Imperial College London

K. Long, 8th April 2008

International Design Study for the Neutrino Factory

The IDS-NF

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- Bringing the ISS to a conclusion
- The International Design Study for the Neutrino Factory
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Motivation

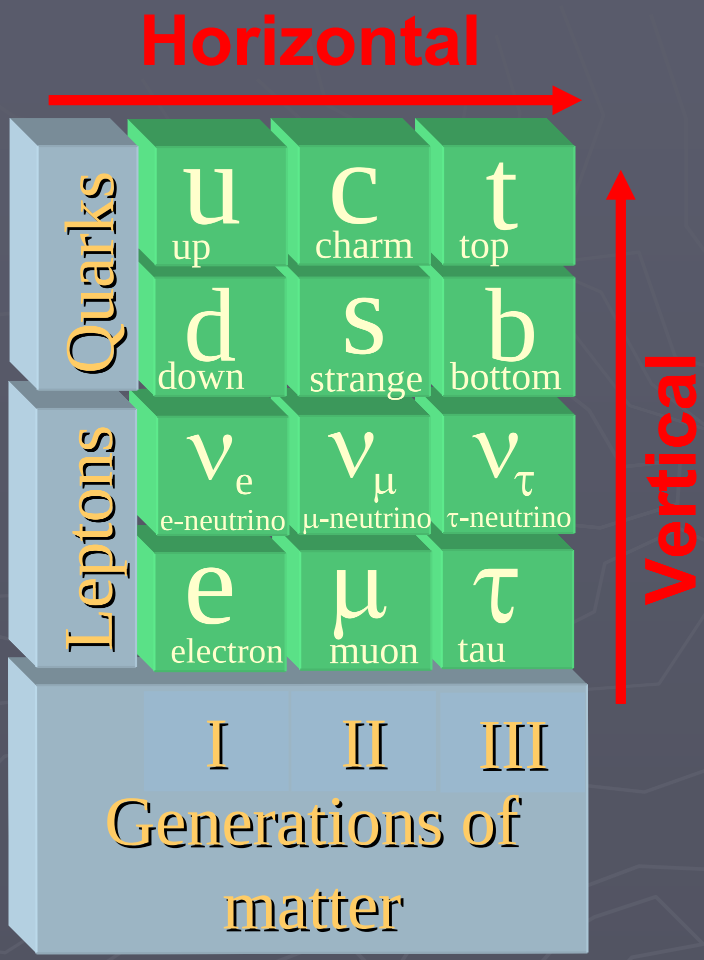
Fundamental questions

- Origin of mass:
  - And why is neutrino mass is so small
- Why is there no antimatter:
  - And can leptonic CP violation make a decisive contribution
- Did neutrinos play a role in:
  - Inflation?
  - Galaxy formation?
- Unification of matter and force:
  - Do the differences between the quark and lepton properties hold the key?

Motivation

Theoretical speculations

- Grand-unified (vertical) symmetry
  - Relate quarks and leptons
- Family (horizontal) symmetry
  - Relate fermions across generations
- Supersymmetry:
  - Heavy Majorana neutrinos
  - See-saw mechanism
    - Light neutrinos
    - Large neutrino mixing angles

