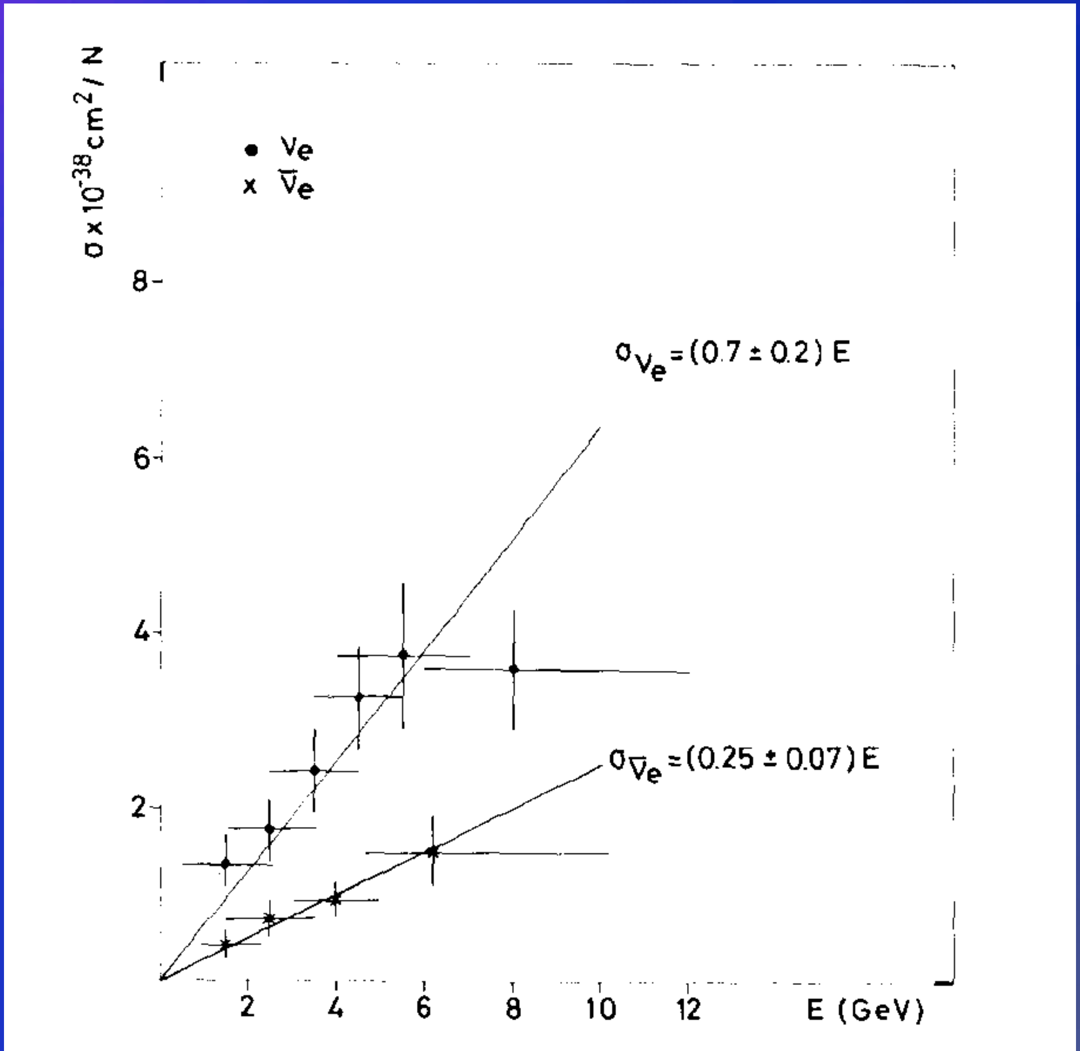
Chris Tunnell
Oxford



Number of useful muon decays

Gargamelle ν_e and ν_e-bar data

200 ν_e evts
60 ν_e-bar evts



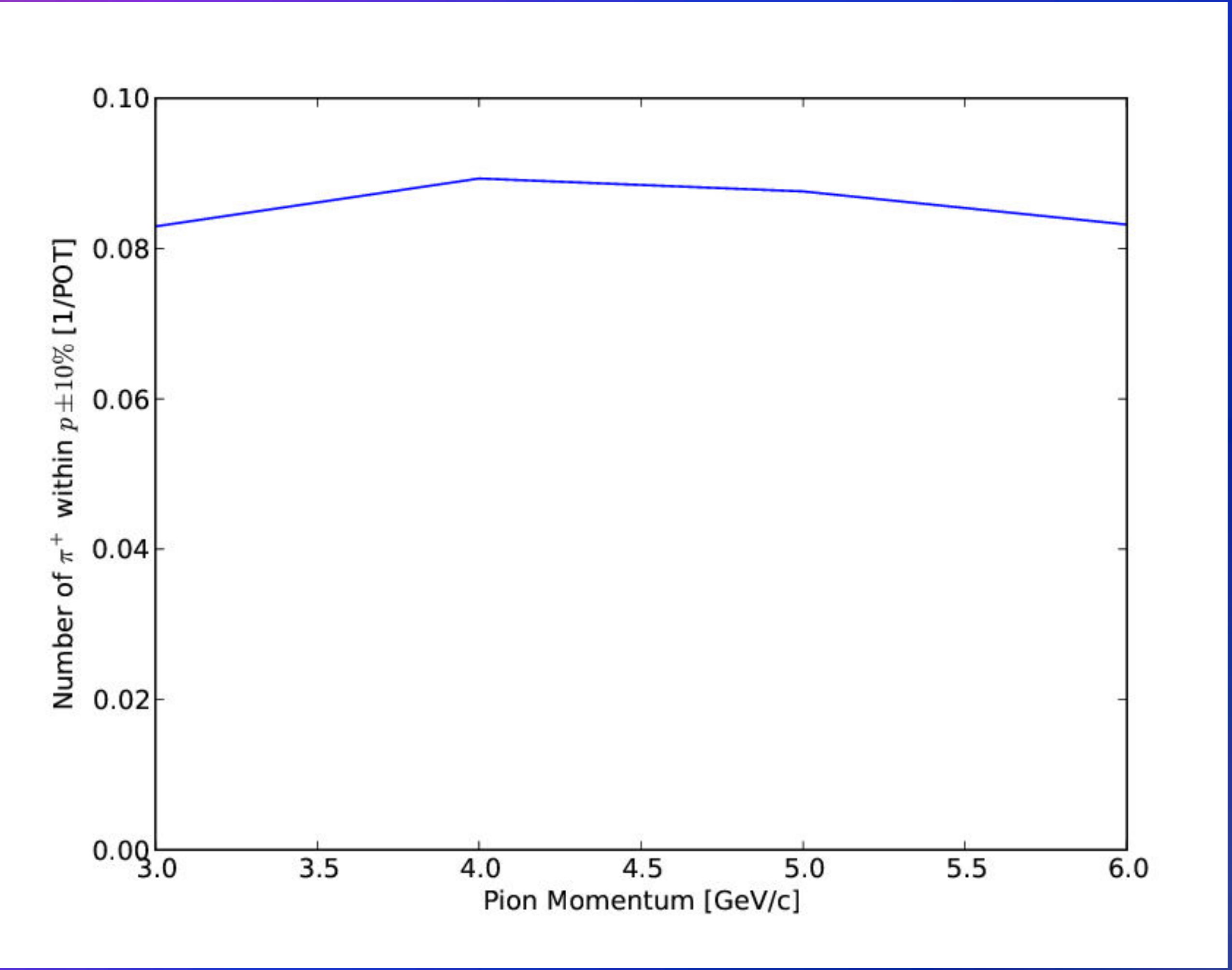
Accelerator

νSTORM

Proton Economics

- Assume new kicker system to kick out 1 booster batch per cycle (≈ 1/6)
  - Mixed-mode operation as in collider days
  - New kickers in cost estimate
- nuSTORM decay ring circumference = booster batch
- 10^{20} POT/year under these assumptions

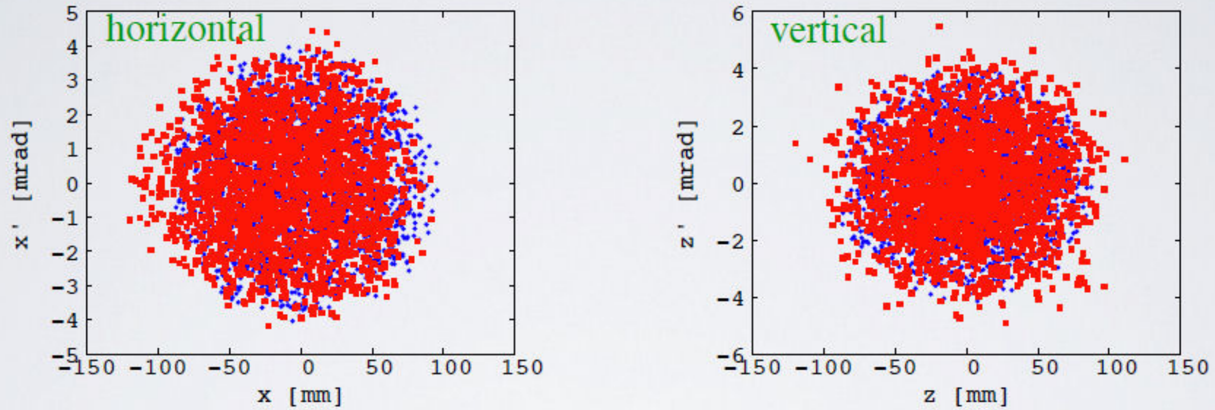
π collection
 # within p ± 10%



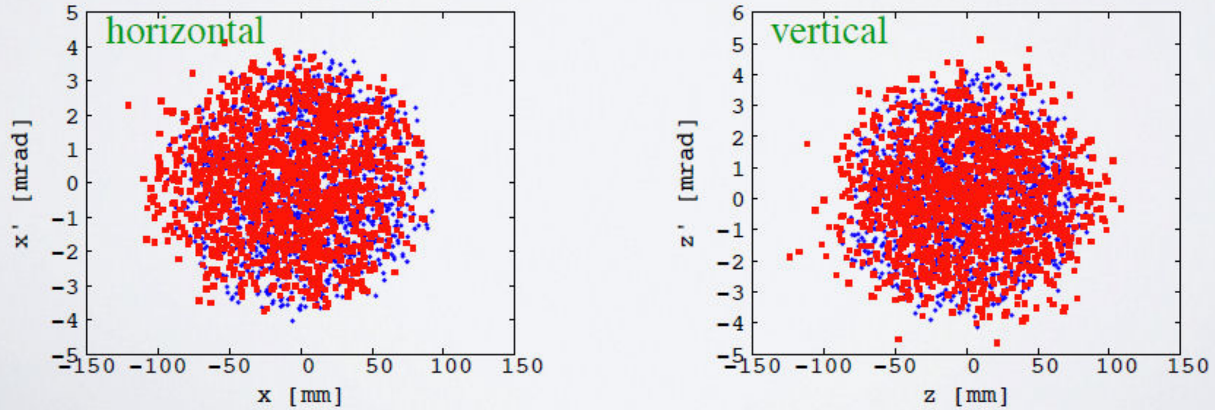
Retune line
(with some loss in efficiency)
to cover $0.3 < E_\nu < 4$ GeV
&
Resultant extension in L/E
X2-2.5 from lattice
considerations

