Neutrinos from Stored Muons

$\nu$ physics with a $\mu$ storage ring
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
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 it 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.
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

- Wilson Hall
- Main Ring
- Main Injector
- Primary Beamline
- Target Station
- Muon Decay Ring
- Near Detector
- Transport Line
- Far Detector
Scope:
nuSTORM Facility near site

$\mu$ decay ring: $P = 3.8 \text{ GeV/c} \pm 10\%$
Scope:
Far site - D0 Assembly Building
nuSTORM Physics program

- Addresses the SBL, large $\delta m^2\nu$-oscillation regime
- Provides a beam for precision $\nu$ interaction physics (GeV-scale high-statistics $\nu_e$ & anti-$\nu_e$ 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 $\mu$ decay ring R&D (instrumentation) & technology demonstration platform
  - Provides a $\nu$ Detector Test Facility
Based on $10^{21}$ 120 GeV POT, we obtain
$\approx 1.9 \times 10^{18}$ useful $\mu$ decays

- In PIP era, extract one Booster batch/cycle ($10^{20}$ POT/yr $\rightarrow$ 10 year run)
- Baseline FODO ring, C target, NUMI style
- 1 horn

- Inconel target + horn optimization + RFFAG $\rightarrow$ X5 (2 year run)
E$_\nu$ spectra (3.8 GeV/c $\mu^+$ stored)

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

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N_{evts}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{\nu}_\mu$ NC</td>
<td>844,793</td>
</tr>
<tr>
<td>$\nu_\mu$ NC</td>
<td>1,387,698</td>
</tr>
<tr>
<td>$\bar{\nu}_\mu$ CC</td>
<td>2,145,632</td>
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<tr>
<td>$\nu_\mu$ CC</td>
<td>3,960,421</td>
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</table>

Event rates at Far detector

<table>
<thead>
<tr>
<th>Channel</th>
<th>$N_{osc}$</th>
<th>$N_{null}$</th>
<th>Diff.</th>
<th>$(N_{osc} - N_{null})/\sqrt{N_{null}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e \rightarrow \nu_\mu$ CC</td>
<td>332</td>
<td>0</td>
<td>$\infty$</td>
<td>$\infty$</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$ NC</td>
<td>47679</td>
<td>50073</td>
<td>-4.8%</td>
<td>-10.7</td>
</tr>
<tr>
<td>$\nu_e \rightarrow \nu_e$ NC</td>
<td>73941</td>
<td>78805</td>
<td>-6.2%</td>
<td>-17.3</td>
</tr>
<tr>
<td>$\bar{\nu}<em>\mu \rightarrow \bar{\nu}</em>\mu$ CC</td>
<td>122322</td>
<td>128433</td>
<td>-4.8%</td>
<td>-17.1</td>
</tr>
<tr>
<td>$\nu_e \rightarrow \nu_e$ CC</td>
<td>216657</td>
<td>230766</td>
<td>-6.1%</td>
<td>-29.4</td>
</tr>
</tbody>
</table>
Appearance: Exclusion contours
\( \nu_e \rightarrow \nu_\mu \) (CPT invariant mode of LSND)

Cross section measurements - $\nu_\mu$

HIRES$\mu$nu straw-tube-based near detector same as proposed for LBNE

Figures show systematics of HIRES$\mu$nu + nuSTORM Beam (1%) added in quadrature
The search for CP in LBL expts. counts $\nu_e$ and anti-$\nu_e$ events (flux $\times$ xsection)

Note: not shown here $\nu_e$ (200 evts) and $\nu_e$-bar (60 evts) inclusive xsection data (1978)
Accelerator R&D

Looking Forward
Capture and inject $\pi_S$ with $P=5 \text{ GeV/c} \pm 10\%$

Only $\sim 50\%$ of $\pi_S$ decay in straight

Need $\pi$ absorber

Note: injection produces a $\nu_\mu$ “flash” from $\pi \rightarrow \mu \nu_\mu$ decay