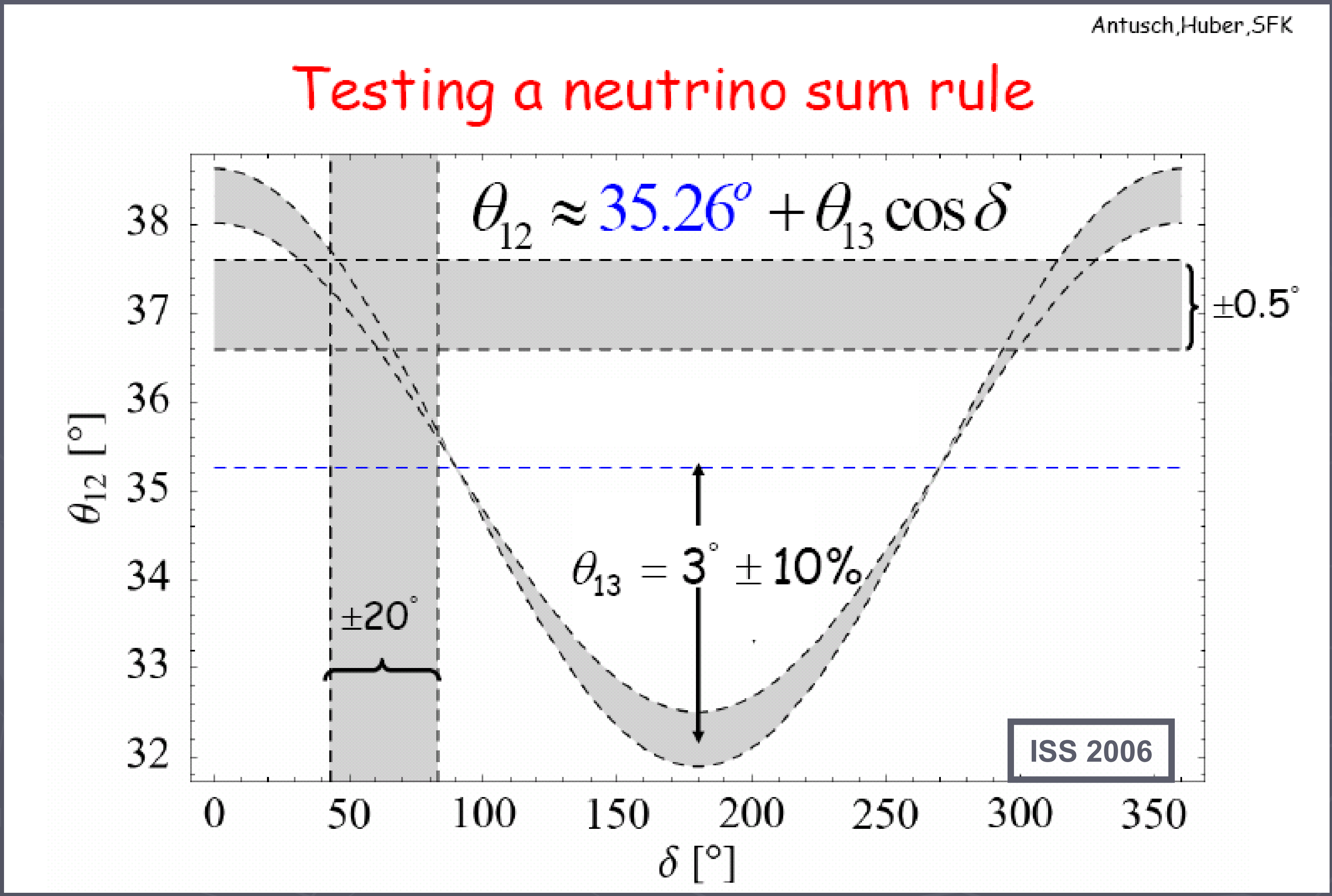


The experimentalists' contribution

- Search for leptonic CP violation
- Determine mass hierarchy
- Measure mixing parameters with a precision sufficient to guide theoretical speculation
  - Or, better, determine structure of theory
    - Standard Model itself established in this way
- Seek to:
  - Determine neutrino-mixing parameters with a precision approaching that of the quark-mixing parameters
    - Ultimate theory must unify quarks and leptons

Motivation

Quark-lepton relationship – example



Motivation

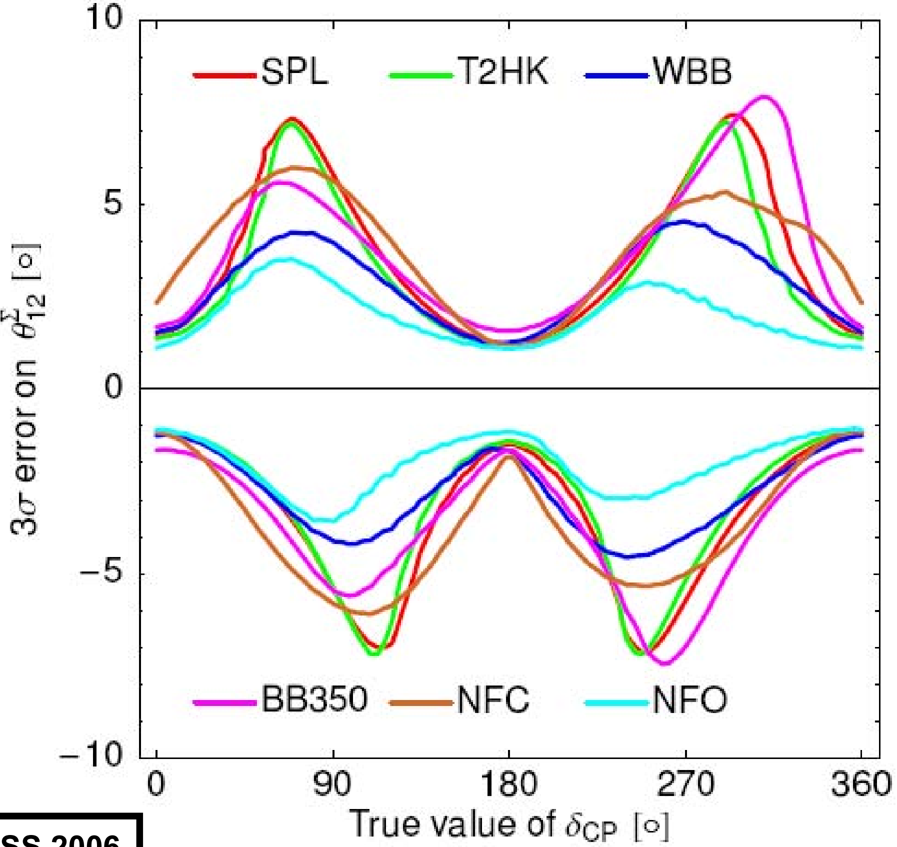
Quark-lepton relationship – example

- Define:

