CP violation at the Neutrino Factory

K. Long, 5 July, 2012

On behalf of the IDS-NF collaboration

Imperial College London

Acknowledgements:

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  - **And in particular the International Design Study for the Neutrino Factory (the IDS-NF) collaboration and the EUROnu collaboration**

International Design Study for the
Neutrino Factory

IDS-NF-020

Interim Design Report

The IDS-NF collaboration

136 authors, 48 Institutes:

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India	HCRI Allahabad, Inst. of Math, Sci. Chennai, SINP Kolkata, TIFR Mumbai
Italy	Milano Bicocca, Universita di Napoli Federico II, Universita di Padova and INFN Padova, Sezione INFN Roma Tre
Japan	Kyoto University RRI, University of Osaka, Tokyo Metropolitan University
Spain	UAM and IFT Madrid, UV/CSIC and IFIC Valencia
Russia	INRR Moscow
Switzerland	CERN, University of Geneva
UK	Brunel University, Daresbury Laboratory, Glasgow University, Imperial College London, IPPP Durham, Oxford University, Rutherford Appleton Laboratory, Sheffield University, Warwick University
USA	Brookhaven National Laboratory, Fermi National Laboratory, Jefferson Laboratory, Laurence Berkeley National Laboratory, University of Mississippi, Michigan State University, Muons Inc., Northwestern University, Oak Ridge National Laboratory, Princeton University, University of California at Riverside, Stony Brook University, University of South Carolina, Virginia Polytechnique Institute, University of California at Los Angeles

https://www.ids-nf.org/wiki/FrontPage/Documentation/IDR

With updates from:
https://www.ids-nf.org/wiki/GLA-2012-04-08

See also:
ICFA Beam Dynamics Newsletter 55:72-78,2011

Contents:

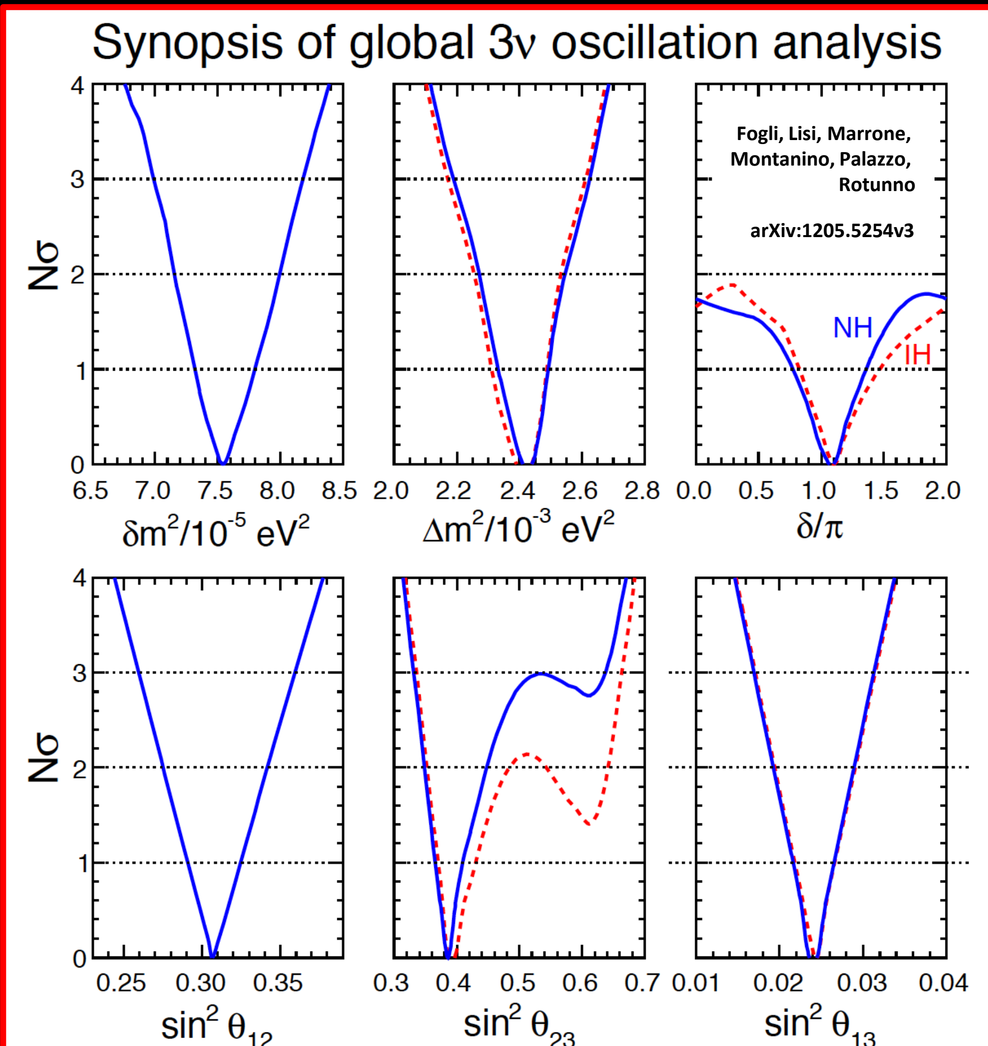
- The θ_{13} dividend
- The IDS-NF baseline Neutrino Factory
- Sensitivity and precision
- Increments and implementation
- Conclusions

CP violation at the Neutrino Factory:

The θ_{13} dividend

Standard Neutrino Model:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



- **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:

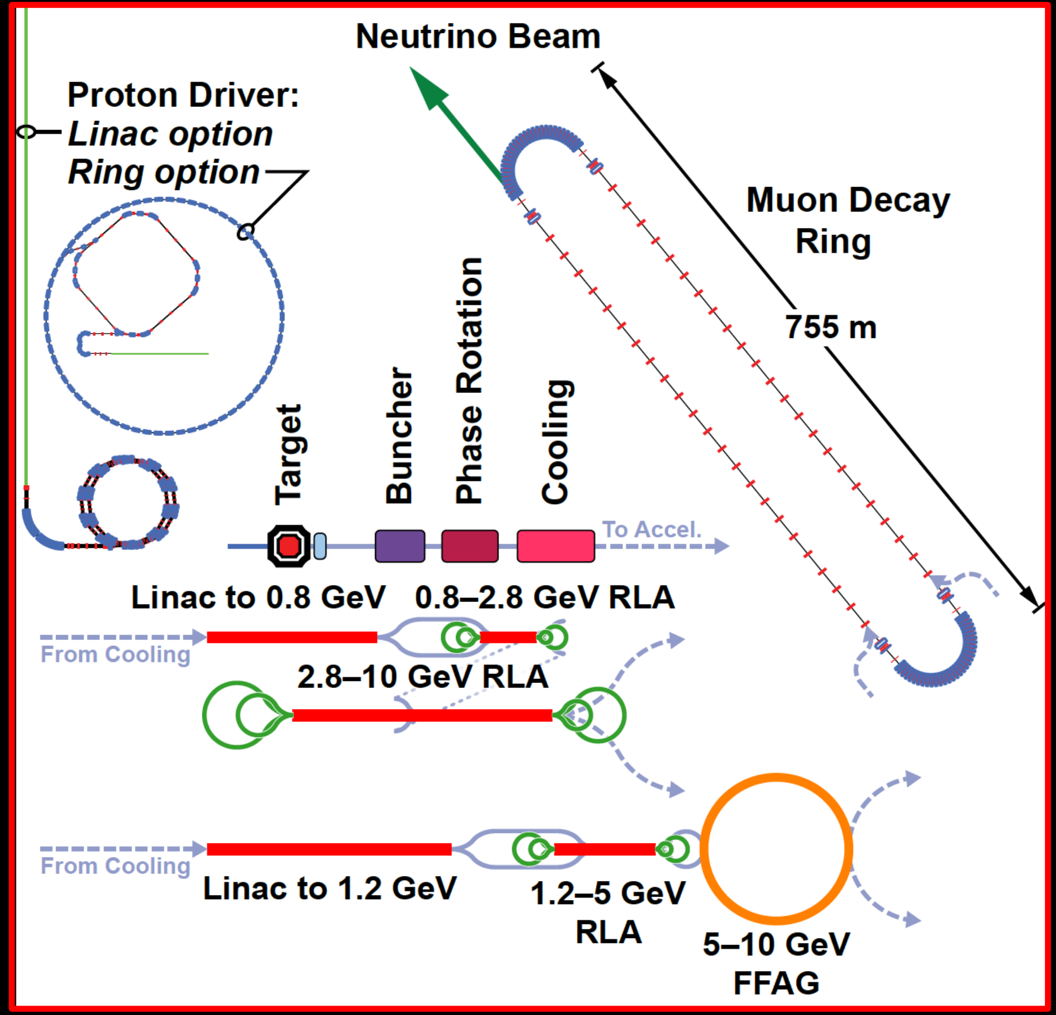
- Precision measurements are essential to:
  - Complete the "Standard Neutrino Model" (SνM):
    - Determine the mass hierarchy
    - Search for (and discover) leptonic CP-invariance violation
  - Establish the SνM as the correct description of nature:
    - Determine precisely the degree to which θ_{23} differs from $\pi/4$
    - Determine θ_{13} precisely
    - Determine θ_{12} precisely
  - Search for deviations from the SνM:
    - 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 "5σ"
      - 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

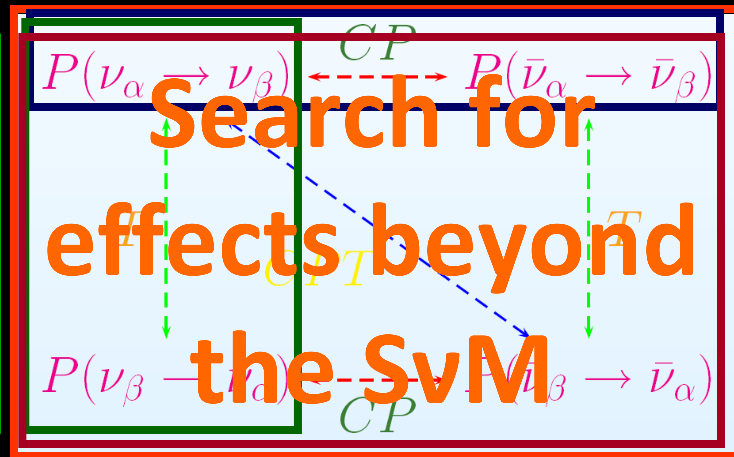
Neutrino Factory:

- Optimise discovery potential for CP and MH:
  - Requirements:
    - Large ν_e ($\bar{\nu}_e$) flux
      - Detailed study of sub-leading effects
- Unique:
  - (Large) high-energy ν_e ($\bar{\nu}_e$) flux
    - Optimise event rate at fixed *L/E*
    - Optimise MH sensitivity
    - Optimise CP sensitivity



Neutrino Factory concept:

$\mu^+ \to e^+ \nu_e \bar{\nu}_\mu$	$\mu^- \to e^- \bar{\nu}_e \nu_\mu$	
$\bar{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	Disappearance
$\bar{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	Appearance (challenging)
$\bar{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	Appearance
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	Disappearance
$\nu_e \to \nu_\mu$	$\bar{\nu}_e \to \bar{\nu}_\mu$	Appearance: "golden" channel
$\nu_e \to \nu_\tau$	$\bar{\nu}_e \to \bar{\nu}_\tau$	Appearance: "silver" channel



- **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**

See P. Soler: IDS-NF acccelerator facility; Track 14; Sat. 12:15
K. Long: MICE status and progress; Track 14; Sat. 12:00
P. Soler: MICE instrumentation; Track 13; Sat. 15:30

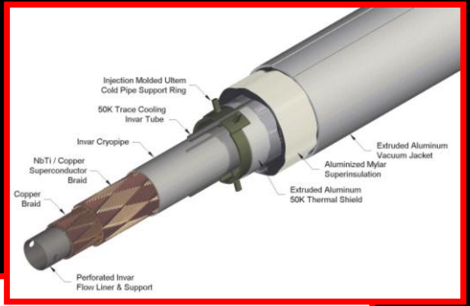
Accelerator facility:

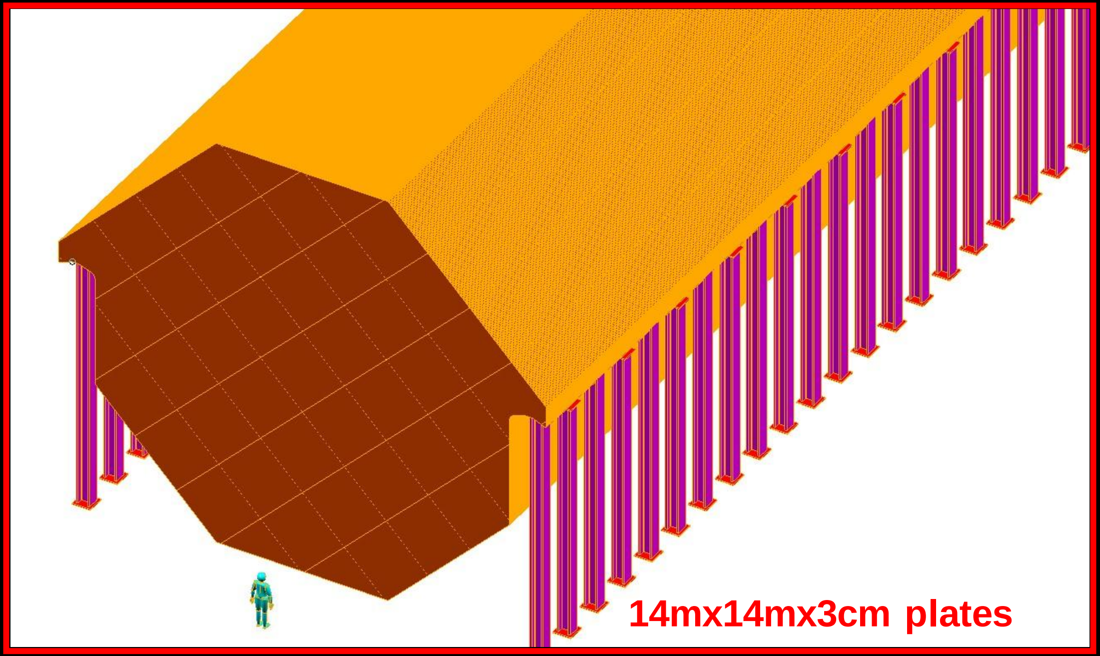
- Proton driver:
  - 4 MW; 5 < Ep < 15 GeV; bunch length 1—3 ns
  - Linac (CERN, FNAL) and ring (RAL, JPARC) options
- Pion-production target:
  - Baseline: liquid mercury jet
  - Options: powder jet or solid
  - Progress: particle shielding, magnetic lattice
- Muon front end:
  - Chicane (new) to remove 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

