CP violation at the Neutrino Factory

K. Long, 5 July, 2012
On behalf of the IDS-NF collaboration
Acknowledgements:

• Many thanks to those who provided information or material:
  – And in particular the International Design Study for the Neutrino Factory (the IDS-NF) collaboration and the EUROnu collaboration

See also:
ICFA Beam Dynamics
Newsletter 55:72-78, 2011
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CP violation at the Neutrino Factory:
The $\theta_{13}$ dividend
Standard Neutrino Model:

- Exciting new data!

- Discovery of leptonic CP-violation is possible:
  - Best chance at the Neutrino Factory

- Increases motivation for precision determination of the parameters and search for “non-standard effects”
The case for exquisite sensitivity:

- **Precision measurements are essential to:**
  - **Complete the “Standard Neutrino Model” (SvM):**
    - Determine the mass hierarchy
    - Search for (and discover) leptonic CP-invariance violation
  - **Establish the SvM as the correct description of nature:**
    - Determine precisely the degree to which \( \theta_{23} \) differs from \( \pi/4 \)
    - Determine \( \theta_{13} \) precisely
    - Determine \( \theta_{12} \) precisely
  - **Search for deviations from the SvM:**
    - Test the unitarity of the neutrino mixing matrix
    - Search for sterile neutrinos, non-standard interactions, ...

- **What determines the goal for sensitivity and precision?**
  - **Sensitivity:**
    - Definitive discovery!
      - Must have sensitivity of at least “5\(\sigma\)”
      - To resolve the LSND/miniBOONE “suite of anomalies” may set the bar higher!
  - **Precision:**
    - Field presently led by experiment;
      - Too many, or too few, theories;
    - Goal to determine parameters with a precision comparable to that with which the quark-mixing parameters are known
CP violation at the Neutrino Factory:

The IDS-NF baseline Neutrino Factory
Neutrino Factory:

• Optimise discovery potential for CP and MH:
  – Requirements:
    • Large $\nu_e (\bar{\nu}_e)$ flux
      – Detailed study of sub-leading effects
  • Unique:
    • (Large) high-energy $\nu_e (\bar{\nu}_e)$ flux
      – Optimise event rate at fixed $L/E$
      – Optimise MH sensitivity
      – Optimise CP sensitivity
IDS-NF baseline Neutrino Factory:

- **Accelerator facility:**
  - $10^{21}$ useful decays/yr
  - 10 GeV stored-muon energy
  - 2000 km source-detector baseline

- **Neutrino detectors:**
  - 100 kT magnetised iron neutrino detector (MIND)
  - Near detector and ring instrumentation suite to:
    - Determine flux
    - Measure cross sections
    - Perform detailed neutrino-scattering physics programme
### Accelerator Facility

#### Proton Driver:
- 4 MW; $5 < E_p < 15$ GeV; bunch length 1—3 ns
- Linac (CERN, FNAL) and ring (RAL, JPARC) options

#### Pion-Production Target:
- Baseline: liquid mercury jet
- Options: powder jet or solid
- Progress: particle shielding, magnetic lattice

#### Muon Front End:
- Chicane (new) to remove secondary hadrons:
  - Bent solenoid transport & beryllium absorber
- Buncher & rotator:
  - Progress: lattice revision in response to engineering study
- Cooling:
  - Baseline: solenoid transport, LiH absorber
  - Options: bucked coils or high-pressure H2
  - Progress: lattice revision in response to engineering study

#### Rapid Acceleration:
- Two options considered for acceleration to 10 GeV:
  - Linac, RLA I and RLA II;
  - Linac, RLA I and FFAG
- Choice based on cost and performance estimates

#### Pion-Production Target:
- MERIT experiment at CERN proved principle of mercury jet target

#### Muon Front End:
- MuCool programme at FNAL:
  - Study of effect of magnetic field on high-gradient, warm, copper cavities;
- MICE experiment at RAL:
  - Proof of principle of ionization-cooling technique

#### Rapid Acceleration:
- EMMA experiment at DL:
  - Proof of principal of non-scaling FFAG technique;
    - Novel technology allows circular acceleration without magnet ramp
Magnetized Iron Neutrino Detector (MIND):

- IDS-NF baseline:
  - Intermediate baseline detector:
    - 100 kton at 1500—2500 km
    - Appearance of “wrong-sign” muons
  - Toroidal magnetic field > 1 T
    - Excited with “superconducting transmission line”
  - Segmentation: 3 cm Fe + 2 cm scintillator
  - 50-100 m long
  - Octagonal shape
  - Welded double-sheet
    - Width 2m; 3mm slots between plates