RFFAG Dynamic Aperture

- Δp/p=+-20%; No particle loss after 60turns

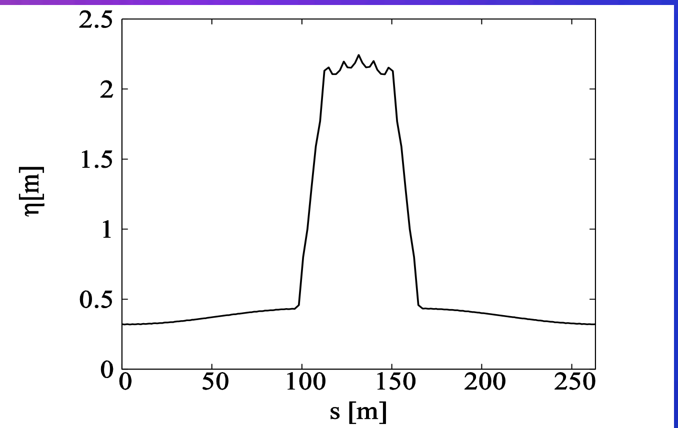


- Δp/p=+-26%; 0.7% particle loss after 60turns

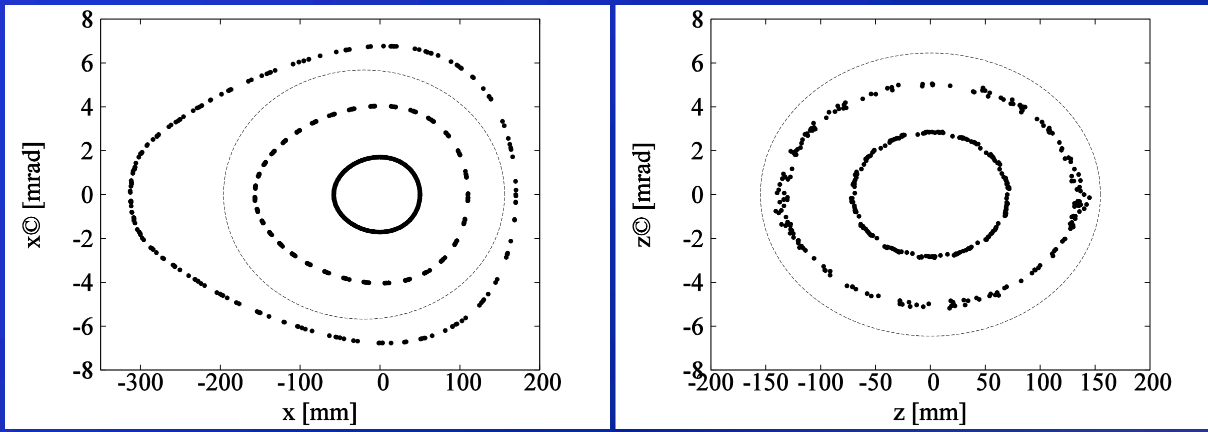


Recent FFAG Decay Ring design

JB Lagrange, Y Mori, J Pasternak, A Sato

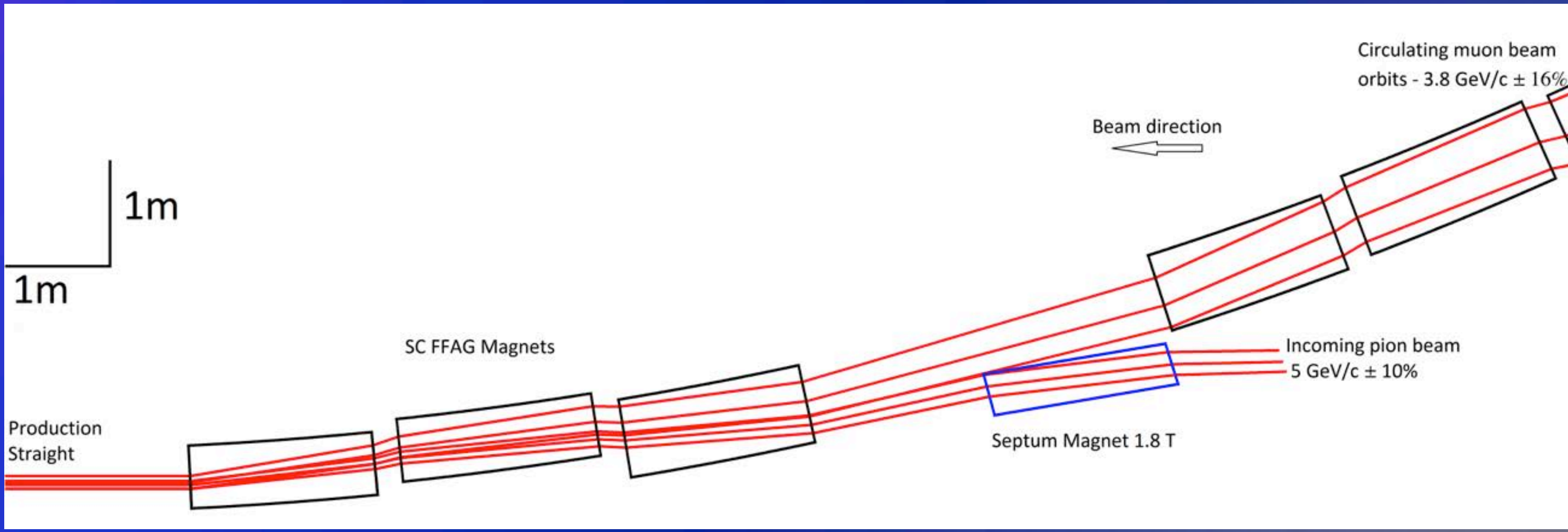


Good dispersion matching (new ring).



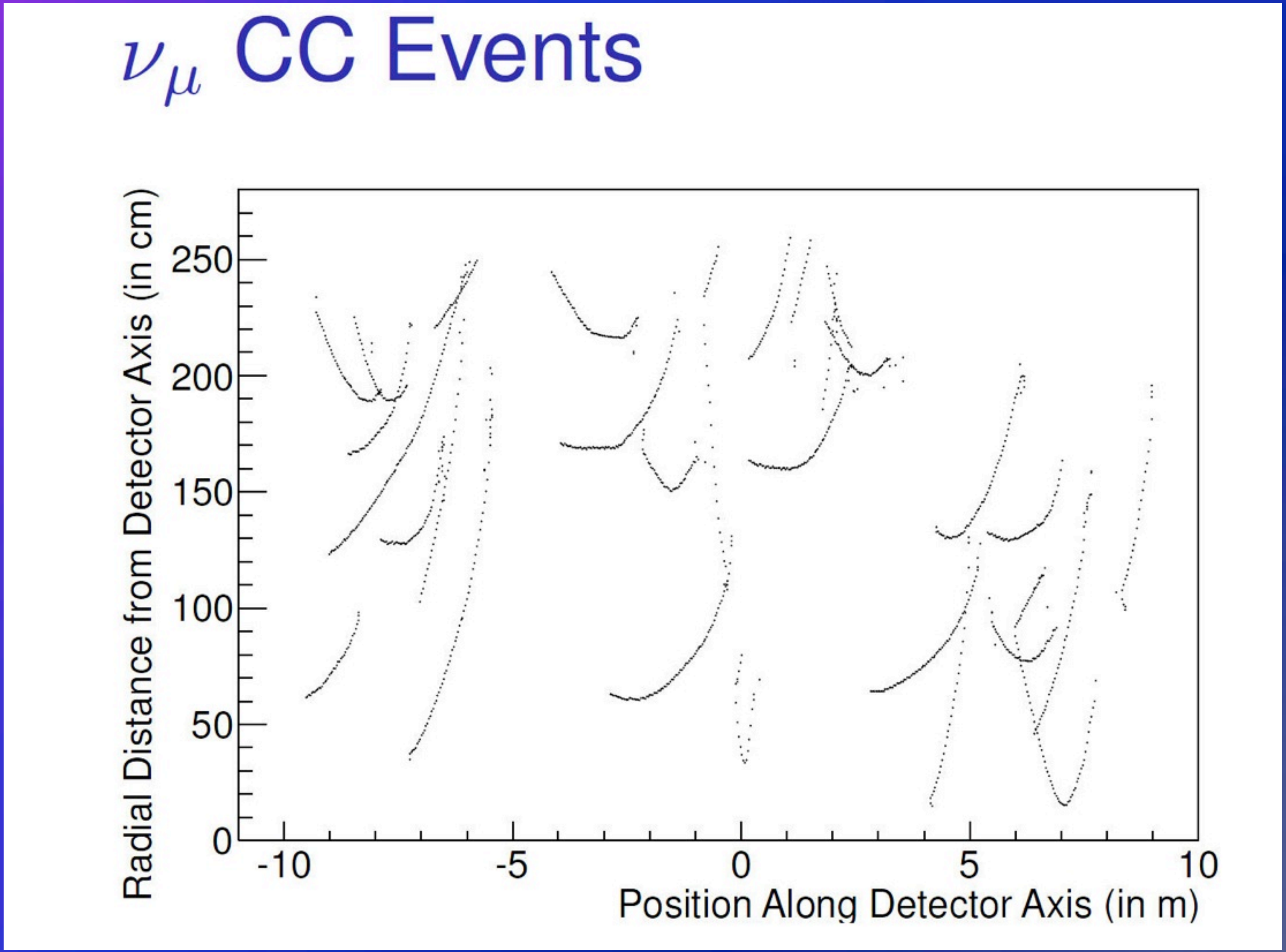
Horizontal (left) and vertical (right) DA (100 turns).