$= \text{integrated flux of the neutrinos from } \mu \text{ decay}$
After 3.48m Fe, we have $\approx 10^{10}$ $\mu$ pulses in $100 < P(\text{MeV/c}) < 300$.
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 $\frac{1}{2}$ TPC (next question)
- Magnets, power supplies, horn/target, detector can all be supplied off-shore
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
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
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

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

Total contingency - 45%

1Near Hall sized for multiple experiments & ND for SBL oscillation physics
21.3kT Far + .2kT Near & include DAB work
3Assumes LBNE estimates: Proj. Office (10%), L2 (9.4%), L3 (4%)
# Conventional Facilities

## Overall contingency on Base Cost + EDIA - 53%

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

**TOTALS** | $68,594,000 | $20,579,000 | $47,200,000 | $11,977,000 | $148,350,000
### 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 $\nu$ interaction studies could fall within NSF MREFC
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
What makes this experiment unique, and how does it 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 $\nu_\mu$ and $\nu_e$, neutrino and anti-neutrino
- $\nu$ interaction physics studies with near detector(s) offer a unique opportunity & can be extended to cover $0.2 < E_\nu (GeV) < 4$
  - Could be "transformational" w/r to $\nu$ interaction physics
    - Unique opportunities for $\nu_e$ interaction studies
- For this physics, nuSTORM should really be thought of as a facility: A $\nu$ "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 $\mu$ source for 6D cooling experiment with intense pulsed beam
Three Pillars of nuSTORM

- Delivers on the physics for the study of sterile $\nu$
  - 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 $\nu$ beams setting a $10\sigma$ benchmark to make definitive statement w/r LSND/MiniBooNE
  - Only facility that can do appearance & disappearance for $\nu$ and anti-$\nu$
- Can add significantly to our knowledge of $\nu$ interactions, particularly for $\nu_e$
  - $\nu$ “Light Source”
- Provides an accelerator science test facility
Thank you
Back Ups
Assuming $10^{20}$ POT/yr. for 5 years, $10\sigma$ contour becomes $8\sigma$
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
## Systematics II

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>Known Measures</th>
<th>Expected Contribution</th>
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<tbody>
<tr>
<td></td>
<td>Signal</td>
<td>Background</td>
</tr>
<tr>
<td>Source luminosity</td>
<td>1%</td>
<td>1%</td>
</tr>
<tr>
<td>Cross section</td>
<td>4%</td>
<td>40%</td>
</tr>
<tr>
<td>Hadronic Model</td>
<td>0</td>
<td>15%</td>
</tr>
<tr>
<td>Electromagnetic Model</td>
<td>2%</td>
<td>0</td>
</tr>
<tr>
<td>Magnetic Field</td>
<td>&lt;1%</td>
<td>&lt;1%</td>
</tr>
<tr>
<td>Steel</td>
<td>0.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>5%</td>
<td>43%</td>
</tr>
</tbody>
</table>

[232], [233] - MINOS
Required $\mu$ charge mis-ID rate needed for given sensitivity

![Graph showing charge misidentification rate vs. number of useful muon decays.](image-url)
Gargamelle $\nu_e$ and $\bar{\nu}_e$ data

200 $\nu_e$ evts
60 $\bar{\nu}_e$-bar evts
Accelerator
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<Eν<4 GeV & Resultant extension in L/E X2-2.5 from lattice considerations
• $\Delta p/p = \pm 20\%; \text{ No particle loss after 60 turns}$

• $\Delta p/p = \pm 26\%; \text{ 0.7\% particle loss after 60 turns}$
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

Circulating muon beam orbits - 3.8 GeV/c ± 16%
Detector Issues
Event Candidates in SuperBIND

$\nu_\mu$ CC Events

Hits
R vs. Z

Diagram showing $\nu_\mu$ CC Events with radial distance from detector axis (in cm) vs. position along detector axis (in m).
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
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 $\varepsilon$

Muon charge mis-ID rate

Excellent $\sigma_E$
## Detector Options

### Technology check List

<table>
<thead>
<tr>
<th></th>
<th>Fid Volume</th>
<th>B</th>
<th>Recon</th>
<th>Costing Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>SuperBIND</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Mag-TASD</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
<tr>
<td>Mag-LAr</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
<td>✔</td>
</tr>
</tbody>
</table>

- ✔️ Yes - OK
- ☑ Maybe
- ☑ Not Yet
NF Physics & 3+n Models
Sterile neutrinos arise naturally in many extensions of the Standard Model.