$$\theta_{12}^{\Sigma} = \theta_{12} - \theta_{13} \cos\delta$$

- Precision evaluated assuming:

$$\theta_{12} = 33.12^{\circ} \quad \theta_{13} = 9^{\circ}$$

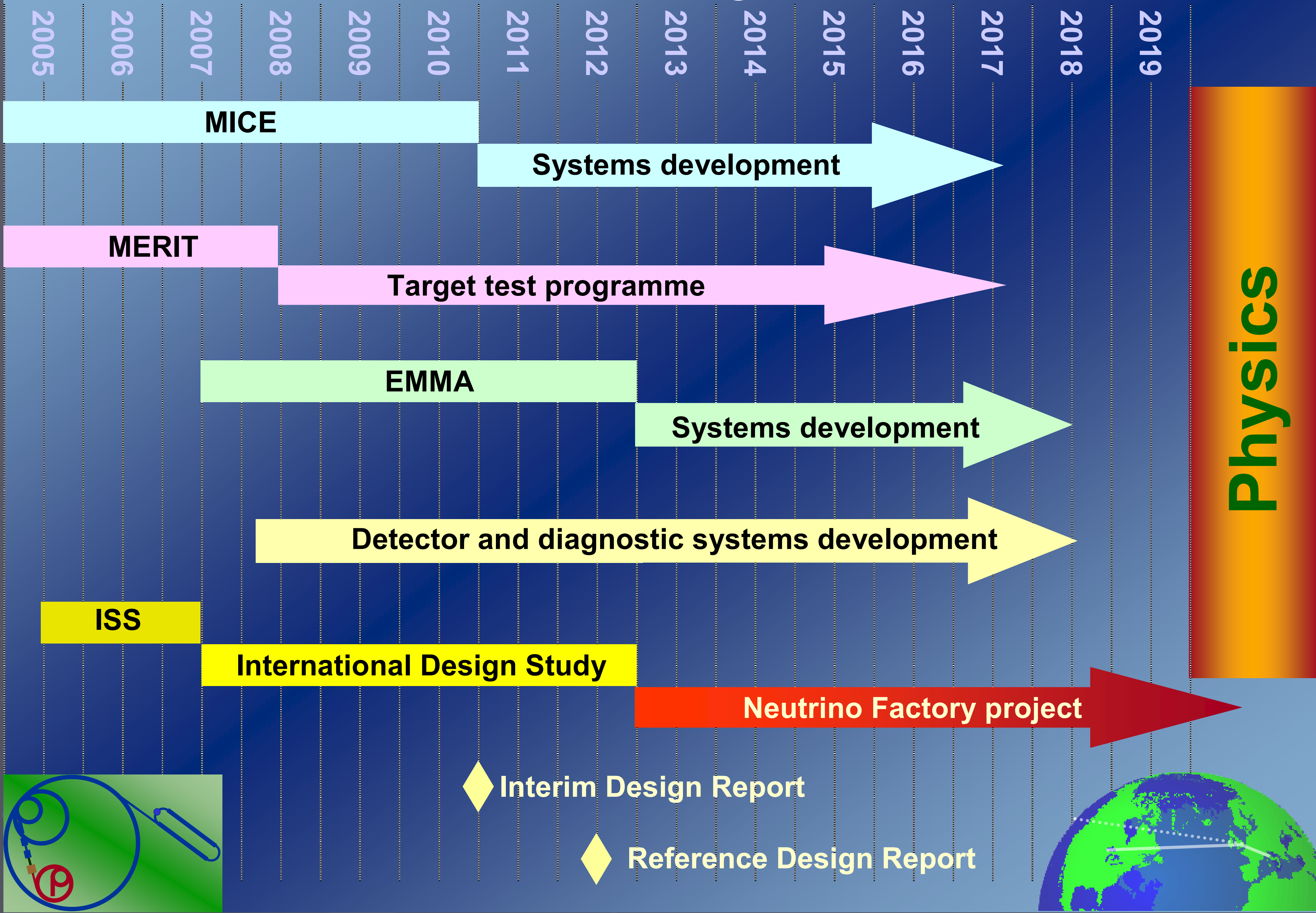


ISS 2006

Timescale

- Emerging consensus:
  - A programme of high statistics, high precision, measurements of neutrino oscillations is required to follow T2K and NOvA;
  - The decision point is likely to be around 2012:
    - Explicit in the C.E.R.N. Strategy Group statement;
    - Endorsed by EPP2010
- Not quite a consensus on what will constitute the programme:
  - Opportunity:
    - Make Neutrino Factory an option on this timescale