Preliminary stochastic injection geometry



Detector Issues

Event Candidates in SuperBIND

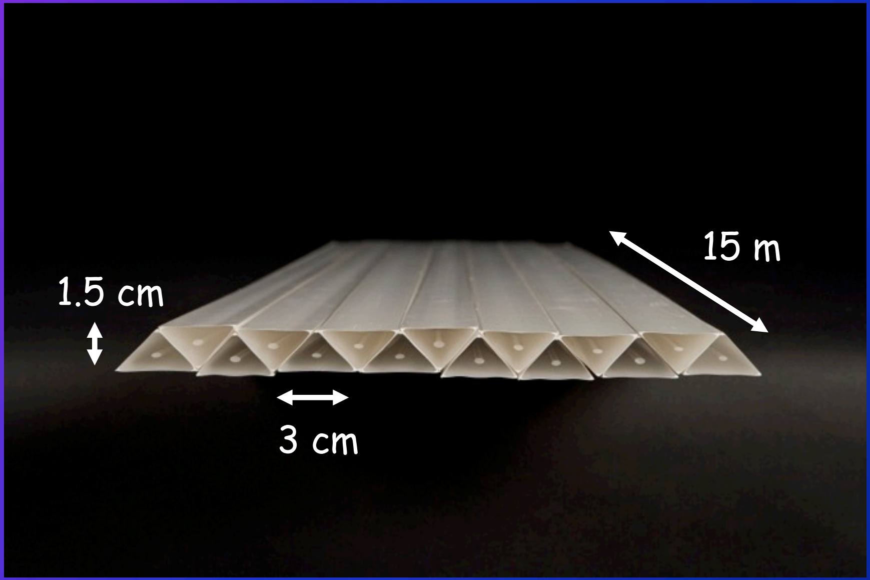


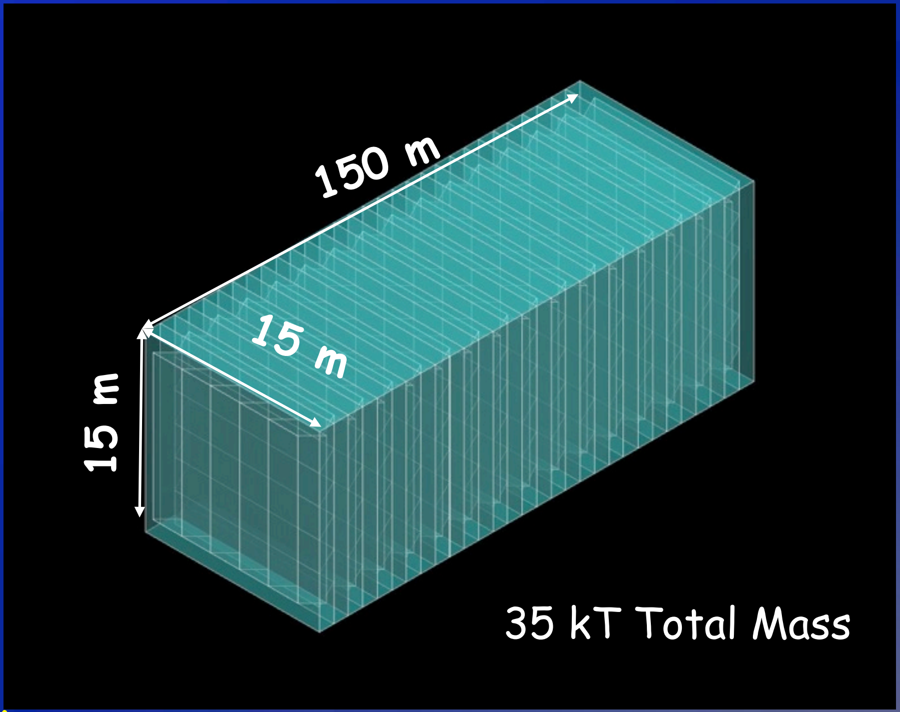
Hits
R vs. Z

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



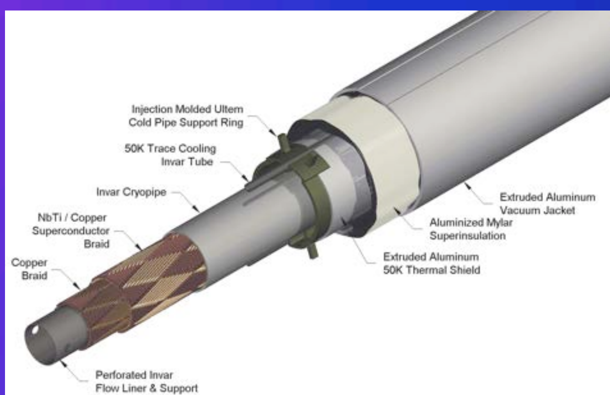


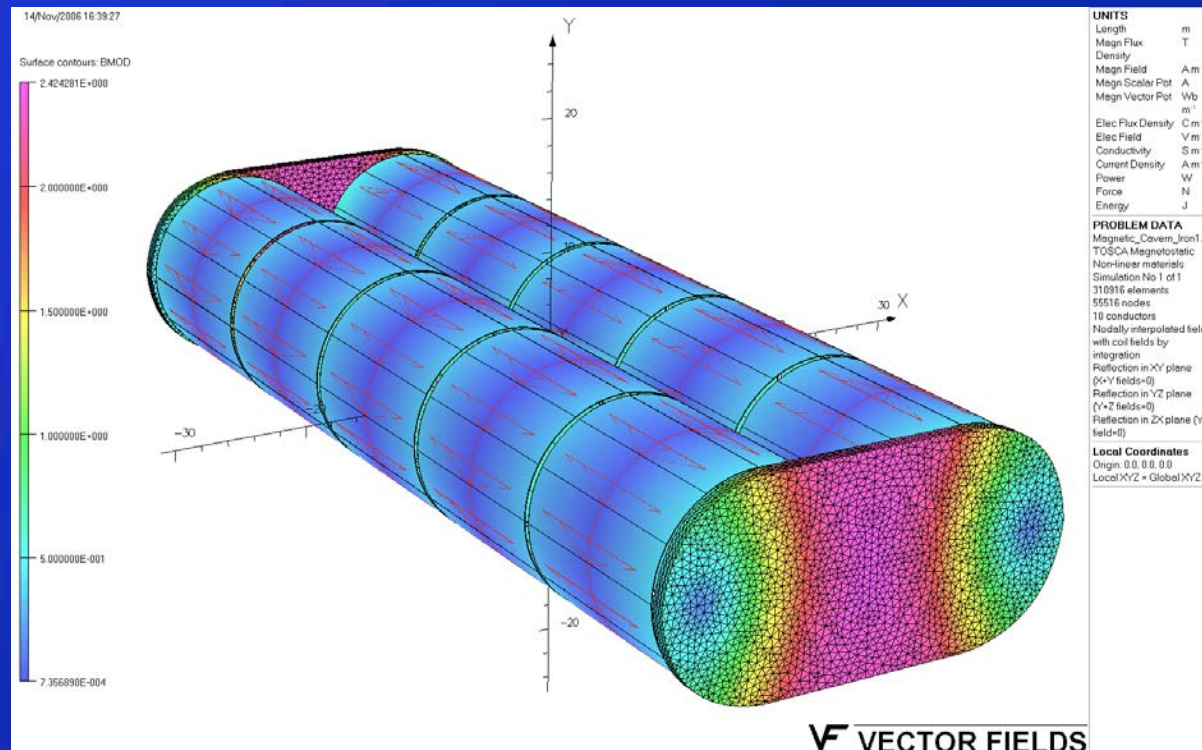
- **Momenta between 100 MeV/c to 15 GeV/c**
- **Magnetic field considered: 0.5 T**
- **Reconstructed position resolution ~ 4.5 mm**