- GUT models
- Seesaw mechanism for neutrino mass
- “Dark” sector
- Extra dimensions

Usually heavy, but light not ruled out.

Experimental hints

- LSND
- MiniBooNE
- Ga
- Reactor “anomaly”

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 $\nu_\mu$ disappearance are included, that tension appears.
Estimates of the effective number of neutrino flavors from fits to cosmological data suggest that this number is greater 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

- 2020 - T2K, NO\(\nu\)A and Daya Bay
  - 0.7MW, 2 \times 10^8 s (10 yrs)
- LBNE - 1300 km, 34 kt
  - 0.7MW, 2 \times 10^8 s (10 yrs)
- LBNO - 2300 km, 100 kt
  - 0.8MW, 1 \times 10^8 s (10 yrs)
- T2HK - 295 km, 560 kt
  - 0.7MW, 1.2 \times 10^8 s (10 yrs)
- 0.025 IDS-NF
  - 700kW (5 yrs)
  - no cooling
  - 2 \times 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 ($\nu_e$ appearance)
    - Need excellent charge ID
  - $E_\mu$ of 5 Gev
  - $L = 1300$ km

- Specifics
  - 700 kW on target
  - $2 \times 10^7$ sec/yr.
  - No cooling

- 1% of baseline NF:
  - $10^{20}$ useful $\mu$ decays/yr.
  - 10 kT of Magnetized LAr
    - Underground

Christensen, Coloma and Huber
arXiv: 1301.7727

Confidence region in the $\theta_{13} - \delta$ plane for a particular point in the parameter space, at $1\sigma$
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

![vSTORM Logo](image)

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

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


![Fermilab Logo](image)

Alan Bross  
P5 Face-to-Face Meeting, Fermilab  
November 3rd, 2013
Lesson: Have access to as many channels as possible and cover as much of the parameter space as possible.
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(?)**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>S:B</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSND</td>
<td>2:1</td>
</tr>
<tr>
<td>MiniBooNE</td>
<td>1:1 → 1:2</td>
</tr>
<tr>
<td>ICARUS/NESSiE</td>
<td>≈1.5:1 / 1:4</td>
</tr>
<tr>
<td>LAr-LAr</td>
<td>1:4</td>
</tr>
<tr>
<td>K⁺ DAR</td>
<td>≈4:1</td>
</tr>
<tr>
<td>LSND Reloaded</td>
<td>5:1</td>
</tr>
<tr>
<td>oscSNS</td>
<td>3:1</td>
</tr>
<tr>
<td>nuSTORM</td>
<td>11:1 → 20:1</td>
</tr>
</tbody>
</table>

- 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
Reactor
Radioactive source
Costing
# Contingency estimating criteria

## Fermilab Guidance for Conventional Facilities for Contingency due to Estimate Uncertainty

<table>
<thead>
<tr>
<th>Code</th>
<th>Design Maturity</th>
<th>Contingency</th>
<th>Remarks</th>
<th>Contributing Factors</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Bottoms Up</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Parametric Scaling</td>
</tr>
<tr>
<td></td>
<td>Project Definition</td>
<td>40-100%</td>
<td>Scope Developed</td>
<td>Estimate Type</td>
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<tr>
<td></td>
<td>Conceptual</td>
<td>20-40%</td>
<td>10-15% design complete</td>
<td>Quote</td>
</tr>
<tr>
<td></td>
<td>Preliminary</td>
<td>10-30%</td>
<td>30% design complete</td>
<td>Estimating Guide</td>
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<td></td>
<td>Final Design</td>
<td>5-20%</td>
<td>Bid Docs Complete</td>
<td>Guess</td>
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<td></td>
<td>Contract Award</td>
<td>0-5%</td>
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<td>Immature Design</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td>Quantity Take Off basis</td>
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<td>Independent Reviews</td>
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<tr>
<td></td>
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<td>Peer Review</td>
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<td></td>
<td></td>
<td>Technical Requirements</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Traditional Building Type / Requirements</td>
</tr>
<tr>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
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<td></td>
<td>Project Complexity</td>
</tr>
<tr>
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<td></td>
<td>Straightforward</td>
</tr>
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<td>Contributing Factors</td>
</tr>
<tr>
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<td></td>
<td>Complex</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Contributing Factors</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>Project Unique Factor</td>
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<td></td>
<td>Fixed Price</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Time and Materials</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Contract Type</td>
</tr>
</tbody>
</table>
Developing the Cost Range