Bross, Soler, Bayes, Cervera
Near detectors:

- Neutrino flux (<1% precision) and extrapolation to far detector
- Charm production (main background) and taus for Non Standard Interactions (NSI) searches
- Cross-sections and other measurements (i.e., PDFs, $\sin^2\theta_W$)
Sensitivity and precision

CP violation at the Neutrino Factory:
Comparison:

- Discovery reach at $3\sigma$:
  - **Neutrino Factory**: 85—90%
  - Beta beam and SPL: 70—80%
  - Super beam: 60—75%
Comparison with alternatives:

- Neutrino Factory offers best precision:
  
  - Issue now is control of systematic effects
• Benefit of luminosity:
  • Solid black lines show effect on precision of scaling luminosity from baseline $10^{21}$ decays per year
  • Potential for definition of staged upgrade programme
CP violation at the Neutrino Factory:

Increments and implementation
Ambition:

• Large value of $\theta_{13}$, makes it likely that the next generation long-baseline experiments will determine the neutrino mass hierarchy;
  – However, sensitivity to CP violation will be limited;

• In the first instance, a combination of long-baseline (wide-band beam) experiments (e.g. LBNE/LBNO) and short baseline experiments (e.g. T2HK) may offer an attractive way forward:
  – In such an approach:
    • CP reach is limited by systematic effects;
    • Hints of CP violation would require follow up by the Neutrino Factory.

• The Neutrino Factory is the facility of choice, but, stored muon beams have not yet been shown to be capable of serving a world-class neutrino programme:
  – Require to push through R&D and complete IDS-NF, considering an incremental implementation in parallel; and
  – Establish a first, realistic, scientifically first-rate neutrino experiment based on a stored muon beam
Systematic uncertainties:

- T2HK, a case study:
  - Narrow-band beam
  - Near and far detector

Huber, Mezzetto, Schwetz, arXiv:0711.2950v2
nuSTORM: conceptual design:

LOI [Bross et al]; submitted to FNAL

• Magnetized Iron
  - 1 kT fiducial volume
    - Following MINOS ND ME design
    - 1 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
    - Extruded scintillator +SiPM
Cross sections:

- Unique opportunity to measure electron-neutrino cross sections
- Also, measure muon-neutrino cross sections
- Full set of neutrino-scattering physics:
  - QCD
  - Structure functions & form factors
  - Electroweak
  - ...
- Concept for detector:
  - Straw tracker, EM Calor, TRD and $\mu$ spectrometer
  - Meets all needs for ND
  - Detector technology exists
  - Costed

Mishra, IDS-NF#8
Sensitivity:

Sterile neutrino search

- Need either $E_\mu = 4$ GeV or $10^{19}$ useful muon decays/polarity to cover best-fit
- Highly competitive compared to alternatives ($\leftrightarrow$ Sterile neutrino white paper)
- Can one improve on “systematics limit”?

**Tunnell, appearance**

$10^{21}$ POT

$\nu$-mode

Stored $\mu^+$

$\Delta m^2_{41}$ [eV$^2$]

99% MB$\nu$/LSND$\bar{\nu}$

$\sin^2 (2\theta_{\mu\nu})$

**Winter, disappearance**

$\sin^2 2\theta$
2. Increment 2:
- Upgrade proton-beam power
- Install cooling
- Upgrade detector mass
  i.e. large $\theta_{13}$ option from IDR

GLoBES 2011 – November 7
Conclusions

CP violation at the Neutrino Factory:
Conclusions:

- Measurement of $\theta_{13}$ emphasises:
  - 5σ discovery sensitivity:
    - Mass hierarchy;
    - CP-invariance violation;
  - Precision measurement of neutrino oscillations

- Neutrino Factory:
  - Unique; meeting the “5σ” sensitivity and precision goals;
  - Mature:
    - Key hardware issues addressed, or being addressed by R&D programmes;
    - Conceptual design documented in IDS-NF IDR
      - Costing in preparation for EUROnu final report and IDS-NF RDR
  - Outstanding opportunity to contribute in the short term: nuSTORM
    - Essential cross section measurements;
    - Sterile-neutrino search
  - Incremental approach to full Neutrino Factory conceivable

- Altogether, an exciting programme!