Mary Bishai (on behalf of LBNF/DUNE)
Brookhaven National Lab

August 14, 2018
The Science and Design of the LBNF Beamline

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DUNE Science Requirements

1. DUNE Science Requirements

2. Beamline overview
   - Primary Beam
   - Neutrino Beam
   - Decay Pipe
   - Absorber

3. Beam Flux Systematics

4. Beam Flux Stability

5. Future Beam Upgrades

6. Summary
Science Requirements for the LBNF Beamline

(b) Impact of CP Phase on Vacuum Oscillations

- Vacuum oscillations, all terms, $\delta_{cp} = 0$
- All terms, $\delta_{cp} = + \pi/2$
- All terms, $\delta_{cp} = - \pi/2$
- All terms, $\delta_{cp} = \pi$
Science Requirements for the LBNF Beamline

(c) Impact of Matter Effects on Oscillations \((\delta_{cp} = 0)\)

- Vacuum oscillations, all terms, \(\delta_{cp} = 0\)
- Matter effect at 1000km, NH
- Matter effect at 2000km, NH
- Matter effect at 3000km, NH
- Matter effect at 3000km, IH
Science Requirements for the LBNF Beamline

\[ \nu_\mu \rightarrow \nu_e \text{ Appearance at 1300 km} \]
Global Science Requirements of the Beam

From DUNE/LBNF’s formal requirement document:

**Glo-Sci-13:** The neutrino beam spectrum shall cover the energy region of the first two oscillation maxima affected by muon-neutrino conversion from the atmospheric parameters.

**Glo-Sci-60:** The neutrino beam spectrum shall extend beyond the first maximum to higher energies, while maintaining a high signal to background ratio to obtain the maximum number of charged current signal events.

**Glo-Sci-14:** The neutrino beam spectrum shall be tunable so that beam with both lower peak energy (below the first oscillation node) and higher peak energy (significantly higher than the first oscillation node) can be achieved without substantial downtime that reduces the overall exposure.
Global Science Requirements of the Beam

**From DUNE/LBNF’s formal requirement document:**

**Glo-sci-16:** The beam shall be sign-selected to provide separate neutrino and anti-neutrino beams with high purity to enable measurement of CP violation mass hierarchy, and precision oscillation measurement.

**Glo-sci-17:** The beam shall be aimed at the far detector with an angular accuracy that allows the determination of the far detector spectrum using the near detector measurements. The angular accuracy shall not be the dominant factor in the determination of oscillation parameters.

**Glo-sci-22:** The beam monitoring systems shall have sufficient energy and spatial and temporal resolution that when combined with the detailed knowledge of the beam line geometry, a timely (few hours) feedback of beam performance, stability, as well as a data-driven estimate of the neutrino flux will be obtained.
LBNF Beamline Design and Optimization
Overview of the LBNF Beamline

- **Primary proton beam 60-120 GeV**
- **Initial 1.2 MW beam power, upgradable to 2.4 MW**
- **Embankment allows target complex to be at grade**
- **Wide-band beam (on-axis) optimized for CP violation sensitivity**
- **Decay pipe: 194m x 4m diameter, He filled**

ND default: 574 m from target, FD: 1300 km
PIP-II Components

- 800 MeV linac
  - Warm Front End
  - SRF section
- Linac-to-Booster transfer line
  - 3-way beam split to: (1) Beam dump, (2) Booster & (3) Mu2e-II
- Upgraded Booster
  - 20 Hz, 800 MeV injection
    - New injection area
    - Resonant Magnet Upgrade
- Upgraded Recycler & MI
  - RF in both rings
- Conventional Facilities
  - Includes 2 empty slots at the linac end (L≈23 m)
  - Up to 1 GeV
- Cryogenic Plant

Recieved DOE CD1* approval Aug ’18. Operations start ~ 2027

* DOE Critical Decision 1: Approve alternative selection and cost range. Conceptual design released
## Primary Beamline Design