B = 0.5T

Magnet- Concept for IDS-NF

- VLHC SC Transmission Line
  - Technically proven
  - Affordable



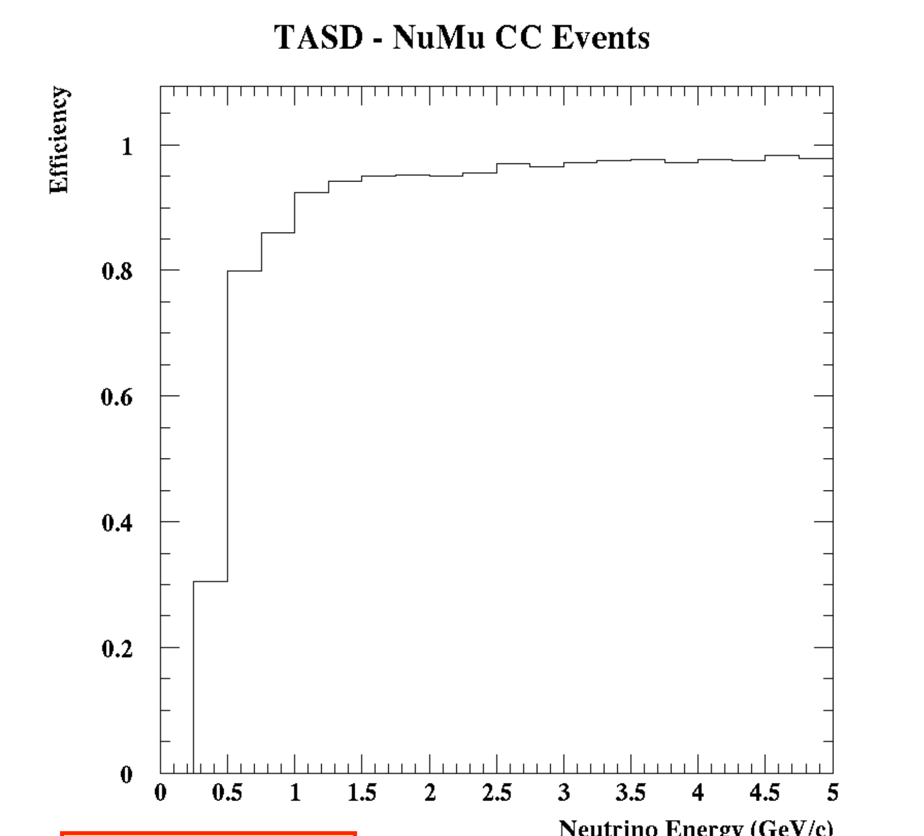


R&D to support concept
Has not been funded

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

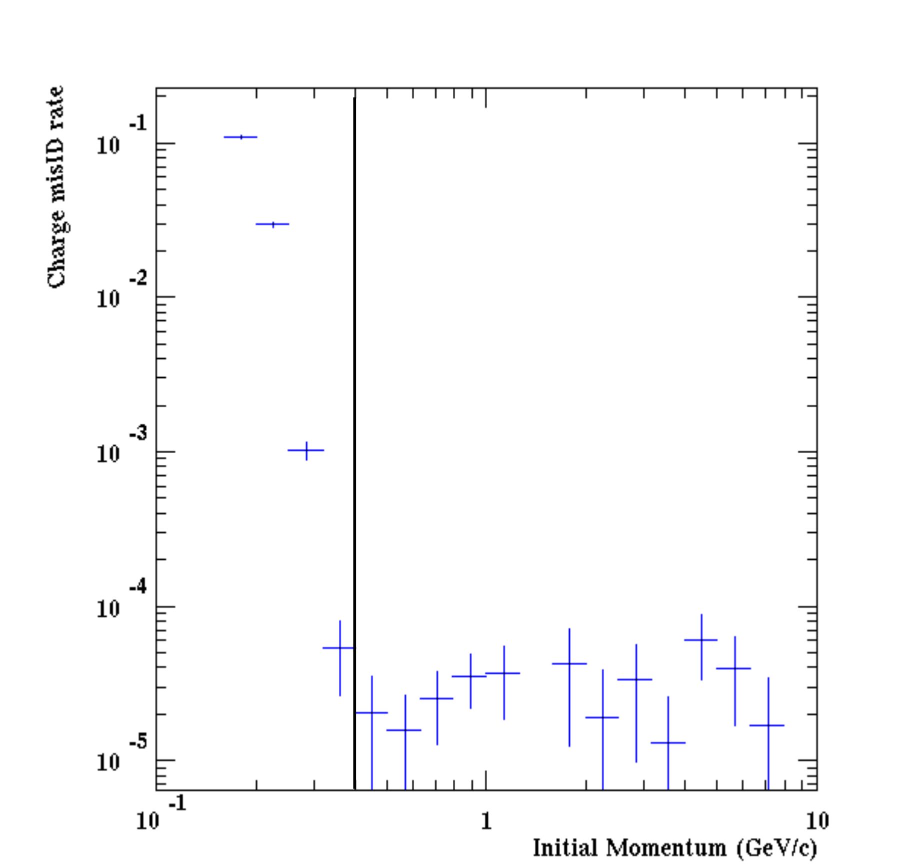
TASD Performance

ν Event Reconstruction ε



Excellent σ_E

Muon charge mis-ID rate



Detector Options

Technology check List

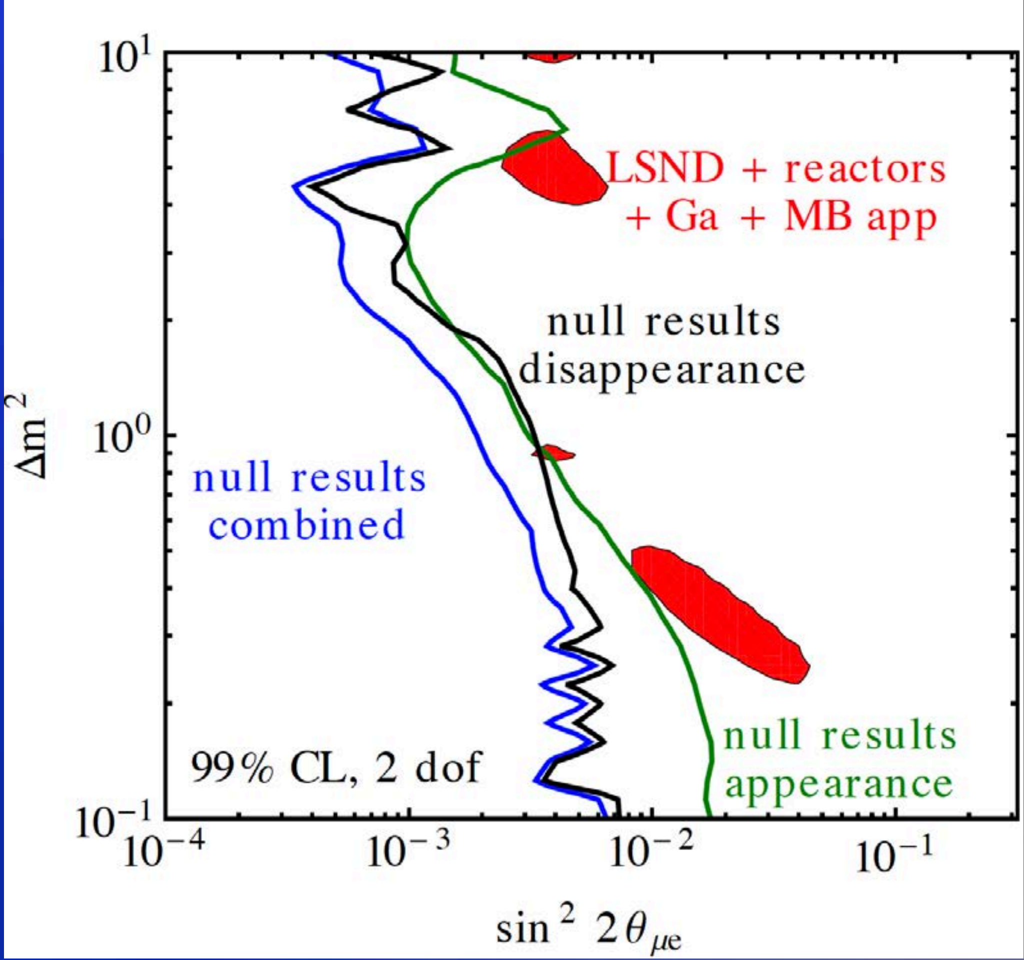
	Fid Volume	B	Recon	Costing Model
SuperBIND	$\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$	$\color{blue}{\checkmark}$
Mag-TASD	$\color{blue}{\checkmark}$	$\color{red}{\checkmark}$	$\color{blue}{\checkmark}$	$\checkmark$
Mag-LAr	$\checkmark$	$\color{red}{\checkmark}$	$\checkmark$	$\color{red}{\checkmark}$

$\color{blue}{\checkmark}$	Yes - OK
$\checkmark$	Maybe
$\color{red}{\checkmark}$	Not Yet

NF Physics & 3+n Models

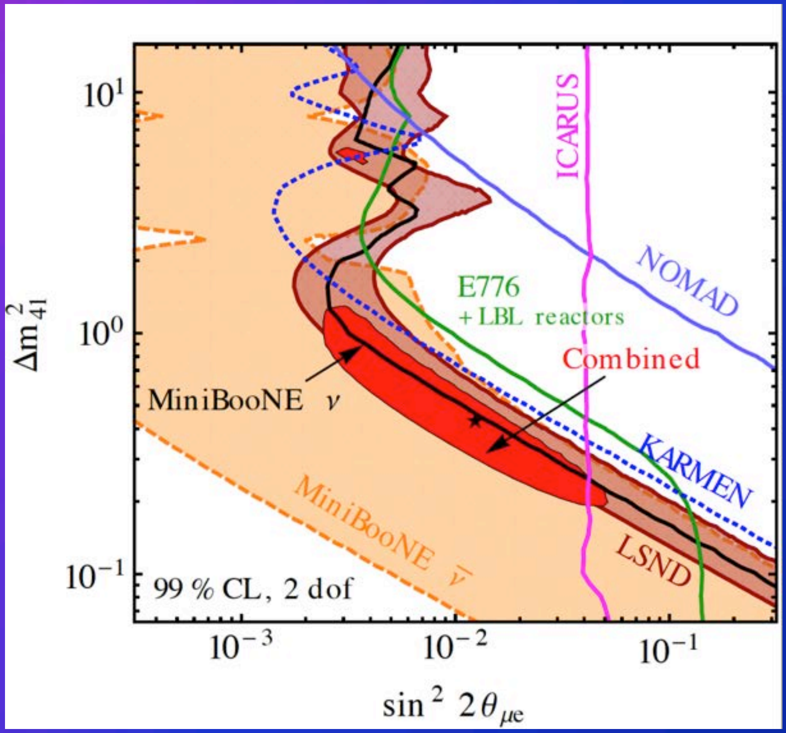
Short-baseline ν oscillation studies

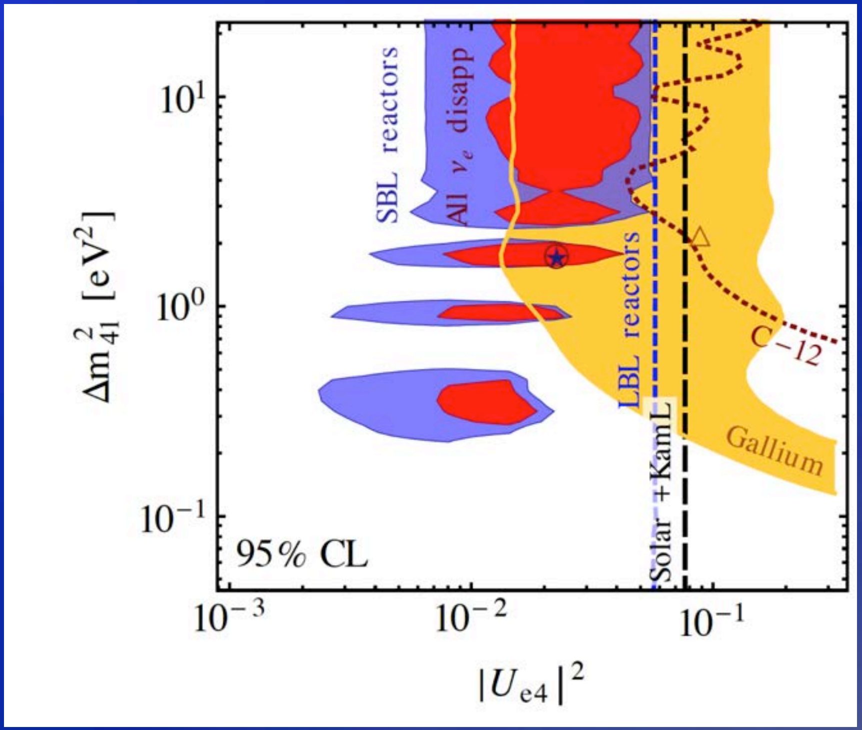
- Sterile neutrinos arise naturally in many extensions of the Standard Model.
  - GUT models
  - Seesaw mechanism for ν mass
  - “Dark” sector
  - Extra dimensions
- Usually heavy, but light not ruled out.
- Experimental hints
  - LSND
  - MiniBooNE
  - Ga
  - Reactor “anomaly”



Kopp, Machado, Maltoni & Schwetz: arXiv:1303.3011".