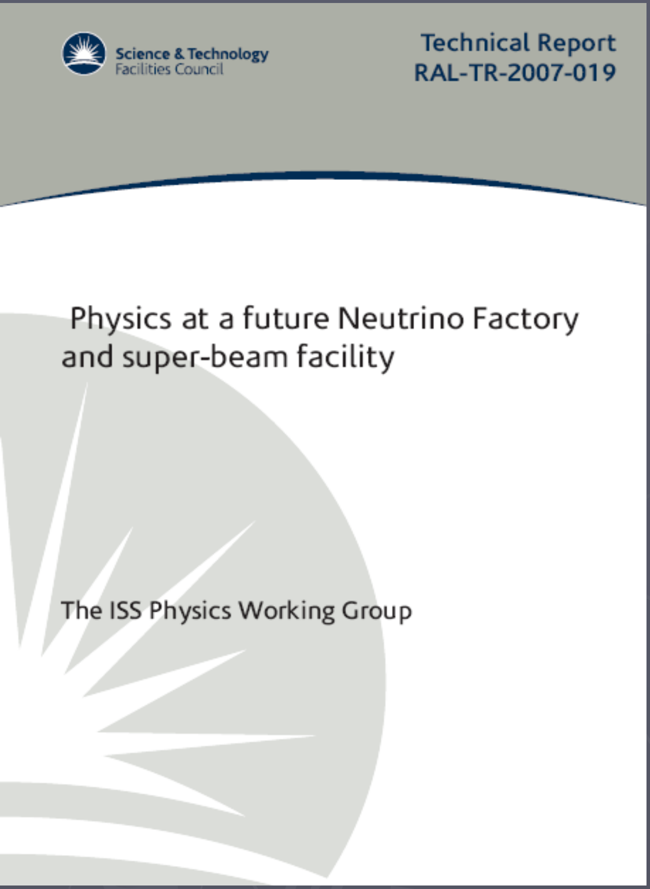
Neutrino Factory roadmap

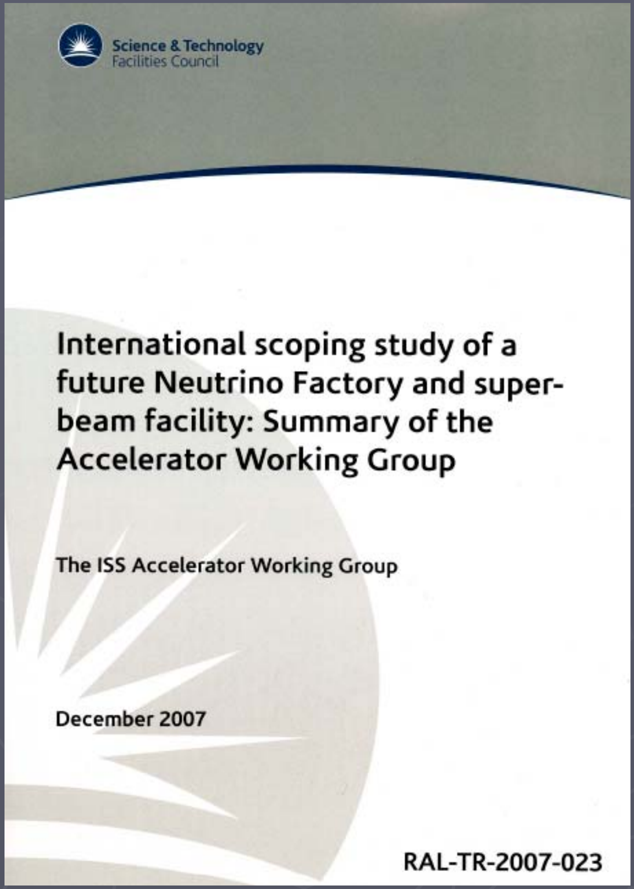


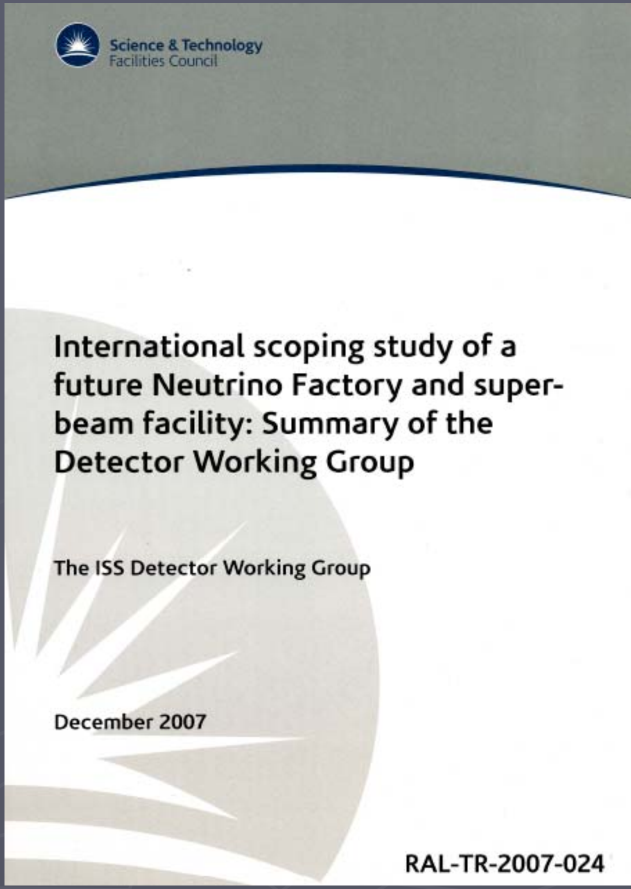
Timescale:

- Are we slipping?
- ISS conceived as a step on the way:
  - A one-year programme to lay the foundation for a more in-depth design study to follow …
- The IDS-NF:
  - Goal: to produce a 'Reference Design Report' for the Neutrino Factory by 2012:
    - The RDR is conceived as the document that will allow the 'decision makers' to consider initiating the Neutrino Factory project
  - The IDS-NF, therefore, differs from the ISS in that the emphasis will increasingly be placed on the engineering in order to:
    - Demonstrate the technical feasibility of the various systems; and
    - Evaluate the cost of the facility at the 30—50% level

Bringing the ISS to a conclusion


Science & Technology Facilities Council
Technical Report
RAL-TR-2007-019
Physics at a future Neutrino Factory and super-beam facility
The ISS Physics Working Group


Science & Technology Facilities Council
International scoping study of a future Neutrino Factory and super-beam facility: Summary of the Accelerator Working Group
The ISS Accelerator Working Group
December 2007
RAL-TR-2007-023


Science & Technology Facilities Council
International scoping study of a future Neutrino Factory and super-beam facility: Summary of the Detector Working Group
The ISS Detector Working Group
December 2007
RAL-TR-2007-024

- Seeking to publish:
  - Physics report in Rep. Prog. Phys.
  - Accelerator and Detector reports in JInst
- Executive summary:
  - 10-pager: written by P.Dornan; almost final

ISS outcomes

- The ISS:
  - Made the case for the high-sensitivity programme of neutrino-oscillation measurement
  - Demonstrated the need to evaluate the performance of cost of the various facilities, and the Neutrino Factory in particular, on the timescale of 2012
  - Demonstrated need for combined approach, optimising accelerator and detector together
  - Developed an internationally agreed baseline for the Neutrino Factory accelerator complex
  - Developed an internationally agreed baseline for the Neutrino Factory neutrino-detection systems
- This is the launch point for the IDS-NF

The IDS-NF

International Design Study of the Neutrino Factory
Steering Group

A.Blondel, K.Long (chair), M.Zisman, Y.Kuno

Physics and Performance Evaluation:
A.Donini, P.Huber, S.Pascoli, W.Winter

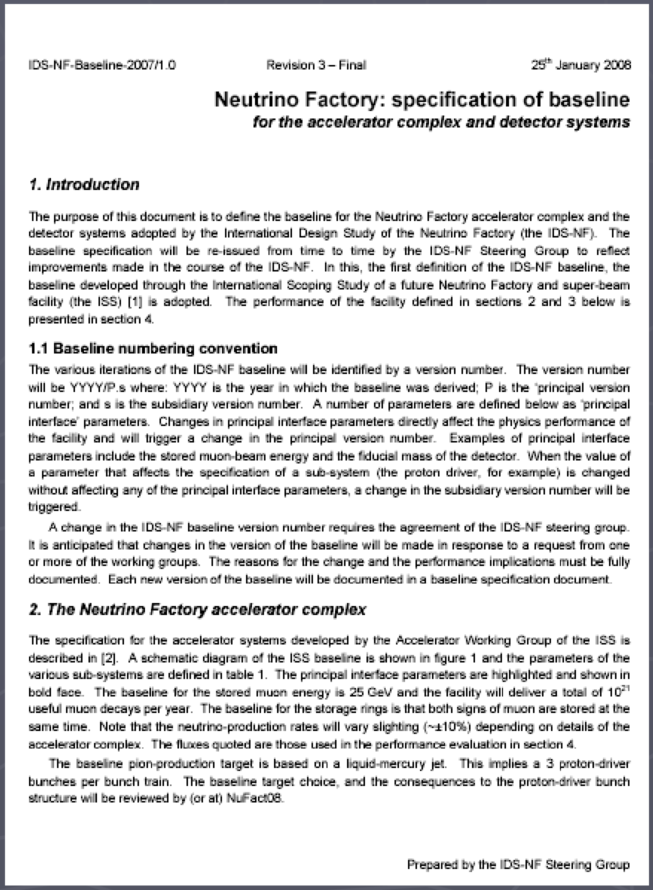
Accelerator:
S.Berg, M.Medahi, Y.Mori, C.Prior, J.Pozimski

Detector:
A.Bross, A.Cervera, N.Mondal, P.Soler

- WWW page for communication:
  - http://www.hep.ph.ic.ac.uk/ids/
- Meetings to date:
  - CERN: 29–31Mar07: initial ISS → IDS-NF transition meeting
  - RAL: 16–17Jan08: Plenary meeting #1 …
  - FNAL: 10–12Jun08: Plenary meeting #2