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Protons per cycle</th>
<th>Cycle Time (sec)</th>
<th>Beam Power (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>≤ 1.2 MW Operation - Current Maximum Value for LBNF</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton Beam Energy (GeV):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>7.5E+13</td>
<td>0.7</td>
<td>1.03</td>
</tr>
<tr>
<td>80</td>
<td>7.5E+13</td>
<td>0.9</td>
<td>1.07</td>
</tr>
<tr>
<td>120</td>
<td>7.5E+13</td>
<td>1.2</td>
<td>1.20</td>
</tr>
<tr>
<td><strong>≤ 2.4 MW Operation - Planned Maximum Value for LBNF 2nd Phase</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proton Beam Energy (GeV):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>1.5E+14</td>
<td>0.7</td>
<td>2.06</td>
</tr>
<tr>
<td>80</td>
<td>1.5E+14</td>
<td>0.9</td>
<td>2.14</td>
</tr>
<tr>
<td>120</td>
<td>1.5E+14</td>
<td>1.2</td>
<td>2.40</td>
</tr>
</tbody>
</table>
Beam optics point to 79 conventional magnets: 25 dipoles, 21 quadrupoles, 23 correctors, 6 kickers, 3 Lambertsons, 1 C Magnet.
## Primary Beamline Design

### Table 6-3: Summary of primary-beam magnet specifications

<table>
<thead>
<tr>
<th>Magnet</th>
<th>Description</th>
<th>Steel Length</th>
<th>Nom. Strength at 120 GeV</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>RKB type Kicker</td>
<td>LBNF extraction</td>
<td>~1.3 m</td>
<td>0.058 T</td>
<td>6</td>
</tr>
<tr>
<td>ILA</td>
<td>MI Lambertson</td>
<td>2.800 m</td>
<td>0.532 / 1.000 T</td>
<td>3</td>
</tr>
<tr>
<td>ICA</td>
<td>MI C Magnet</td>
<td>3.353 m</td>
<td>1.003 T</td>
<td>1</td>
</tr>
<tr>
<td>IDA</td>
<td>MI Dipole 6 m</td>
<td>6.100 m</td>
<td>1.003 - 1.604 T</td>
<td>13</td>
</tr>
<tr>
<td>IDD</td>
<td>MI Dipole 4 m</td>
<td>4.067 m</td>
<td>1.003 - 1.604 T</td>
<td>12</td>
</tr>
<tr>
<td>3Q120</td>
<td>120 inch quadrupole</td>
<td>3.048 m</td>
<td>9.189 - 16.546 T/m</td>
<td>17</td>
</tr>
<tr>
<td>3Q60</td>
<td>60 inch quadrupole</td>
<td>1.524 m</td>
<td>11.135 - 17.082 T/m</td>
<td>4</td>
</tr>
<tr>
<td>IDS</td>
<td>LBNF trim dipoles</td>
<td>0.305 m</td>
<td>Up to 0.365 T</td>
<td>23</td>
</tr>
</tbody>
</table>
The Neurino Beamline

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DUNE Science Requirements

Beamline overview
Primary Beam Neutrino Beam Decay Pipe Absorber

Beam Flux Systematics
Beam Flux Stability
Future Beam Upgrades
Summary
Initial conceptual design was of a *tunable wide-band* NuMI-style focusing:

- **Decay Pipe**: 194 m long, 4 m in diameter, double-wall carbon steel, helium filled, air-cooled.
- **Target Chase**: 2.2 m/2.0 m air-filled and air & water-cooled.

LBNF has switched to CPV optimized focusing design with 3 horns.
The 2015 CD1R reference design for LBNF/DUNE is a NuMI-like movable target (segmented rectangular graphite fins with water cooling $\approx 1\text{m long}$) and 2 modified NuMI horns 6.6m apart.

In Sep 2017 LBNF adopted a focusing design with 3 horns optimized using a genetic algorithm with the physics parameter to be measured (CPV sensitivity) used to gauge fitness.