Appearance & disappearance



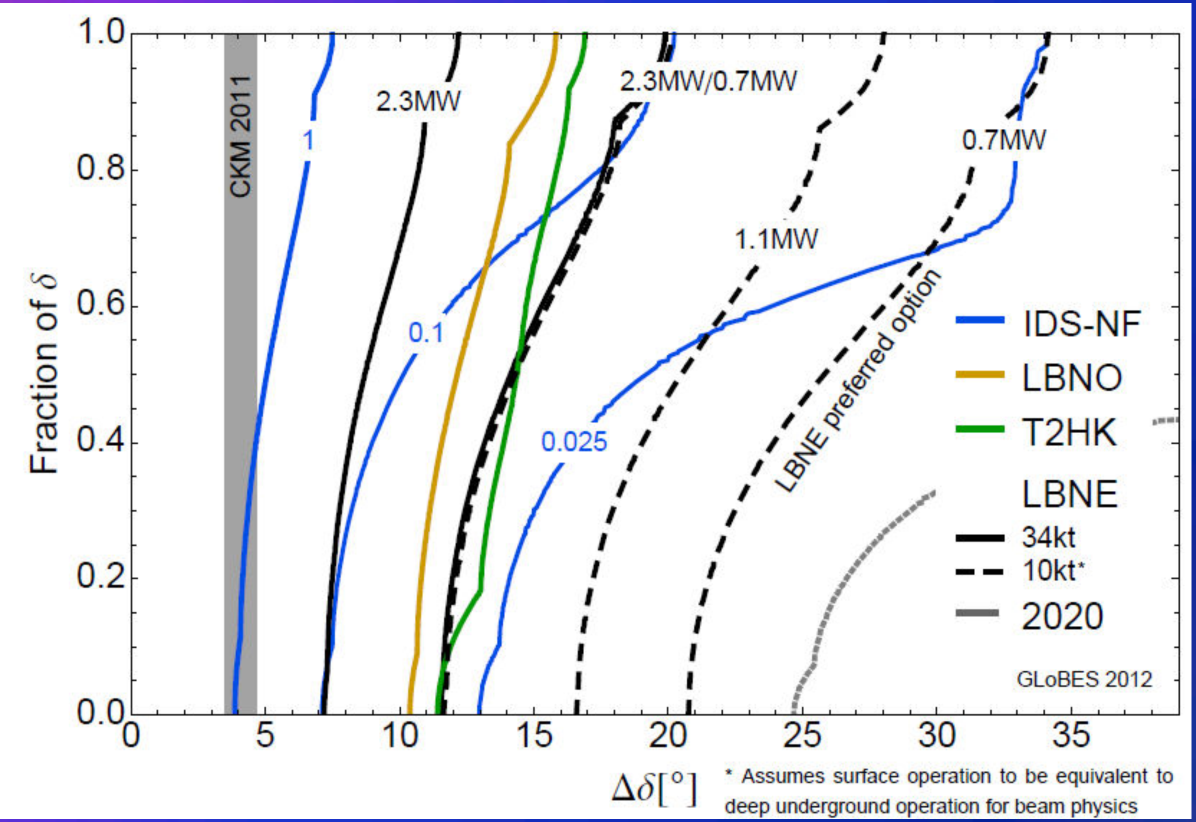


Subsets of appearance and disappearance data are found to be consistent, and it is only when they are combined and when, in addition, exclusion limits on ν_μ disappearance are included, that tension appears.

Steriles and Cosmology

- Estimates of the effective number of neutrino flavors from fits to cosmological data suggest that this number is greater than than 3 (although smaller than 4)
- Sterile neutrinos that have self-interactions could avoid these bounds altogether
  - A self-induced MSW potential for the steriles suppresses mixing of active and sterile neutrinos in the early Universe, so that oscillations of active to sterile neutrinos become strongly suppressed
    - Hannestad, Hansen and Tram, arXiv:1310.5926
    - Dagupta and Kopp, arXiv:1310.6337

NF Upgrade path

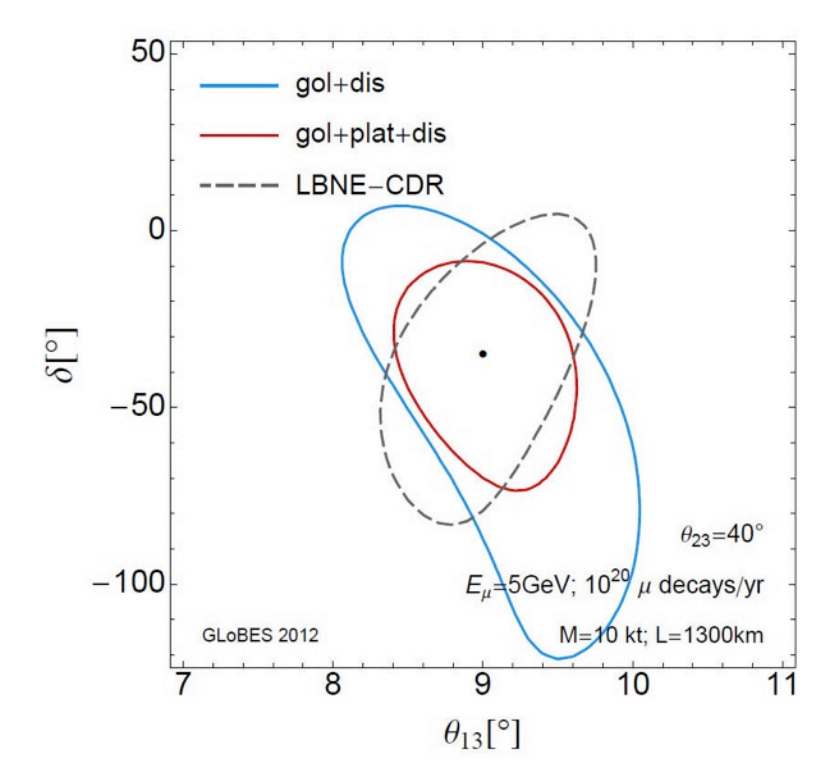


P. Coloma, P.Huber, J. Kopp, W. Winter, Phys.Rev. D87 (2013)

- 2020 – T2K, NOνA and Daya Bay
- LBNE – 1300 km, 34 kt
  - 0.7MW, 2×10^8 s (10 yrs)
- LBNO – 2300 km, 100 kt
  - 0.8MW, 1×10^8 s (10 yrs)
- T2HK – 295 km, 560 kt
  - 0.7MW, 1.2×10^8 s (10 yrs)
- 0.025 IDS-NF
  - 700kW (5 yrs)
  - no cooling
  - 2×10^8 s running time
  - 10 kt detector
  - Still Very Expensive
    - LBNE (10kt, surface)

Think even smaller (cheaper)

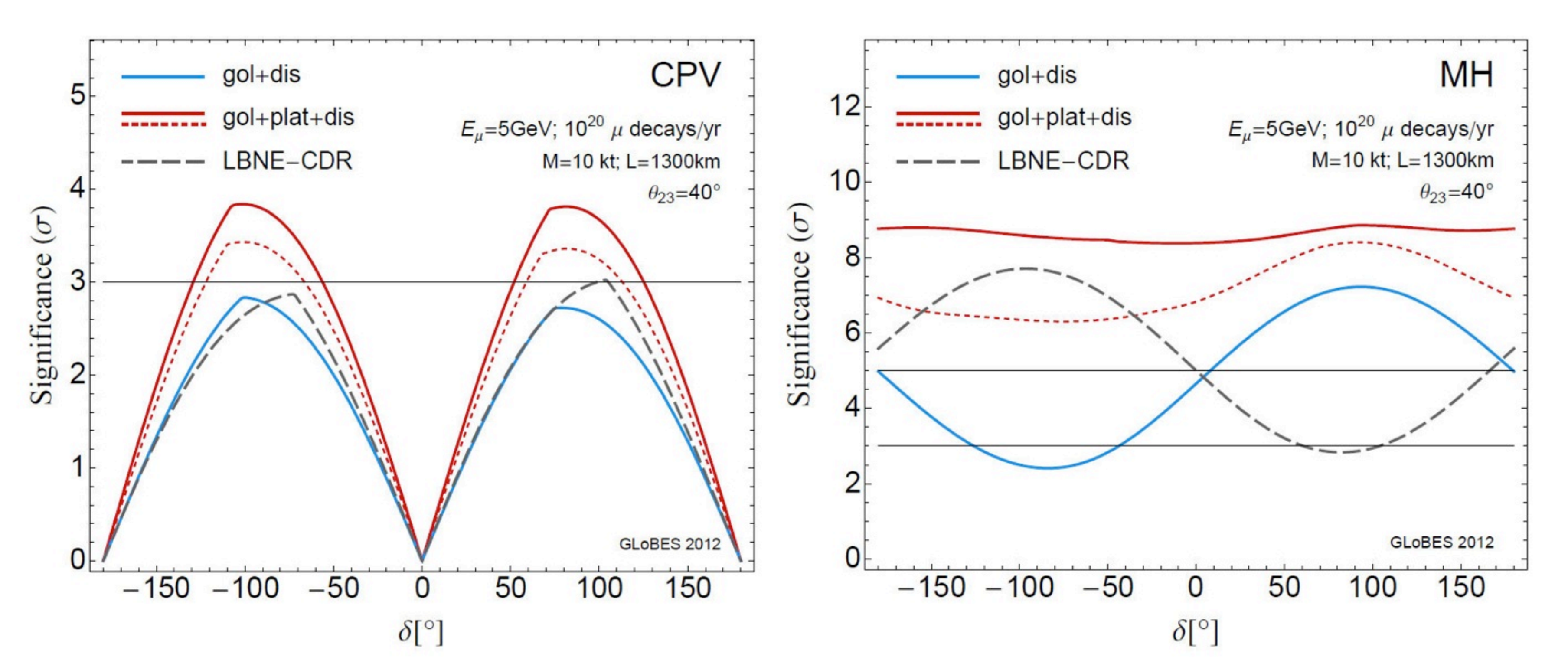
- Low energy Low luminosity NF (L3NF)
  - Add platinum channel (ν_e appearance)
    - Need excellent charge ID
  - E_μ of 5 Gev
  - L = 1300 km
- Specifics
  - 700 kW on target
  - 2 X 10^7 sec/yr.
  - No cooling
- 1% of baseline NF:
  - 10^{20} useful μ decays/yr.
  - 10 kT of Magnetized LAr
    - Underground



Christensen, Coloma and Huber
arXiv: 1301.7727

Confidence region in the θ_{13} – δ plane for a particular point in the parameter space, at 1σ

L3NF: CPV and MH



What is still so compelling about the NF is how robust its physics case is. Even at only 1% of the baseline Flux X (Fiducial Mass), it still can do world-class physics. It also presents a tenable upgrade path to explore with much greater precision the νSM and to look beyond, NSIs, heavy ν……?.