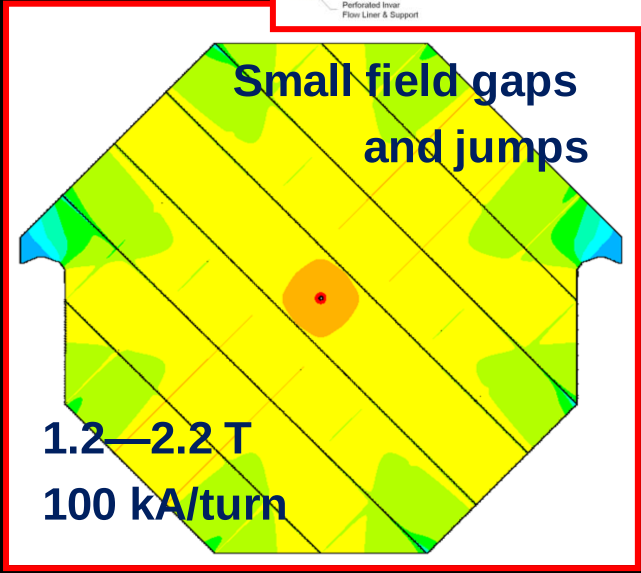
- Proton driver:
  - Development of high-power, pulsed proton source underway at proton labs
- Pion-production target:
  - MERIT experiment at CERN proved principle of mercury jet target
- Muon front end:
  - MuCool programme at FNAL:
    - Study of effect of magnetic field on high-gradient, warm, copper 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





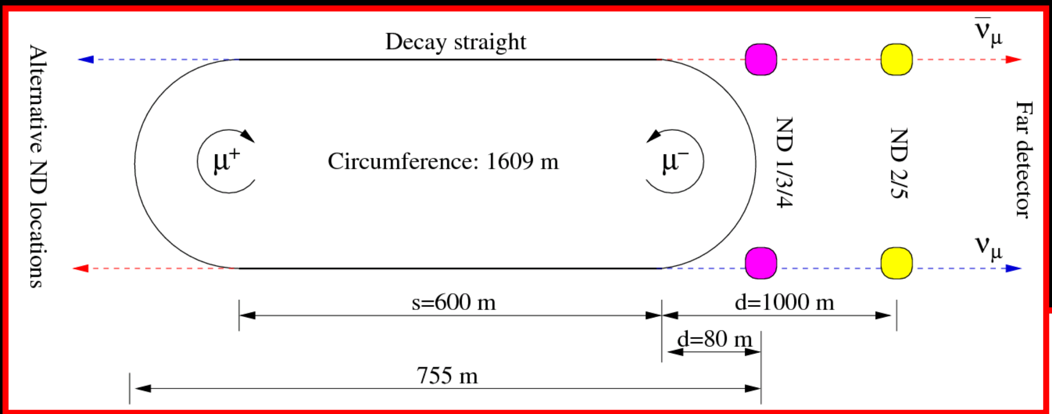


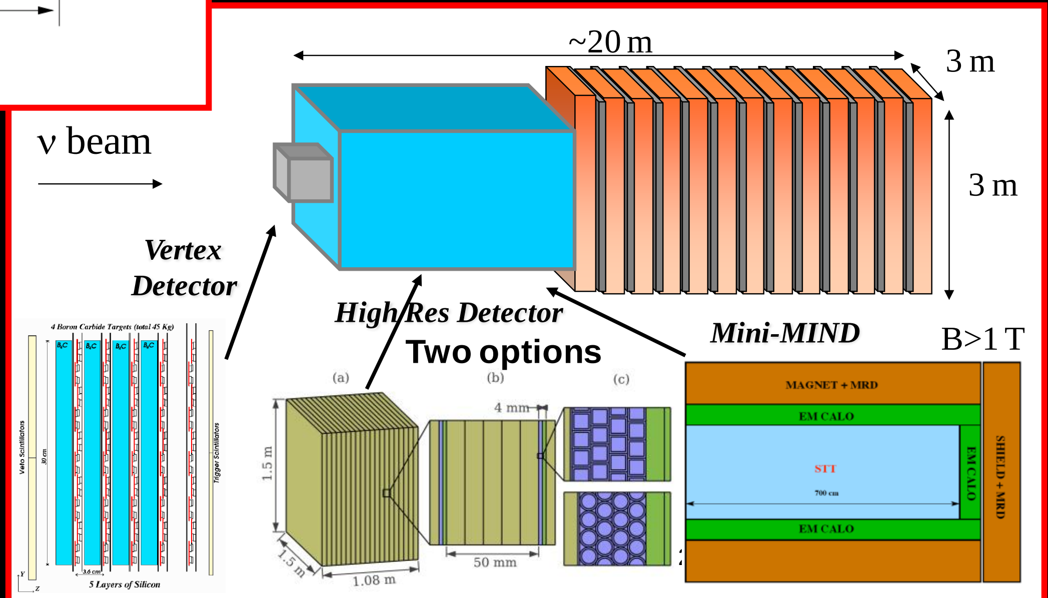
Bross, Soler, Bayes, Cervera

Morfin, Tsenov

Near detectors:

- **Near detector missions:**
  - 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 (ie PDFs, $\sin^2\theta_W$)