Target geometry is optimized at the same time, as well as proton beam energy with realistic Main Injector power profile (1.03 MW at 60 GeV to 1.2 MW at 120 GeV).

Limits on horn current, diameter and length are imposed based on experience with T2K and NuMI horn manufacturing.

Limits on horn separation imposed based on size of target chase.
Optimization of flux for Physics: CP Violation

Horn parameters used in GEANT4 simulation for GA optimization:
Schematic of the Genetic Algorithm:

```
  Horn 1 Radius Horn 1 Length Horn 2 Radius Horn 2 Length Horn 2 Position Decay Pipe Len Target Length Target Width Target Position Proton Energy Horn Current
  "mother"
  "father"
  "child"
```

**CP Fitness** = minimum significance with which 75% of $\delta_{cp}$ can be determined $\neq 0$ or $\pi$ for a given exposure

Fast CP Fitness estimator was determined by calculating the change in CP sensitivity given some fixed change in a single energy bin.
Optimized horn design with 297kA current:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horn A Length (mm)</td>
<td>2218</td>
<td>Horn A F1 (% of length)</td>
<td>53</td>
</tr>
<tr>
<td>Horn A R1 (mm)</td>
<td>43</td>
<td>Horn A OC Radius (mm)</td>
<td>369</td>
</tr>
<tr>
<td>Horn A R2 (mm)</td>
<td>33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horn B Length (mm)</td>
<td>3932</td>
<td>Horn C Length (mm)</td>
<td>2184</td>
</tr>
<tr>
<td>Horn B R1 (mm)</td>
<td>159</td>
<td>Horn C R1 (mm)</td>
<td>284</td>
</tr>
<tr>
<td>Horn B R2 (mm)</td>
<td>81</td>
<td>Horn C R2 (mm)</td>
<td>131</td>
</tr>
<tr>
<td>Horn B R3 (mm)</td>
<td>225</td>
<td>Horn C R3 (mm)</td>
<td>362</td>
</tr>
<tr>
<td>Horn B F1 (% of length)</td>
<td>31</td>
<td>Horn C F1 (% of length)</td>
<td>20</td>
</tr>
<tr>
<td>Horn B F2 (% of length)</td>
<td>22</td>
<td>Horn C F2 (% of length)</td>
<td>9</td>
</tr>
<tr>
<td>Horn B F3 (% of length)</td>
<td>2</td>
<td>Horn C F3 (% of length)</td>
<td>7</td>
</tr>
<tr>
<td>Horn B F4 (% of length)</td>
<td>16</td>
<td>Horn C F4 (% of length)</td>
<td>35</td>
</tr>
<tr>
<td>Horn B OC Radius (mm)</td>
<td>634</td>
<td>Horn C OC Radius (mm)</td>
<td>634</td>
</tr>
<tr>
<td>Horn B Position (mm)</td>
<td>2956</td>
<td>Horn C Position (mm)</td>
<td>17806</td>
</tr>
</tbody>
</table>

Optimized target is $4\lambda$ (2m C) with $\sigma_{\text{beam}} = 2.7\text{mm}$, $E_p \sim 110\text{ GeV}$
Optimization of flux for Physics: CP Violation

Laura Fields

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DUNE Science Requirements
Beamline overview
Primary Beam Neutrino Beam Decay Pipe Absorber
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Beam Flux Stability
Future Beam Upgrades
Summary

Computationally advanced optimization techniques =
significant gain in flux and CPV sensitivity from many small changes

Gain in sensitivity ≡ 70% increase in FD mass
Scan over some sample optimization parameters:

Horn A length

Horn B length

Target length

Optimization of flux for Physics: CP Violation

Laura Fields
Engineering the neutrino beam optimized design
Engineering the neutrino beam optimized design

Horn A and 2m target design
Engineering the neutrino beam optimized design

Upstream section of target in Horn A (RAL design)
Engineering the neutrino beam optimized design