IDS-NF plenary #1: achievements:

- Agreed first version of the IDS-NF baseline:
  - See http://www.hep.ph.ic.ac.uk/ids/docs/IDS-NF-Baseline-2007-1.0R3-Final.pdf



IDS-NF-Baseline-2007/1.0 Revision 3 – Final 25th January 2008

Neutrino Factory: specification of baseline
for the accelerator complex and detector systems

1. Introduction

The purpose of this document is to define the baseline for the Neutrino Factory accelerator complex and the detector systems adopted by the International Design Study of the Neutrino Factory (the IDS-NF). The baseline specification will be re-issued from time to time by the IDS-NF Steering Group to reflect improvements made in the course of the IDS-NF. In this, the first definition of the IDS-NF baseline, the baseline developed through the International Scoping Study of a future Neutrino Factory and super-beam facility (the ISS) [1] is adopted. The performance of the facility defined in sections 2 and 3 below is presented in section 4.

1.1 Baseline numbering convention

The various iterations of the IDS-NF baseline will be identified by a version number. The version number will be YYYY/P.s where: YYYY is the year in which the baseline was derived; P is the 'principal version number; and s is the subsidiary version number. A number of parameters are defined below as 'principal interface' parameters. Changes in principal interface parameters directly affect the physics performance of the facility and will trigger a change in the principal version number. Examples of principal interface parameters include the stored muon-beam energy and the fiducial mass of the detector. When the value of a parameter that affects the specification of a sub-system (the proton driver, for example) is changed without affecting any of the principal interface parameters, a change in the subsidiary version number will be triggered.

A change in the IDS-NF baseline version number requires the agreement of the IDS-NF steering group. It is anticipated that changes in the version of the baseline will be made in response to a request from one or more of the working groups. The reasons for the change and the performance implications must be fully documented. Each new version of the baseline will be documented in a baseline specification document.

2. The Neutrino Factory accelerator complex

The specification for the accelerator systems developed by the Accelerator Working Group of the ISS is described in [2]. A schematic diagram of the ISS baseline is shown in figure 1 and the parameters of the various sub-systems are defined in table 1. The principal interface parameters are highlighted and shown in bold face. The baseline for the stored muon energy is 25 GeV and the facility will deliver a total of 10^{21} useful muon decays per year. The baseline for the storage rings is that both signs of muon are stored at the same time. Note that the neutrino-production rates will vary slighting (~±10%) depending on details of the accelerator complex. The fluxes quoted are those used in the performance evaluation in section 4.

The baseline pion-production target is based on a liquid-mercury jet. This implies a 3 proton-driver bunches per bunch train. The baseline target choice, and the consequences to the proton-driver bunch structure will be reviewed by (or at) NuFact08.