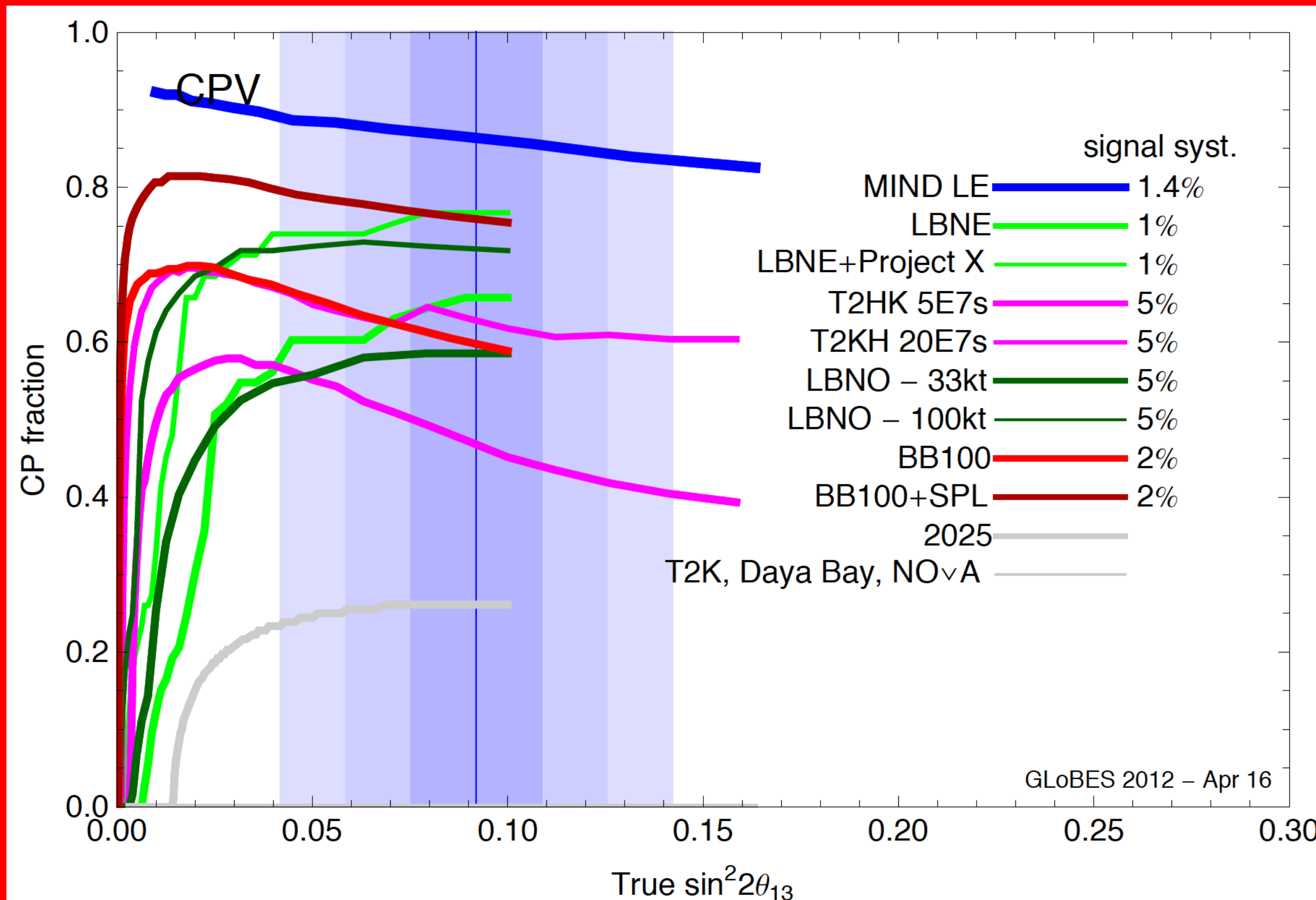
CP violation at the Neutrino Factory:

Sensitivity and precision

P. Coloma, P. Huber et al, IDS-NF#8:
https://www.ids-nf.org/wiki/GLA-2012-04-18/Agenda

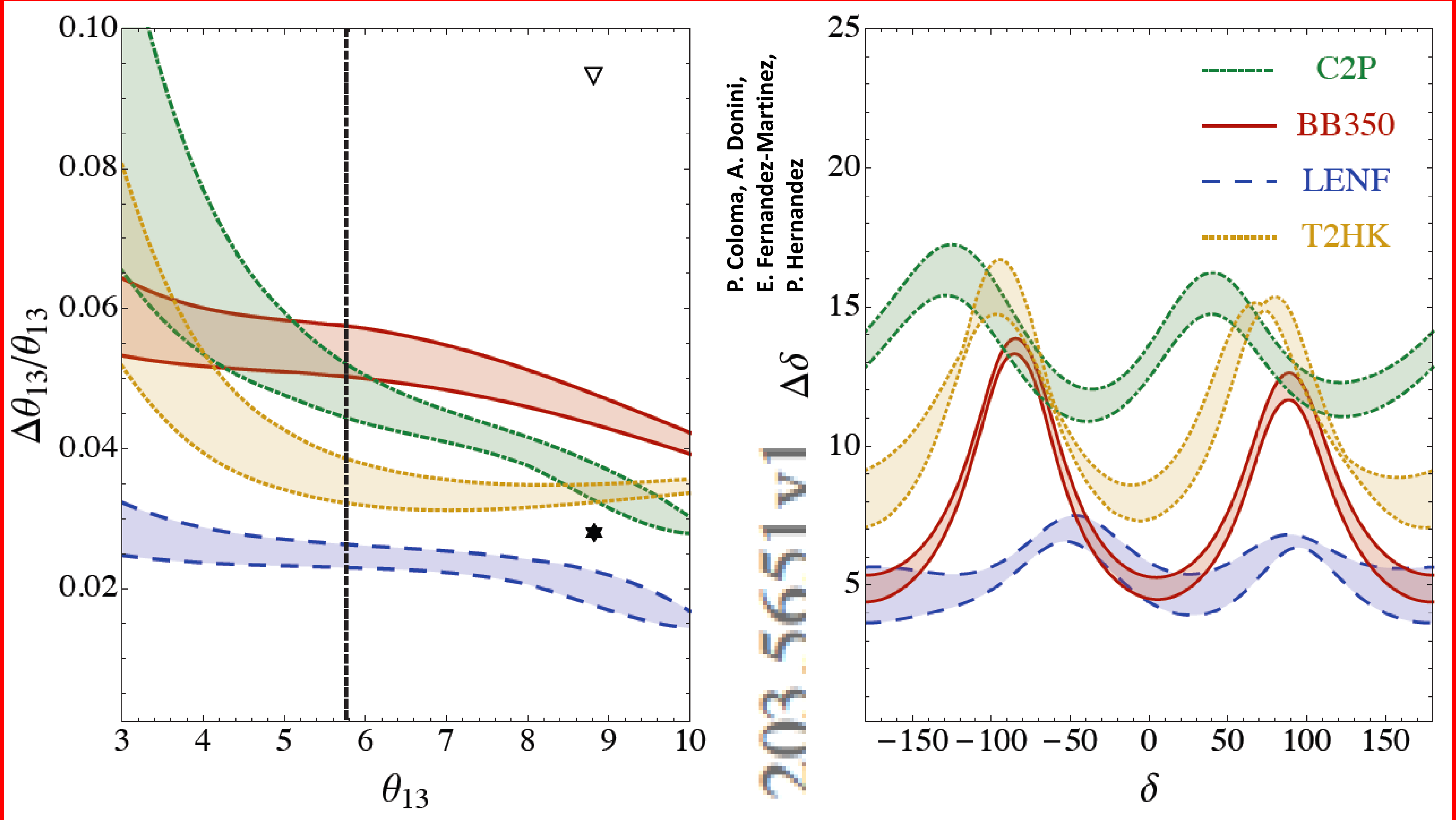
Comparison:

- **Discovery reach at 3σ:**
  - **Neutrino Factory: 85—90%**
  - **Beta beam and SPL: 70—80%**
  - **Super beam: 60—75%**



P. Coloma, A. Donini, IDS-NF#8

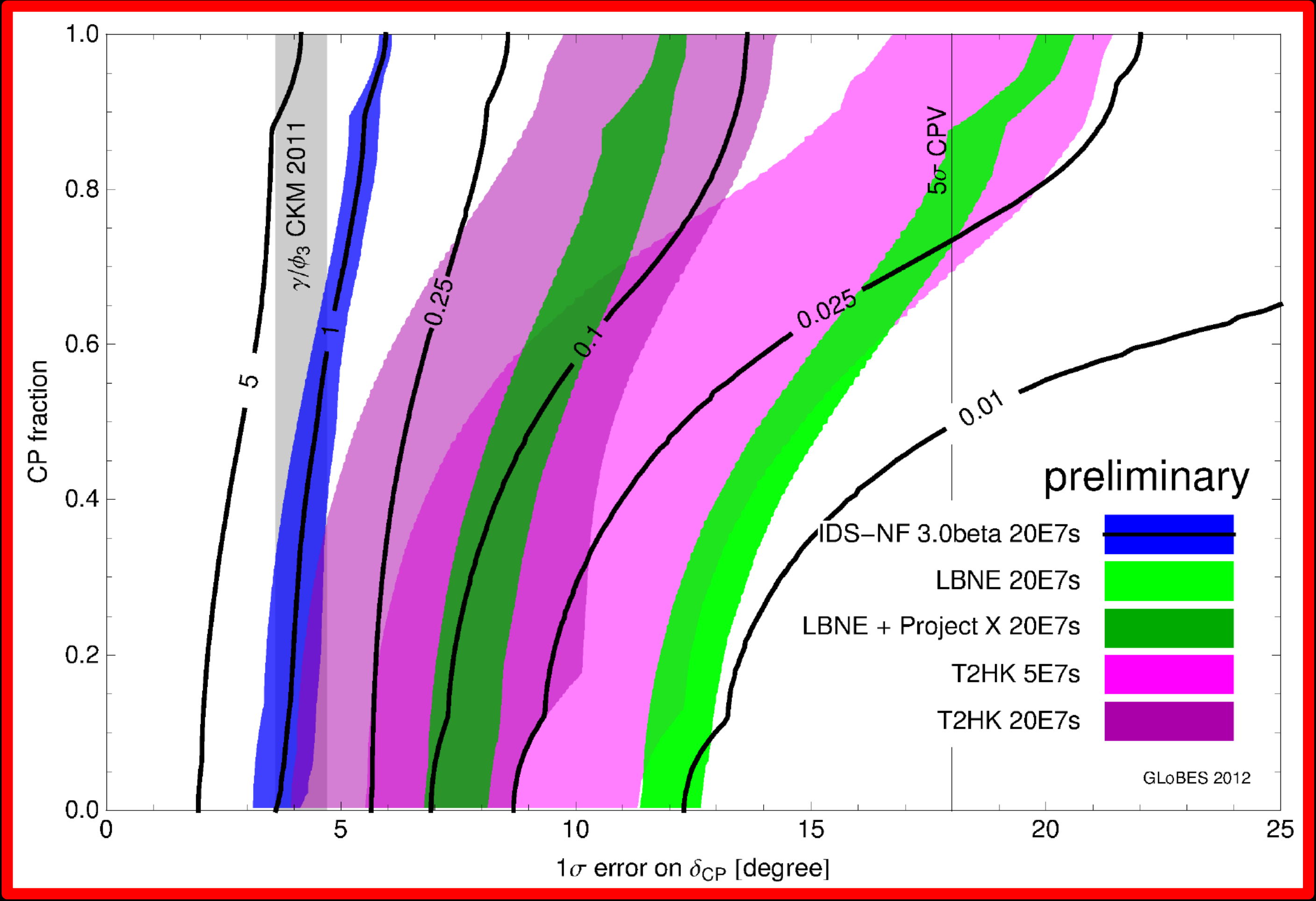
Comparison with alternatives:



- **Neutrino Factory offers best precision:**
  - **Issue now is control of systematic effects**

Huber

Comparison:



- **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

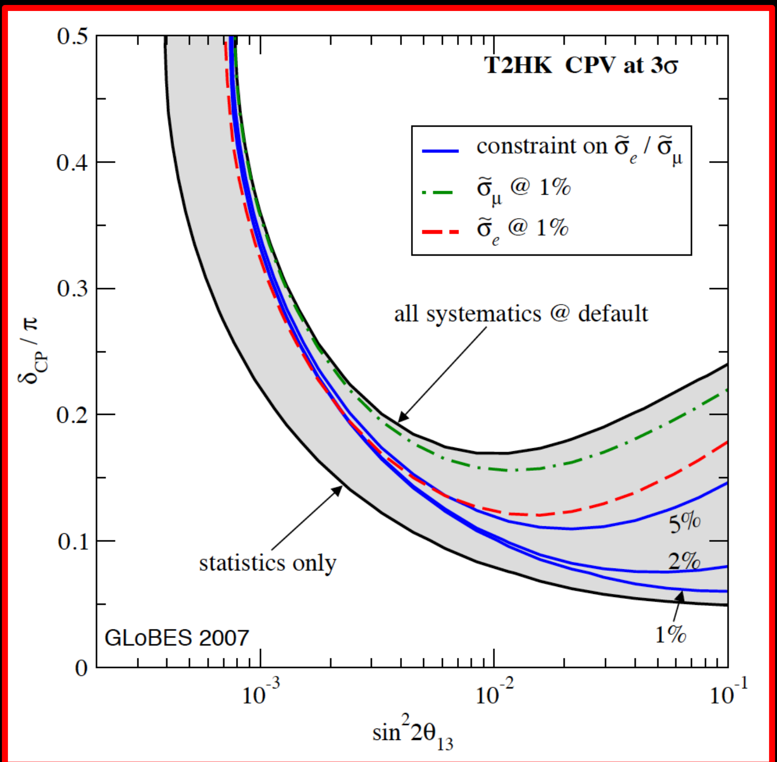
Ambition:

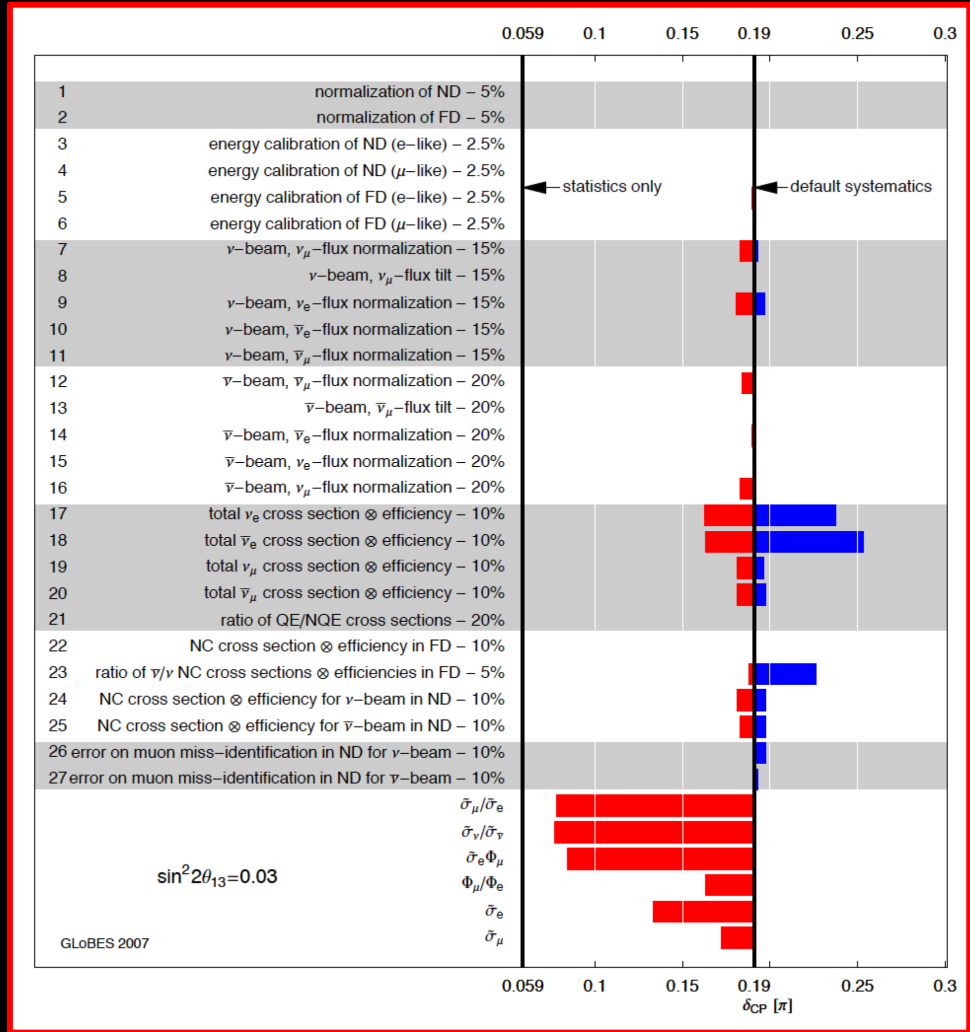
- Large value of θ_{13}, makes it likely that the next generation long-baseline experiments will determine the neutrino mass hierarchy;
  - However, sensitivity to CP violation will be limited;
- In the first instance, a combination of long-baseline (wide-band beam) experiments (e.g. LBNE/LBNO) and short 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:

— critical at large θ_{13}

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

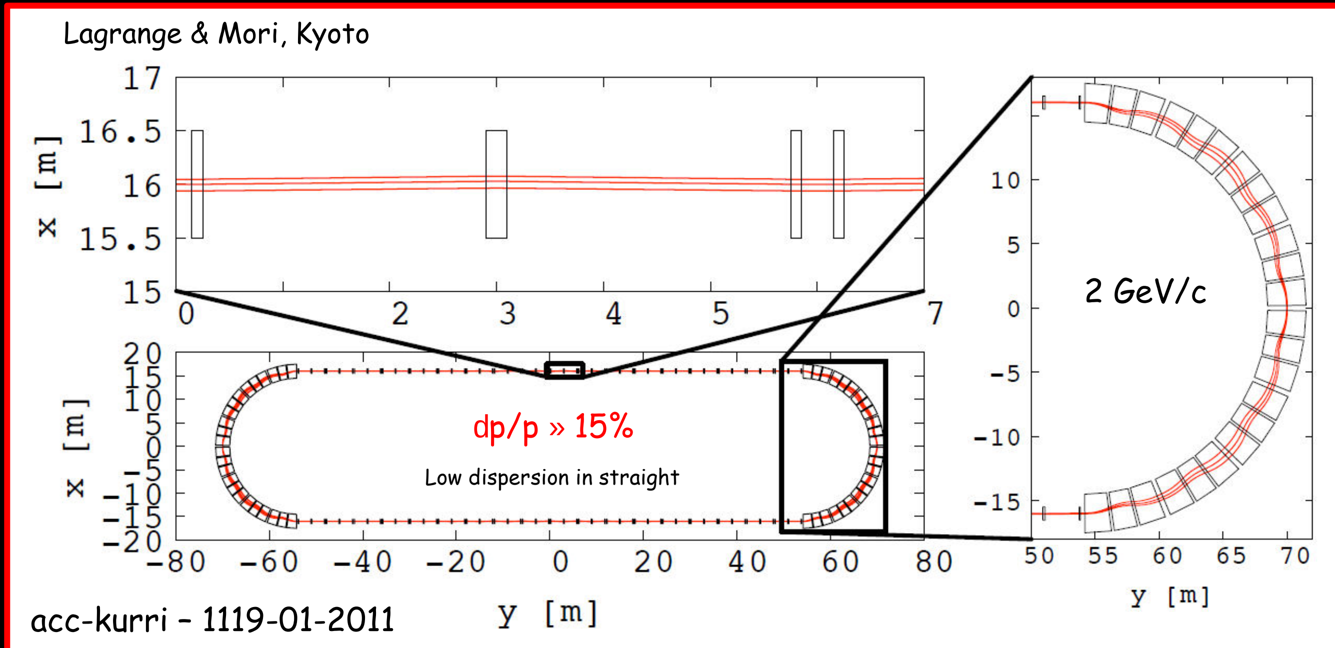


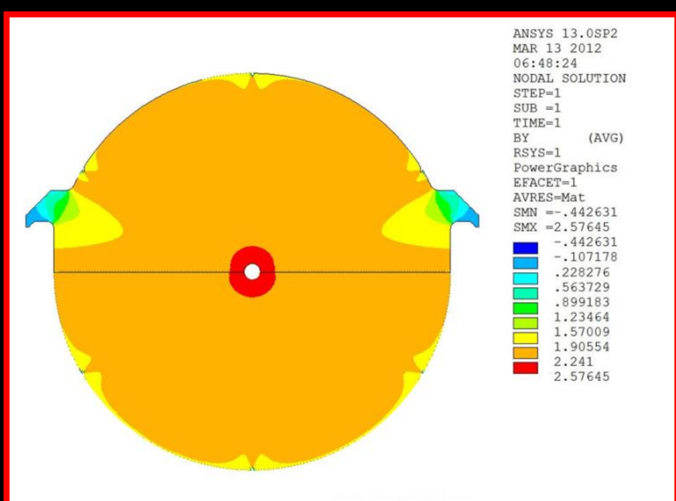


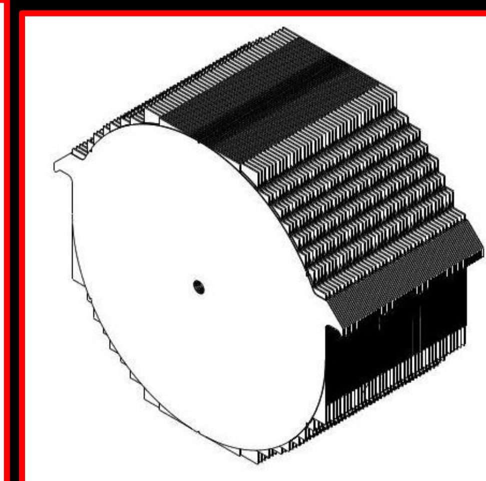
Huber, Mezzetto, Schwetz, arXiv:0711.2950v2