3 + 3 Model

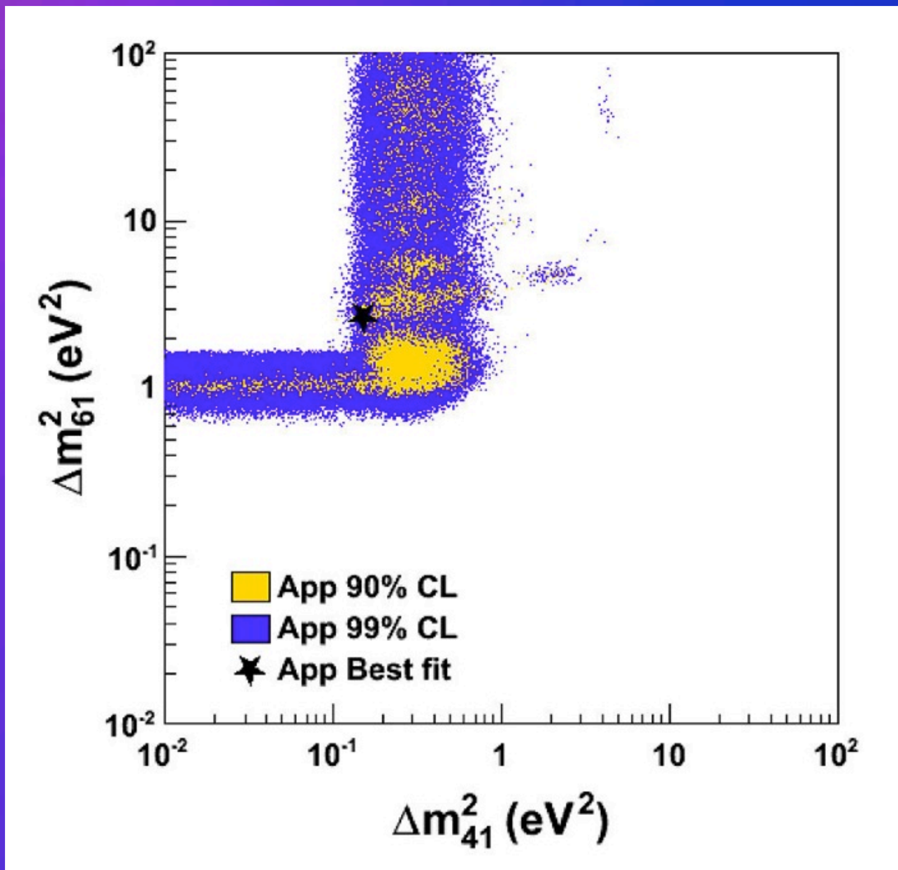
	χ^2_{min} (dof)	χ^2_{null} (dof)	P_{best}	P_{null}	χ^2_{PG} (dof)	PG (%)
3+1						
All	233.9 (237)	286.5 (240)	55%	2.1%	54.0 (24)	0.043%
App	87.8 (87)	147.3 (90)	46%	0.013%	14.1 (9)	12%
Dis	128.2 (147)	139.3 (150)	87%	72%	22.1 (19)	28%
ν	123.5 (120)	133.4 (123)	39%	25%	26.6 (14)	2.2%
$\overline{\nu}$	94.8 (114)	153.1 (117)	90%	1.4%	11.8 (7)	11%
App vs. Dis	-	-	-	-	17.8 (2)	0.013%
ν vs. $\overline{\nu}$	-	-	-	-	15.6 (3)	0.14%
3+2						
All	221.5 (233)	286.5 (240)	69%	2.1%	63.8 (52)	13%
App	75.0 (85)	147.3 (90)	77%	0.013%	16.3 (25)	90%
Dis	122.6 (144)	139.3 (150)	90%	72%	23.6 (23)	43%
ν	116.8 (116)	133.4 (123)	77%	25%	35.0 (29)	21%
$\overline{\nu}$	90.8 (110)	153.1 (117)	90%	1.4%	15.0 (16)	53%
App vs. Dis	-	-	-	-	23.9 (4)	0.0082%
ν vs. $\overline{\nu}$	-	-	-	-	13.9 (7)	5.3%
3+3						
All	218.2 (228)	286.5 (240)	67%	2.1%	68.9 (85)	90%
App	70.8 (81)	147.3 (90)	78%	0.013%	17.6 (45)	100%
Dis	120.3 (141)	139.3 (150)	90%	72%	24.1 (34)	90%
ν	116.7 (111)	133.4 (123)	34%	25%	39.5 (46)	74%
$\overline{\nu}$	90.6 (105)	153 (117)	84%	1.4%	18.5 (27)	89%
App vs. Dis	-	-	-	-	28.3 (6)	0.0081%
ν vs. $\overline{\nu}$	-	-	-	-	110.9 (12)	53%

- *A 3+3 model has recently been shown to better fit all available data*

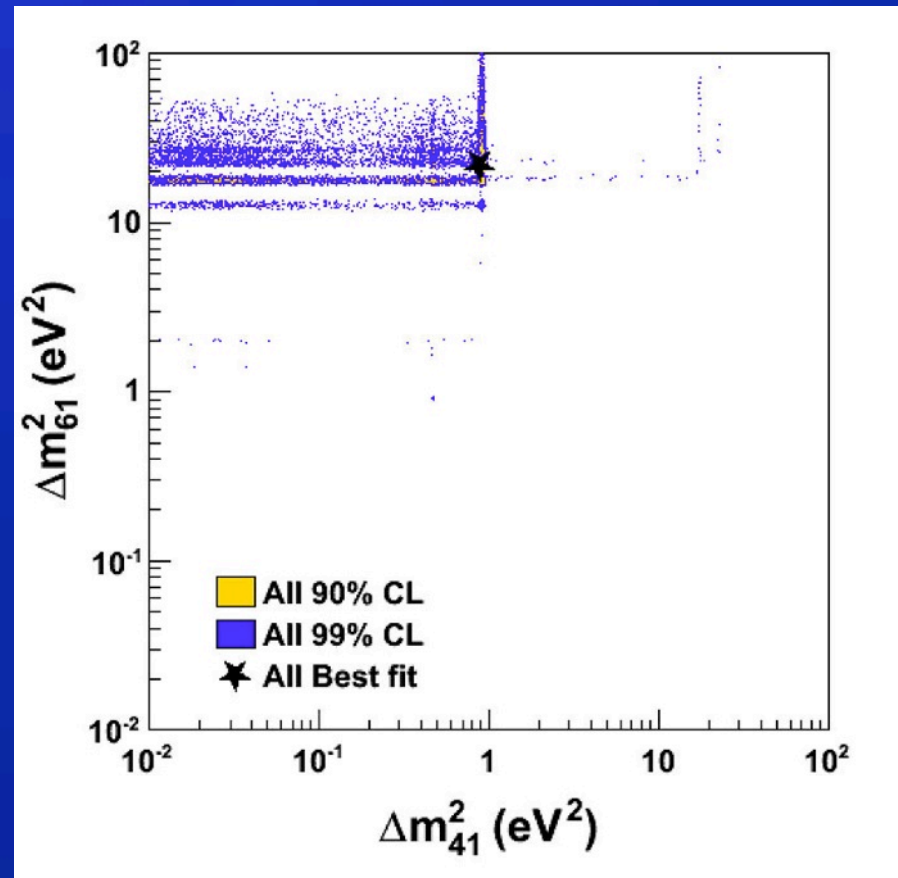
Tag	Section	Process	ν vs. $\bar{\nu}$	App vs. Dis
LSND	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN	3.2.1	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
KARMEN/LSND(xsec)	3.2.1	$\nu_e \to \nu_e$	ν	Dis
BNB-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB($\bar{\nu}$app)	3.2.2	$\bar{\nu}_\mu \to \bar{\nu}_e$	$\bar{\nu}$	App
NuMI-MB(νapp)	3.2.2	$\nu_\mu \to \nu_e$	ν	App
BNB-MB(νdis)	3.2.2	$\nu_\mu \to \nu_\mu$	ν	Dis
NOMAD	3.2.3	$\nu_\mu \to \nu_e$	ν	App
CCFR84	3.2.3	$\nu_\mu \to \nu_\mu$	ν	Dis
CDHS	3.2.3	$\nu_\mu \to \nu_\mu$	ν	Dis
Bugey	3.2.4	$\bar{\nu}_e \to \bar{\nu}_e$	$\bar{\nu}$	Dis
Gallium	3.2.4	$\nu_e \to \nu_e$	ν	Dis
MINOS-CC	3.2.5	$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\bar{\nu}$	Dis
ATM	3.2.5	$\nu_\mu \to \nu_\mu$	ν	Dis

J.M. Conrad, C.M. Ignarra, G. Karagiorgi, M.H. Shaevitz, J. Spitz (arXiv:1207.4765v1)

3 + 3 Model II



Appearance Data

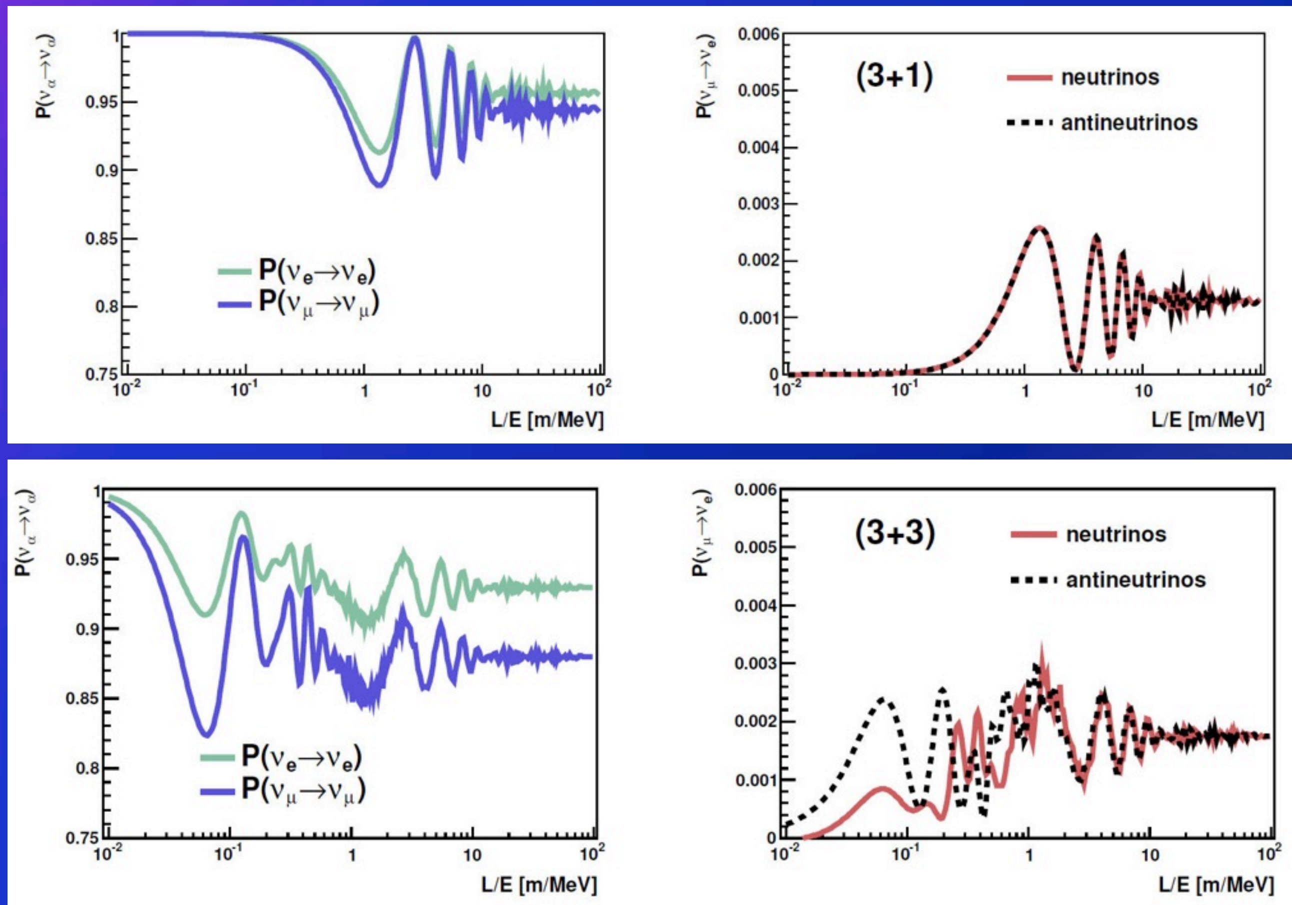


All Data

Lesson: Have access to as many channels as possible and cover as much of the parameter space as possible

νSTORM

L/E dependence



Very different L/E dependencies for different models
Experiments covering a wide range of L/E regions are required.