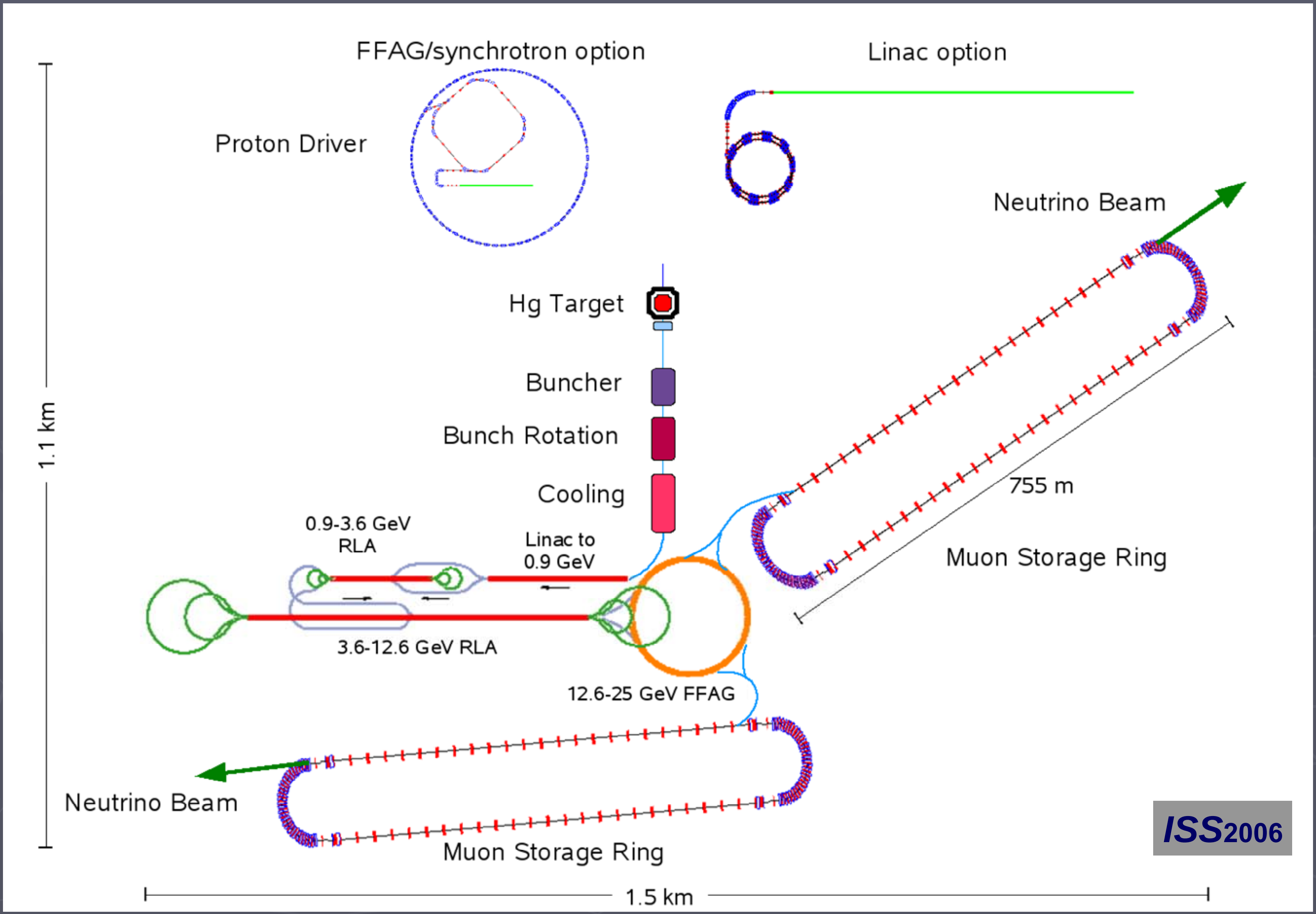
Prepared by the IDS-NF Steering Group

- Also, agreed work plan for period to NuFact08, Valencia, 30Jun—05Jul
  - See (for example) http://www.cap.bnl.gov/mumu/project/IDS/workplan.html

- IDS-NF starting (albeit a little slowly)

The IDS-NF

Accelerator baseline



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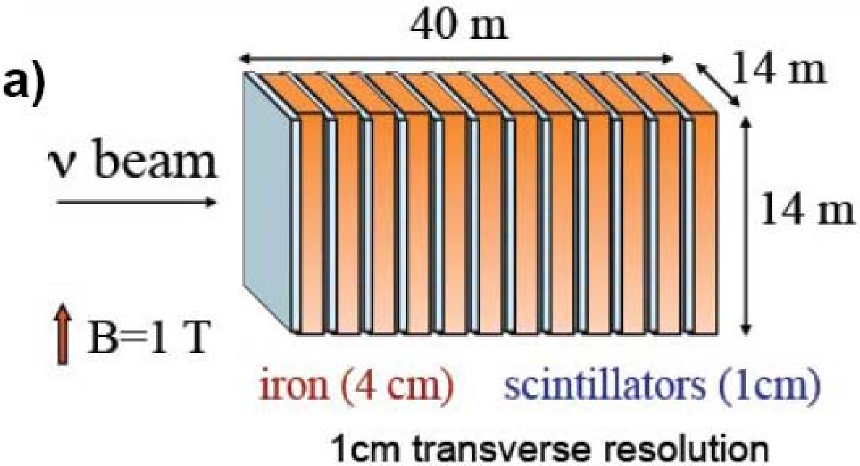
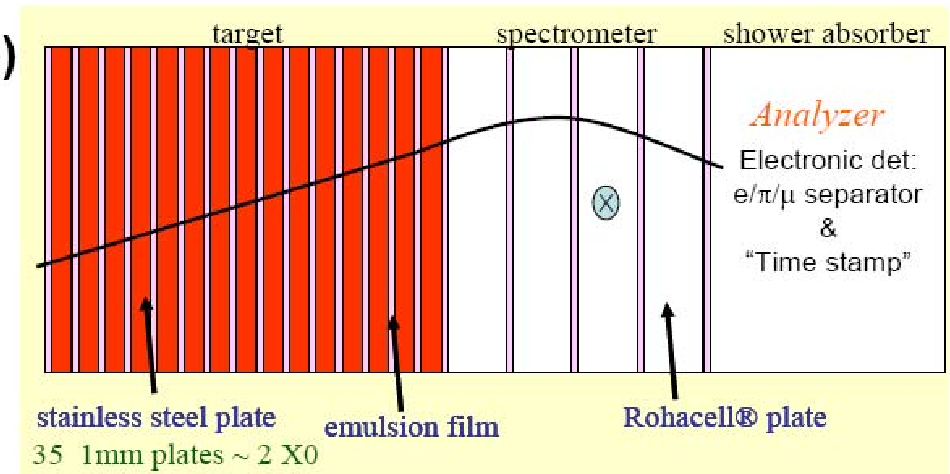
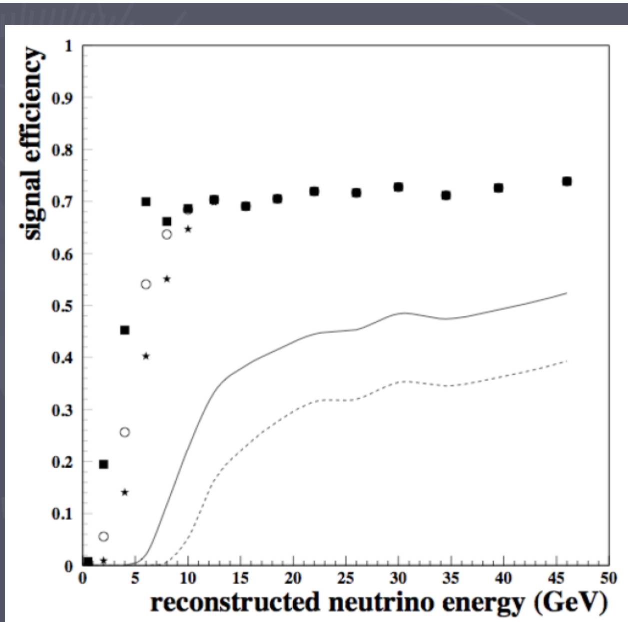
Accelerator baseline