LOI [Bross et al]; submitted to FNAL

nuSTORM: conceptual design:



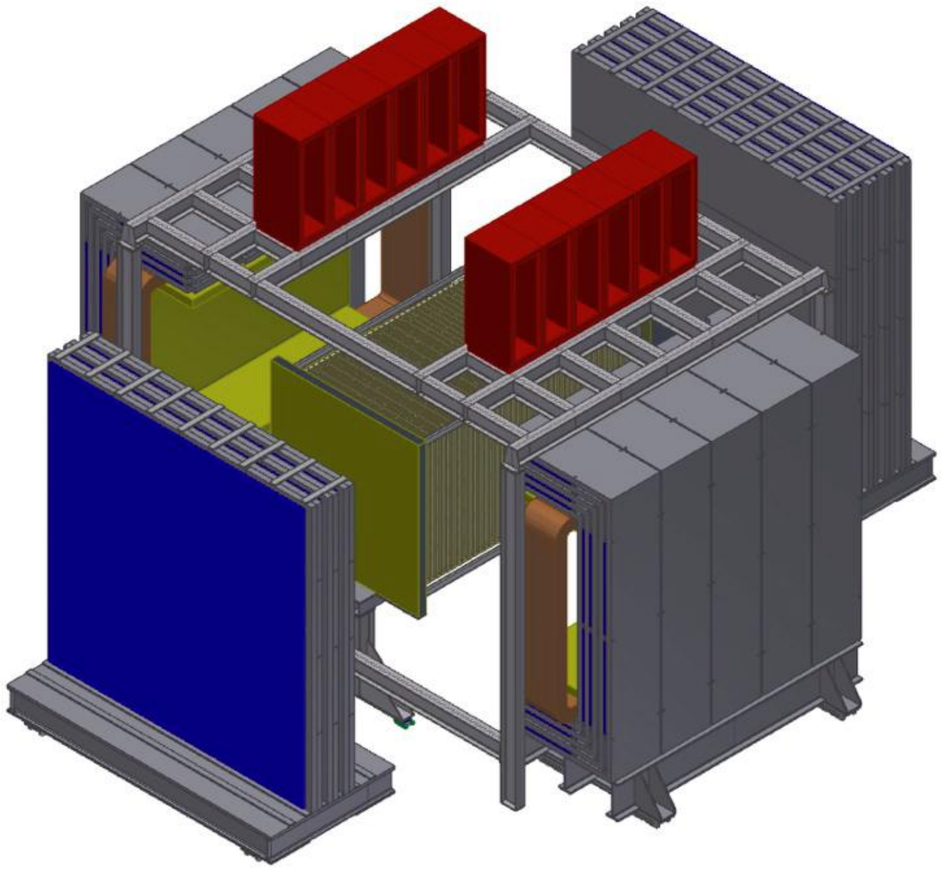




- Magnetized Iron
  - 1 kT fiducial volume
    - Following MINOS ND ME design
    - 1 cm Fe plate
    - 5 m diameter
  - Utilize superconducting transmission line for excitation
    - Developed 10 years ago for VLHC
  - Extruded scintillator +SiPM

Cross sections:

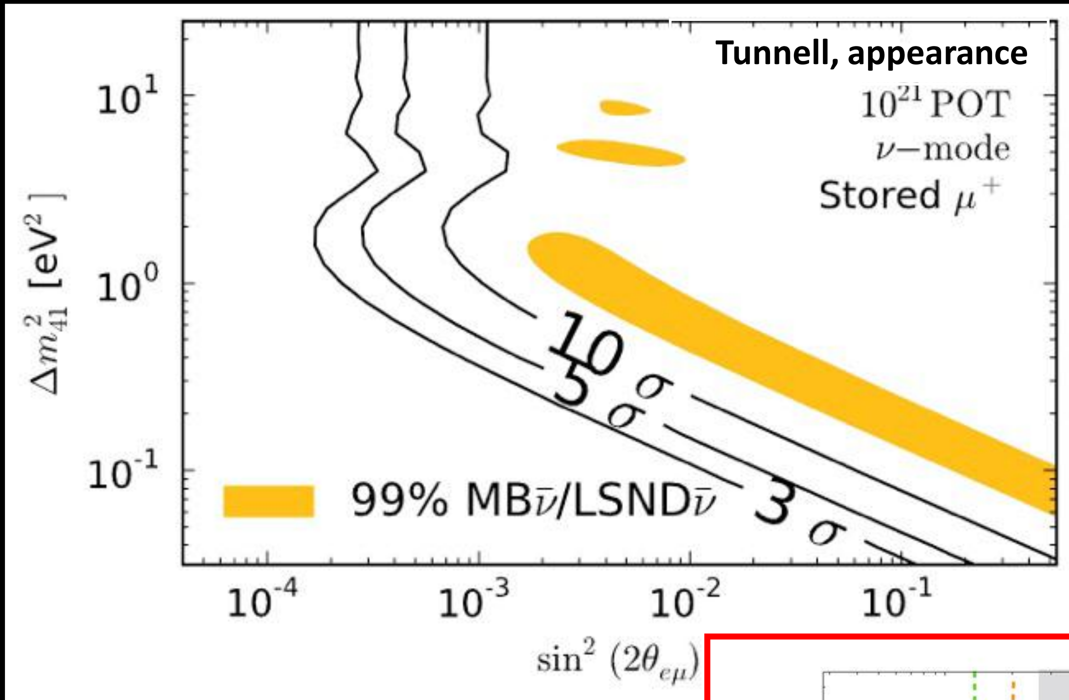
- Unique opportunity to measure electron-neutrino cross sections
- Also, measure muon-neutrino cross sections
- Full set of neutrino-scattering physics:
  - QCD
  - Structure functions & form factors
  - Electroweak
  - …
- Concept for detector:
  - Straw tracker, EM Calor, TRD and μ spectrometer
  -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