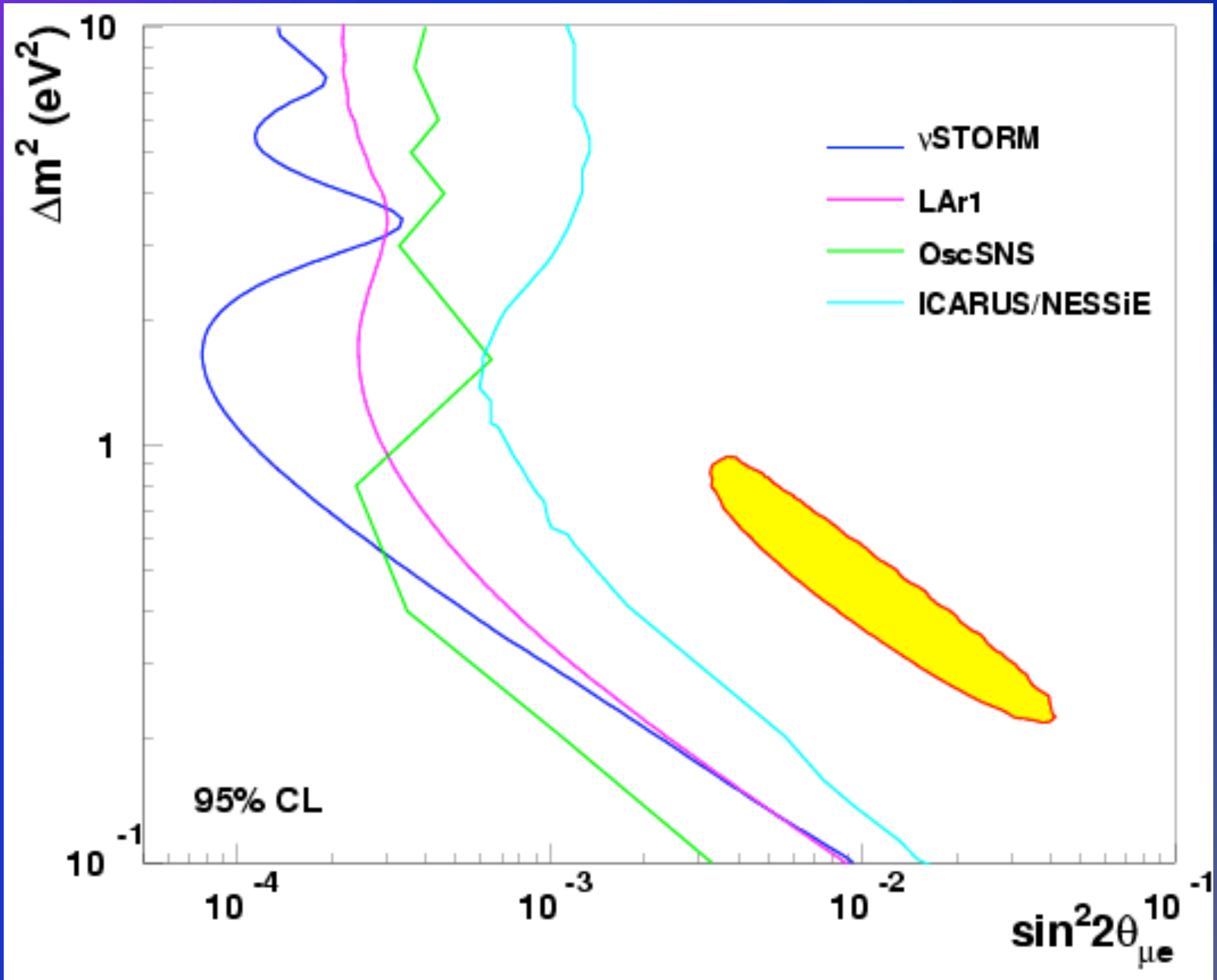
Future sterile searches

S:B for Appearance Channel
Past and Future(?)

Experiment	S:B
LSND	2:1
MiniBooNE	1:1 → 1:2
ICARUS/NESSiE	≈1.5:1 / 1:4
LAr-LAr	1:4
K^+ DAR	≈4:1
LSND Reloaded	5:1
oscSNS	3:1
nuSTORM	11:1 → 20:1

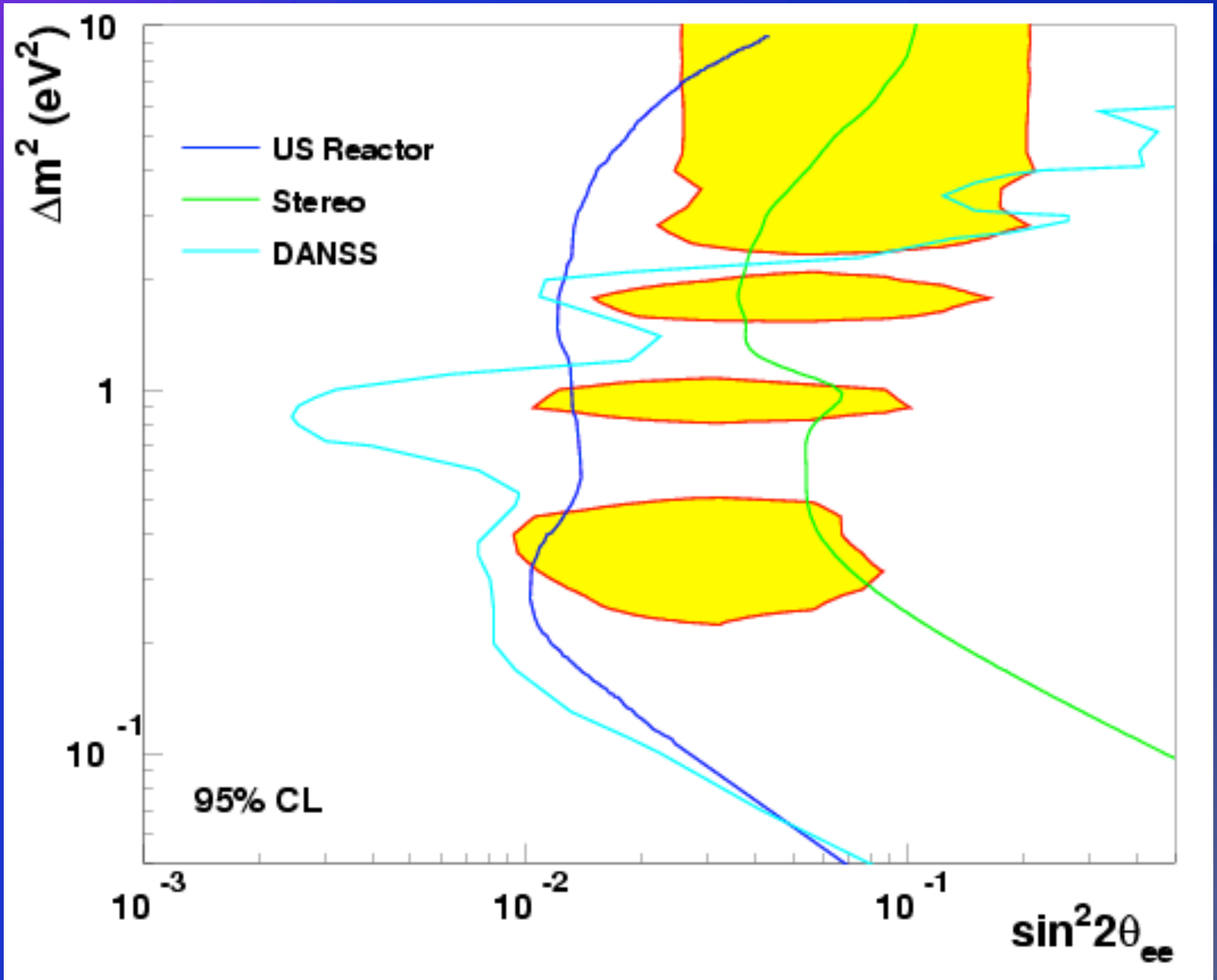
- Note: There are a number of experiments with megaCi to petaCi sources next to large detectors that have an exquisite signature of steriles (# evts/unit length displays oscillatory behavior in large detector) and have large effective S:B
  - SNO+Cr, Ce-Land, LENS, Borexino, Daya Bay
  - IsoDAR
  - A number of very-short baseline reactor experiments