Downstream section of target in Horn A (RAL design)
Target hall layout 3-horn optimized vs CD1R reference designs:

- Horn A (w/ Target)
- Horn B
- Horn C
- Baffle
- Upstream Decay Pipe Window
- Target Carriage
- Horn 1
- Horn 2
- Upstream Decay Pipe Window
Target Chase: 2.2 m/2.0 m wide, 34.3 m long nitrogen-filled and nitrogen plus water-cooled (replaceable cooling panels).
Decay Pipe Design

Decay pipe is 194m long and 4m in diameter, He filled
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Decay Pipe Cooling

NOTE: The target pile N\textsubscript{2} cooling system and the decay pipe N\textsubscript{2} cooling system are two separate systems.
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Summary

Absorber Core (water cooled)

- Made of removable, water-cooled Al and Steel “T-Blocks” (based on NuMI T-Block design)
- Gun drilled water channels in core blocks.
- Flexible, modular design that can be repaired/replaced or upgraded in the future.

Absorber Core Module Assy.

Supply and return tubes
Support bar
Steel shielding
Pins
NuMI T-Block
Tubes protection cover
Core block

Hadron Absorber Conceptual Design 2015-2017
Absorber Design

Overall Absorber dimensions (L x W x H):
460in x 408in x 554in [11.7m x 10.4m x 14.1m]
Steel shielding: 2,500 ton
Aluminum: 39 ton
MARS15 simulation (N. Mokhov):

Baseline NuMI style

Optimized with 42cm wings

Optimized focusing design and wings added to target could reduce peak energy deposition in absorber core 8-12 ×.
Optimizing Absorber Design

Absorber design at CD1R (2015) was not optimized - non-uniformity makes monitoring of tertiary beam muons difficult. Uniform absorber design developed in 2017-2018:

**Ref. Hadron Absorber (RHA)**
Non-uniformity, sculpting needed for RD

**Uniform Hadron Abs (UHA)**
No sculpting, larger uniform masks, larger core blocks (60”->67”), 1/16” windows on mask blocks – better for muon measurements

CFD simulation points to temperature reduction by 40% (89°C) in the optimized design with UHA

Uniform absorber is now LBNF baseline design
Large diameter core with uniform density to enable good muon monitoring

Flexible, modular hanger design of water cooled core

1 ft thick core blocks are easily replaceable via Remote Handling

Gas cooling of Bulk shielding
MARS15-ANSYS analysis of the uniform absorber core in the optimized beam completed for normal case. Spoiler and steel blocks are cool and show low stress:

UHA – 28 C \( M_{\text{ax}} \) (RHA 88 C \( M_{\text{ax}} \))

UHA – 20 MPa \( M_{\text{ax}} \) (RHA 103 MPa \( M_{\text{ax}} \))

Temperature

Pressure

Accident case has been analyzed and is fine
Beam Flux Systematics with Optimized Design
Neutrino Beam Flux Comparisons

(For 50 kton.years* of exposure. No detector effects)

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Baseline</th>
<th>$\nu_\mu \rightarrow \nu_\mu$</th>
<th>$\nu_\mu \rightarrow \nu_\tau$</th>
<th>$\nu_\mu \rightarrow \nu_e$</th>
<th>$\delta_C P$ range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Current Experiments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T2K</td>
<td>295km (off-axis)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>30 GeV, 750 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$9 \times 10^{20}$ POT/year</td>
<td></td>
<td>900</td>
<td>&lt; 1</td>
<td></td>
<td>40 - 70</td>
</tr>
<tr>
<td>MINOS LE</td>
<td>735km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120 GeV, 700 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6 \times 10^{20}$ POT/year</td>
<td></td>
<td>11,000</td>
<td>115</td>
<td></td>
<td>230-340</td>
</tr>
<tr>
<td>NO$\nu$A</td>
<td>810km (off-axis)</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>120 GeV, 700 kW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$6 \times 10^{20}$ POT/year</td>
<td></td>
<td>1500</td>
<td>10</td>
<td></td>
<td>120 - 200</td>
</tr>
<tr>
<td><strong>Future Experiments</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LBNF/DUNE LE$^\dagger$</td>
<td>1,300km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80 GeV, 1.1MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1.5 \times 10^{21}$ POT/year</td>
<td></td>
<td>4300</td>
<td>160</td>
<td></td>
<td>350 - 600</td>
</tr>
<tr>
<td>LBNF/DUNE ME$^\dagger$</td>
<td>1,300km</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>120 GeV, 1.2MW</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$1.1 \times 10^{21}$ POT/year</td>
<td></td>
<td>12,000</td>
<td>690</td>
<td></td>
<td>290 - 430</td>
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<tr>
<td>T2HK</td>
<td>(see T2K numbers)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* Facility duty factor taken into consideration