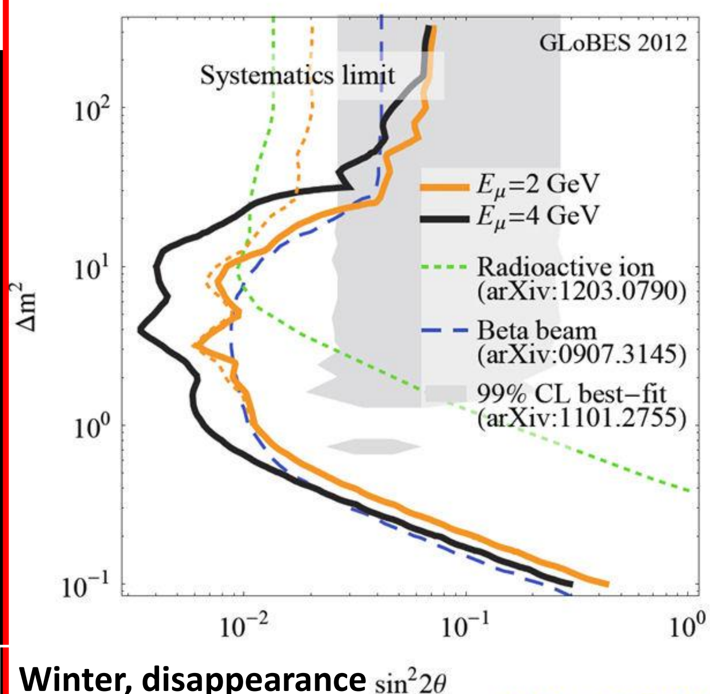


Mishra, IDS-NF#8

Sensitivity:

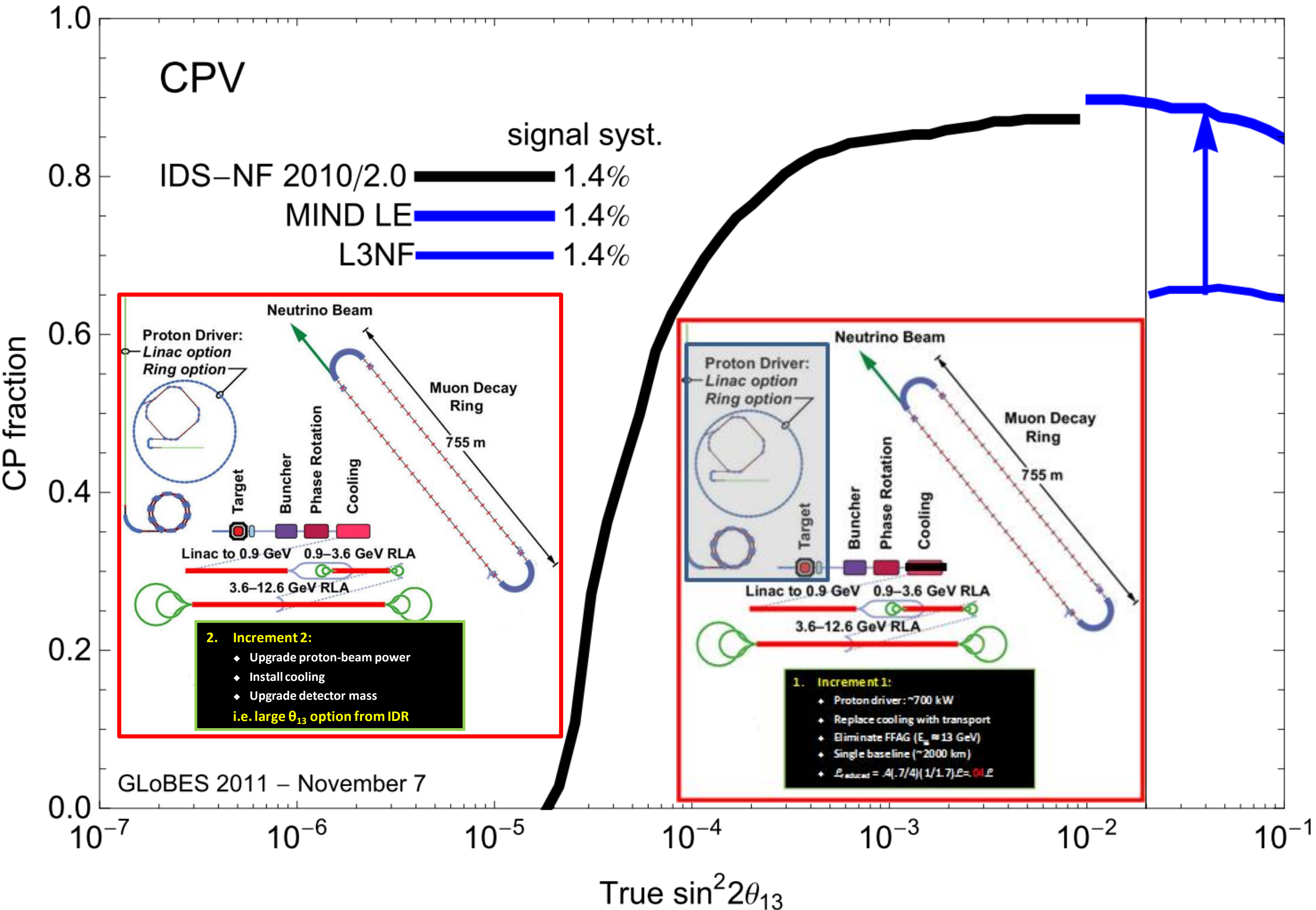
Sterile neutrino search





- Need either E_μ=4 GeV or 10^{19} useful muon decays/polarity to cover best-fit
- Highly competitive compared to alternatives
  (⇨Sterile neutrino white paper)
- Can one improve on "systematics limit"?

(WW, arXiv:1204.2671)


1.0
0.8
0.6
0.4
0.2
0.0
CP fraction
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
True $\sin^2 2\theta_{13}$
CPV
signal syst.
IDS–NF 2010/2.0 1.4%
MIND LE 1.4%
L3NF 1.4%
GLoBES 2011 – November 7
Neutrino Beam
Proton Driver:
Linac option
Ring option
Muon Decay Ring
755 m
Target
Buncher
Phase Rotation
Cooling
Linac to 0.9 GeV
0.9–3.6 GeV RLA
3.6–12.6 GeV RLA
2. Increment 2:
Upgrade proton-beam power
Install cooling
Upgrade detector mass
i.e. large θ_{13} option from IDR
Neutrino Beam
Proton Driver:
Linac option
Ring option
Muon Decay Ring
755 m
Target
Buncher
Phase Rotation
Cooling
Linac to 0.9 GeV
0.9–3.6 GeV RLA
3.6–12.6 GeV RLA
1. Increment 1:
Proton driver: ~700 kW
Replace cooling with transport
Eliminate FFAG ($E_\mu \approx$ 13 GeV)
Single baseline (~2000 km)
$\mathcal{L}_{reduced} = .4(.7/4)(1/1.7)\mathcal{L} = .04\mathcal{L}$

CP violation at the Neutrino Factory:

Conclusions

Conclusions:

- Measurement of θ_{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!