<table>
<thead>
<tr>
<th>Estimate Class</th>
<th>Primary Characteristic</th>
<th>Secondary Characteristic</th>
<th>Expected Accuracy Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 5</td>
<td>0% to 2%</td>
<td>Concept screening</td>
<td>L: -20% to -50%</td>
</tr>
<tr>
<td></td>
<td>End Usage</td>
<td></td>
<td>H: +30% to +100%</td>
</tr>
<tr>
<td>Class 4</td>
<td>1% to 15%</td>
<td>Study or feasibility</td>
<td>L: -15% to -30%</td>
</tr>
<tr>
<td></td>
<td>End Usage</td>
<td></td>
<td>H: +20% to +50%</td>
</tr>
<tr>
<td>Class 3</td>
<td>10% to 40%</td>
<td>Semi-detailed unit costs</td>
<td>L: -10% to -20%</td>
</tr>
<tr>
<td></td>
<td>30% to 70%</td>
<td>with assembly level line</td>
<td>H: +10% to +30%</td>
</tr>
<tr>
<td>Class 2</td>
<td>Check estimate or bid/tender</td>
<td>Detailed unit cost with</td>
<td>L: -5% to -15%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>forced detailed take-off</td>
<td>H: +5% to +20%</td>
</tr>
<tr>
<td>Class 1</td>
<td>70% to 100%</td>
<td>Detailed unit cost with</td>
<td>L: -3% to -10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>detailed take-off</td>
<td>H: +3% to +15%</td>
</tr>
</tbody>
</table>
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)

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

Example: LBNE

Alan Bross                     P5 Face-to-Face Meeting, Fermilab            November 3rd, 2013
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.

<table>
<thead>
<tr>
<th>130</th>
<th>L.B.N.E.</th>
<th>Cost Range Estimate to Complete (in M)</th>
<th>Cost to Date (in M) thru 6/2012</th>
<th>TPC Cost Range (in M)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>minus (-)</td>
<td>plus (+)</td>
<td>minus (-)</td>
</tr>
<tr>
<td>130.01</td>
<td>Project Office</td>
<td>$75.2</td>
<td>$106.2</td>
<td>$7.0</td>
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<tr>
<td>130.02</td>
<td>Beamline</td>
<td>$129.0</td>
<td>$164.9</td>
<td>$7.4</td>
</tr>
<tr>
<td>130.03</td>
<td>Near Detector</td>
<td>$13.1</td>
<td>$18.5</td>
<td>$4.6</td>
</tr>
<tr>
<td>130.04</td>
<td>Water Cherenkov Detector</td>
<td>$0.0</td>
<td>$0.0</td>
<td>$11.2</td>
</tr>
<tr>
<td>130.05</td>
<td>LAr Far Detector</td>
<td>$184.9</td>
<td>$271.9</td>
<td>$7.8</td>
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<tr>
<td>130.06</td>
<td>LBNE Conventional Facilities</td>
<td>$239.8</td>
<td>$338.5</td>
<td>$6.9</td>
</tr>
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<td></td>
<td>Grand Total</td>
<td>$642.0</td>
<td>$899.9</td>
<td>$44.8</td>
</tr>
<tr>
<td></td>
<td>% Contingency</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Top of Range provides for 53% contingency above Base Estimate.
Program Committee Reviews
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.
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.
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