$\dagger$ 2012 LBNE CDR Reference Design with NuMI style focusing

Future LB experiments expect $\mathcal{O}(1000) \nu_\mu \rightarrow \nu_e$ CC events

Need to control total systematics to a few %
Flux components at near and far

Baseline scaled to 1km from middle of decay channel
Flux components at near and far

Baseline scaled to 1km from middle of decay channel
Near to Far Extrapolation

Simple ratio of Near/Far spectrum:

Neutrino parent decay location in decay pipe:

π/K decay kinematics and decay channel geometry are primary reason for strange shape of N/F ratio
To correctly relate near to far fluxes - need to use a correlation matrix:

Flux correlation matrix comes from simulation and is highly correlated
Flux Uncertainties

Uncertainty on ND flux prediction

Residual uncertainty at FD

How well do we actually trust the simulation to correctly estimate the uncertainties on near → far extrapolation?
Proposal by Laura Fields at Fermilab:

The **LBNF Spectrometer** is a concept for a thick-target hadron production measurement after the focusing horns. It would involve a replica of the LBNF target and horns in an external beamline at Fermilab. In addition to hadron production in the target, the spectrometer would also measure hadron production and absorption in the horns and the effects of the magnetic fields in the horns.

**Detector technology is always challenging**

**Need to get more people interested and involved to succeed**
Monitoring the Neutrino Flux Stability
High intensity makes it difficult to measure $\mu$ spectrum accurately. With a 2.4 MW beam, the absorber thickness is too large to sample the lower energy muons. But these systems play an essential role in monitoring flux stability.
Correlation between neutrino and muon spectrum

**ν Spectrum Changes**

- **Beam X Shift, 1 mm**
  - Work in progress

- **Horn A x Shift, 1 mm**
  - Work in progress

- **Target Density Reduction, 5%**
  - Work in progress

- **Horn A y Tilt, 2.5 mm**
  - Work in progress
Correlation between neutrino and muon spectrum

**μ Spectrum Changes**

- **Ref. Abs. Horn A y Shift**
  - Reduction in total flux
  - Shape changes at max near 5 GeV

- **Ref. Abs. Horn A y Tilt (US end +2.5 mm in y, DS end -2.5 mm in y)**
  - Work in progress

**Changes are v. small - need novel detector concepts**
Muon Monitor Technologies under R&D

- **Array of ionization detectors:** Measures muon beam center and intensity. Spill by spill monitoring of beam stability. Both diamond and silicon under study.

- **Threshold gas Cherenkov detector (R&D):** Uses signal intensity at different gas pressure and angles to extract rough muon spectrum.

- **Stopped muon counters (R&D):** Separate stations with steel shielding in between could measure muon flux at several energies. Better measurement of beam flux spectrum and composition.