Appearance



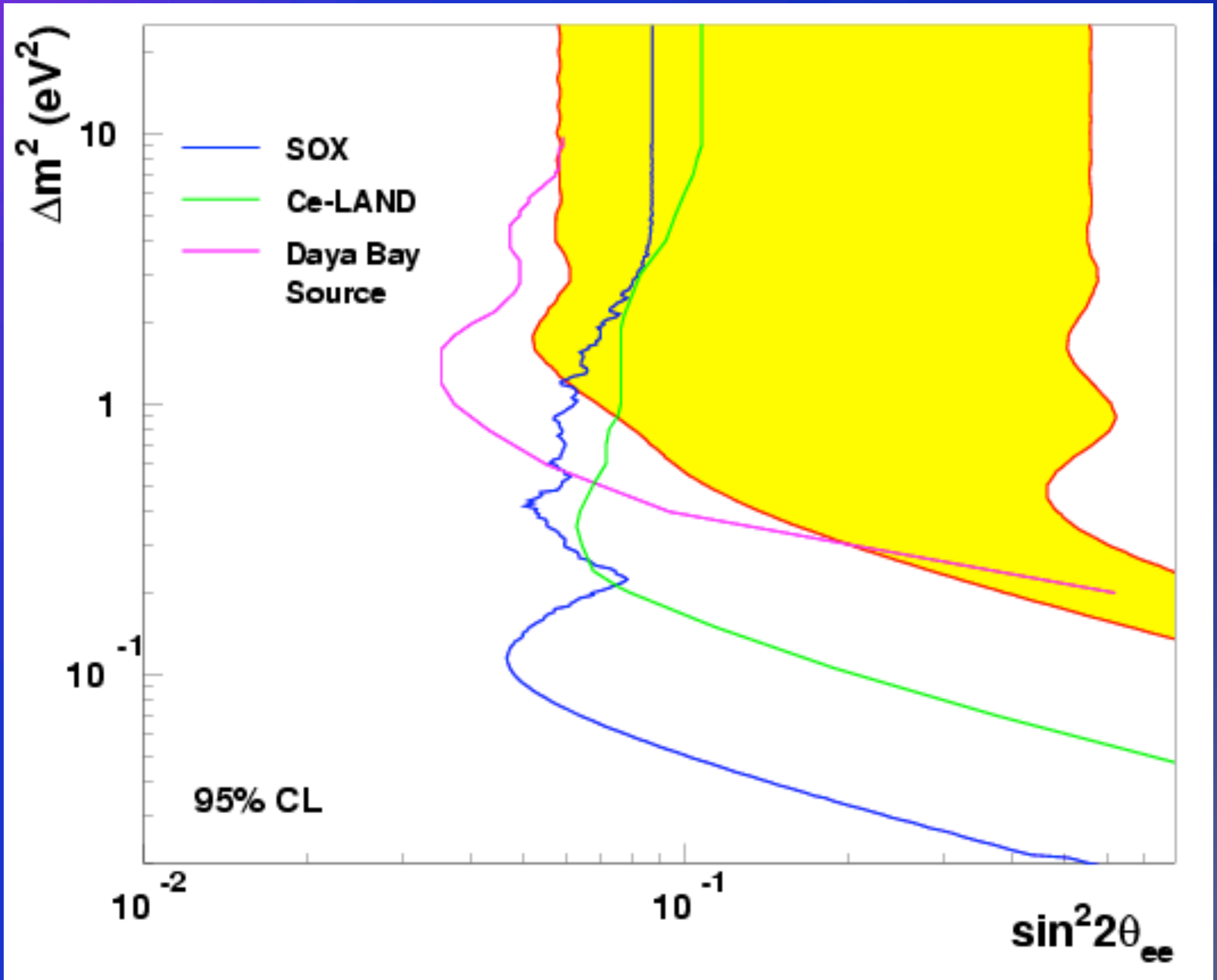
Δm^2 (eV^2)
10
1
10^{-1}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
$\sin^2 2\theta_{\mu e}$
νSTORM
LAr1
OscSNS
ICARUS/NESSiE
95% CL

Reactor



US Reactor
Stereo
DANSS
95% CL
Δm^2 (eV^2)
$\sin^2 2\theta_{ee}$
10
1
10^{-1}
10^{-3}
10^{-2}
10^{-1}

Radioactive source

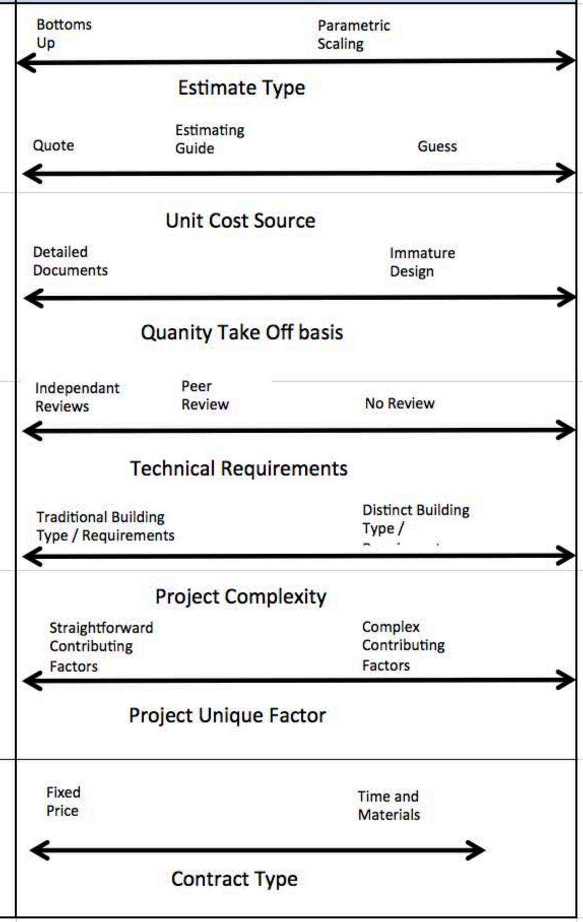


Costing

Contingency estimating criteria

Fermilab Guidance for Conventional Facilities for Contingency due to Estimate Uncertainty			
Code	Design Maturity	Contingency	Remarks
	Project Definition	40-100%	Scope Developed
	Conceptual	20-40%	10-15% design complete
	Preliminary	10-30%	30% design complete
	Final Design	5-20%	Bid Docs Complete
	Contract Award	0-5%	

Contributing Factors



Association for the Advancement of Costing Engineering (AACE)

Bob O'Sullivan

Developing the Cost Range

	Primary Characteristic	Secondary Characteristic		
ESTIMATE CLASS	**DEGREE OF PROJECT DEFINITION** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 70%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	70% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Example: LBNE

Elements of the Estimate - TPC

- Total Project Cost (TPC)
  - TPC includes the sum of all Estimate Elements,
  - The TPC provides 40% Contingency, with an expected Confidence Level of 95% (Project Director's Assessment)

130 L.B.N.E.	Cost to Date (in M)	Estimate to Complete (ETC) (in M)	Bottoms Up Estimate Uncertainity Contingency (in M)	Risk Based Contingency (in M)	Top Down Contingency (in M)	TPC (in M)
	thru 6/2012	beyond 6/2012				
130.01 Project Office	$7.0	$50.0	$8.9	$7.2	$30.0	$103.1
130.02 Beamline	$7.4	$121.9	$33.5	$1.8		$164.7
130.03 Near Detector	$4.6	$7.3	$1.3	$9.4		$22.6
130.04 Water Cherenkov Detector	$11.2	$0.0				$11.2
130.05 LAr Far Detector	$7.8	$173.6	$61.9	$9.9		$253.1
130.06 LBNE Conventional Facilities	$6.9	$234.3	$57.8	$13.8		$312.8
Grand Total	**$44.8**	**$587.1**	**$163.7**	**$42.1**	**$30.0**	**$867.4**
% Contingency			**28%**	**7%**	**5%**	**40%**

νSTORM

LBNE cost range

Calculating the Cost Range

- Actuals thru June 2012 were then added to Cost Range for Estimate to Complete to determine the TPC Cost Range
- Per AACE, following this approach provides a 95% confidence level that the actual costs will fall below the upper end of the cost range.

130 L.B.N.E.	Cost Range Estimate to Complete (in M)		Cost to Date (in M)	TPC Cost Range (in M)	
	minus (-)	plus (+)	thru 6/2012	minus (-)	plus (+)
130.01 Project Office	$75.2	$106.2	$7.0	$82.2	$113.2
130.02 Beamline	$129.0	$164.9	$7.4	$136.4	$172.3
130.03 Near Detector	$13.1	$18.5	$4.6	$17.7	$23.1
130.04 Water Cherenkov Detector	$0.0	$0.0	$11.2	$11.2	$11.2
130.05 LAr Far Detector	$184.9	$271.9	$7.8	$192.6	$279.6
130.06 LBNE Conventional Facilities	$239.8	$338.5	$6.9	$246.6	$345.4
Grand Total	**$642.0**	**$899.9**	**$44.8**	**$686.8**	**$944.7**
% Contingency				**9%**	**53%**

Top of Range provides for 53% contingency above Base Estimate

Program Committee Reviews

Fermilab PAC – June, 2013

- The PAC received the proposal to build a muon storage ring facility to produce a neutrino beam from 3.8 GeV muon decays and a baseline set of near and far detectors. The PAC reiterates the opinion that such a configuration would provide an ideal and unique setup to study eV-scale oscillation physics in appearance and disappearance modes, to measure electron and muon neutrino cross-sections with an unprecedented precision, and to provide a test bed for muon accelerator technologies.

- The Collaboration is commended for its comprehensive proposal, which includes detailed conceptual designs for the target region, the storage ring, and the conventional facilities for near and far detectors.

- The PAC notes the small size of the Collaboration compared to the scale of the NuSTORM project, and encourages the team to find ways to enlarge the community interested in using the facility. In this regard, the PAC suggests that now would be an excellent time to welcome wider participation, as the project is in its formative stages. The PAC is especially interested in understanding potential collaboration with CERN.

- 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 an attractive and intriguing project. Resources are, of course, limited. The PAC therefore recommends Stage-1 approval and consideration at the upcoming Snowmass meeting and by P5.

CERN SPSC

- Response from SPSC:
  - The SPSC recognizes the nuSTORM project as an important step in the long-term development of a neutrino factory, presently considered as the ultimate facility to study CP violation in the neutrino sector. nuSTORM would also constitute a test bed for accelerator and beam physics R&D. The Committee appreciates that, in addition to these long term goals, nuSTORM could also provide the opportunity to settle important questions in the sector of sterile neutrinos, and to perform precise neutrino cross section measurements for the future neutrino programmes.
  - Currently, conventional long baseline LA-based programmes are being discussed in Europe (LBNO) and in the US (LBNE), aiming at the determination of CP violation in the neutrino sector on a shorter time scale than neutrino factories. The Committee **notes** that the nuSTORM collaboration is also exploring the possibility of being hosted by Fermilab and that there is a sizeable overlap with the LBNO community. All projects under discussion would involve a large amount of funding and resources, which calls for adequate cooperation and prioritisation within the neutrino community.
  - In this context, the SPSC considers that, in line with the recently updated European Strategy, an involvement in nuSTORM could be part of the CERN contributions to the development of future neutrino programmes. A further review of the project would require a more focused proposal identifying which tasks could be performed at CERN within a more general project defined in cooperation with Fermilab and other contributing institutes.

CERN Participation

- It is under discussion that two CERN Fellows, one in the BE Department, the second in the PH Department, be recruited to take forward the nuSTORM program as follows:
  - BE Department: Under the leadership of Elena Wildner, the BE Department CERN Fellow will play a leading role in the work described in the EoI, i.e.: consider how nuSTORM could be implemented at CERN and how a European collaboration with CERN at its heart could contribute to the nuSTORM if it were to be carried out at FNAL; and
  - PH Department: The PH Department CERN Fellow will work within the emerging neutrino activity led by Marzio Nessi to evaluate the impact of systematic uncertainties on future long-baseline neutrino oscillation experiments and to evaluate the experimental programmes required to address these uncertainties. An important and substantial part of this work would be the study of the measurement of (electron-)neutrino-nucleus scattering cross sections and the importance of nuSTORM.
  - In addition support from members of the technical departments would be required to carry out the site-specific and site-independent investigation.
    - Magnet and beam line instrumentation groups