Currently only ionization detectors included in the beam design.
Ionization detector: Diamond Detector Prototype

Use polycrystal chemical vapor deposition (pCVD) diamond - detects ionizing radiation when a large voltage potential (1V per m of thickness) is applied across two sides of the diamond. Diamond is radiation hard.

pCVD detector prototype installed in NuMI during 2018 shutdown.
Stopped Muon Concept

Strategy

- Counting the decay electrons from muons stopping at the wall of μ-pit
- Measuring spatial and time distributions of events

• Energy loss of muons in the beam dump
• Range of electrons in the concrete

We can measure muons of 5.2–7.0 GeV/c by counting the decay electrons

From K. Hiraide, Muon monitor using the decay electrons, NB12003 Workshop
Prototypes being commissioned with cosmics.
Possible Future Upgrades to the LBNF Beamline to enhance the DUNE Physics Program
NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

2015 two horn optimized design $E_p = 66$ GeV:

- $\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km
- $\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_e$ 290 events $\quad$ $\nu_\mu \rightarrow \nu_\tau$ 60 events

in 40 ktons, 1 year at 1.2 MW
Tunability of beam and $\nu_\tau$ Flux (v. preliminary)

NuMI-like reference design could be tuned to higher energy to observe $\nu_\mu \rightarrow \nu_\tau$ with high statistics.

LBNF target -2m from horn 1, NuMI focusing 230 kA, horns 17m apart

$\nu_\mu \rightarrow \nu_e$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_\tau$ Appearance at 1300 km

$\nu_\mu \rightarrow \nu_e$ 330 events
$\nu_\mu \rightarrow \nu_\tau$ 700 events
in 40 ktons, 1 year at 1.2 MW

Increase $\nu_\tau$ appearance 10x!!!

Increase high energy $\nu_e$ appearance - good for NSI/Sterile searches
Study NSI sensitivity with GLoBeS using $\nu_\mu \rightarrow \nu_{\mu,e}$ and 3 sample LBNF-like beam tunes: LE, ME and HE$^*$. 

NSI parameters used:

$|\epsilon_{e\mu}| = 0.04$, $|\epsilon_{e\tau}| = 0.04$, $\epsilon_{ee} = 0.4$, $\phi_{e\mu} = 0$, $\phi_{e\tau}$

NSI effects in $\nu_\mu \rightarrow \nu_e$ are larger at higher energy

* 2 NuMI horns, 230kA, 6.6m apart and horns were not moved for higher energy beam tunes (non-optimal beams). Decay pipe was assumed to be 250m.
SI/NSI separation metric:
(the abbreviations \( tr \) and \( ts \) indicate true and test respectively.)
Thus for the NSI-SI separation,

\[
\chi^2(\delta_{tr}) = \min_{\delta_{ts}} \sum_{i=1}^{x} \sum_{j} 2 \left[ N_{NSI}^{i,j}(\delta_{tr}, |\varepsilon|, \varphi) - N_{SI}^{i,j}(\delta_{ts} \in [-\pi, \pi]) \right]^2
\]

where, we have marginalised over the standard CP phase \( \delta \) in the test dataset. This \( \chi^2 \) was calculated using a set of conservative values of the NSI parameters (see Table 2).
M. Masud, P. Mehta, M. Bishai arXiv:1704.08650

Fraction of SI $\delta_{cp}$ for which SI/NSI can be separated at the $3/5\sigma$ level:

Can achieve $3\sigma$ separation for $>80\%$ of true $\delta_{cp}$

No beam optimization attempted yet!
Summary and Conclusions
The LBNF beam design is advancing towards a preliminary design for CD2 (expected end of 2019)

The CPV optimized neutrino beamline design with 3 horns is now the baseline design

The challenging design of Horn A with a $4\lambda$ graphite target is proceeding

The simplified hadron absorber redesign for the optimized beam is well advanced.

A “real-time” beam monitoring system is a requirement for the LBNF beamline, and R&D for a muon monitoring system is proceeding but is still very challenging.

New physics capabilities with high energy beams produced from the 2015 CD1R reference design are being explored.

A full evaluation of the flux uncertainties from the optimized beam has been carried out. Uncertainties are at the 1% level in the oscillation region.