Baseline specification for the Neutrino Factory accelerator complex			Version
Sub-system	**Parameter**	**Value**	**2007/1.0**
Proton driver	Average beam power (MW)	4	
	Pulse repetition frequency (Hz)	50	
	Proton kinetic energy (GeV)	10 ± 5	
	Proton rms bunch length (ns)	2 ± 1	
	Number of proton bunches per pulse	3	
	Sequential extraction delay (μs)	≥ 17	
	Pulse duration, liquid-Hg target (μs)	≤ 40	
Target: liquid-mercury jet	Jet diameter (cm)	1	
	Jet velocity (m/s)	20	
	Solenoidal field at interaction point (T)	20	
Pion collection			
Tapered solenoidal channel	Length (m)	12	
	Field at target (T)	20	
	Diameter at target (cm)	15	
	Field at exit (T)`	1.75	
	Diameter at exit (cm)	25	
Decay channel	Length (m)	100	
Adiabatic buncher	Length (m)	50	
Phase rotator	Length (m)	50	
	Energy spread at exit (%)	10.5	
Ionisation cooling channel	Length (m)	80	
	RF frequency (MHz)	201.25	
	Absorber material	LiH	
	Absorber thickness (cm)	1	
	Input emittance (mm rad)	17	
	Output emittance (mm rad)	7.4	
	Central momentum (MeV/c)	220	
	Solenoidal focussing field (T)	2.8	
Acceleration system	Total energy at input (MeV)	244	
	Total energy at end of acceleration (GeV)	25	
	Input transverse acceptance (mm rad)	30	
	Input longitudinal acceptance (mm rad)	150	
Pre-acceleration linac	Final total energy (GeV)	0.9	
RLA(1)	Final total energy (GeV)	3.6	
RLA(2)	Final total energy (GeV)	12.6	
NFFAG	Final total energy (GeV)	25	
Decay rings	Ring type	Race track	
	Straight-section length (m)	600.2	
	Race-track circumference (m)	1,608.80	
	Number of rings (number of baselines)	**2**	
	Stored muon energy (total energy, GeV)	**25**	
	Beam divergence in production straight (γ^{-1})	**0.1**	
	Bunch spacing (ns)	**≥ 100**	
	Number of $\mu^{\pm}$ decays per year per baseline	**5×10^{20}**	

Detector baseline







- Two baselines:
  - 3000 – 5000 km
  - 7000 – 8000 km
- Magnetised Iron Neutrino Detector (MIND) at each location
- Magnetised Emulsion Cloud Chamber at intermediate baseline for tau detection

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Detector baseline

Baseline specification for the Neutrino Factory long-baseline neutrino detectors			Version
Sub-system	**Parameter**	**Value**	**2007/1.0**
Configuration	**Number of baselines**	**2**	
	Intermediate baseline (km)	3,000 to 5,000	
	Long baseline (km)	7,000 to 8,000	
	Detectors at intermediate baseline	MECC, MIND	
	Detector at long baseline	MIND	
MIND	**Fiducial mass (kTonne)**	**50**	
	Magnetic field (T)	1	
	Neutrino energy resolution ($GeV^{-0.5}$)	$55\%/E_{\nu}^{0.5}$	
Background fraction	Charged current (GeV^{-2})	See table 3	
	Neutral current (GeV^{-2})	See table 3	
Efficiency	ν_{μ} appearance: efficiency	See table 3	
	ν_{μ} disappearance: efficiency	0.9 (from 1 GeV)	
Systematic uncertainty	Uncertainty on number of events in signal sample	2.50%	
	Uncertainty on number of events in background sample	20%	
MECC	**Fiducial mass (kTonne)**	**10**	
	Magnetic field (T)	**1**	

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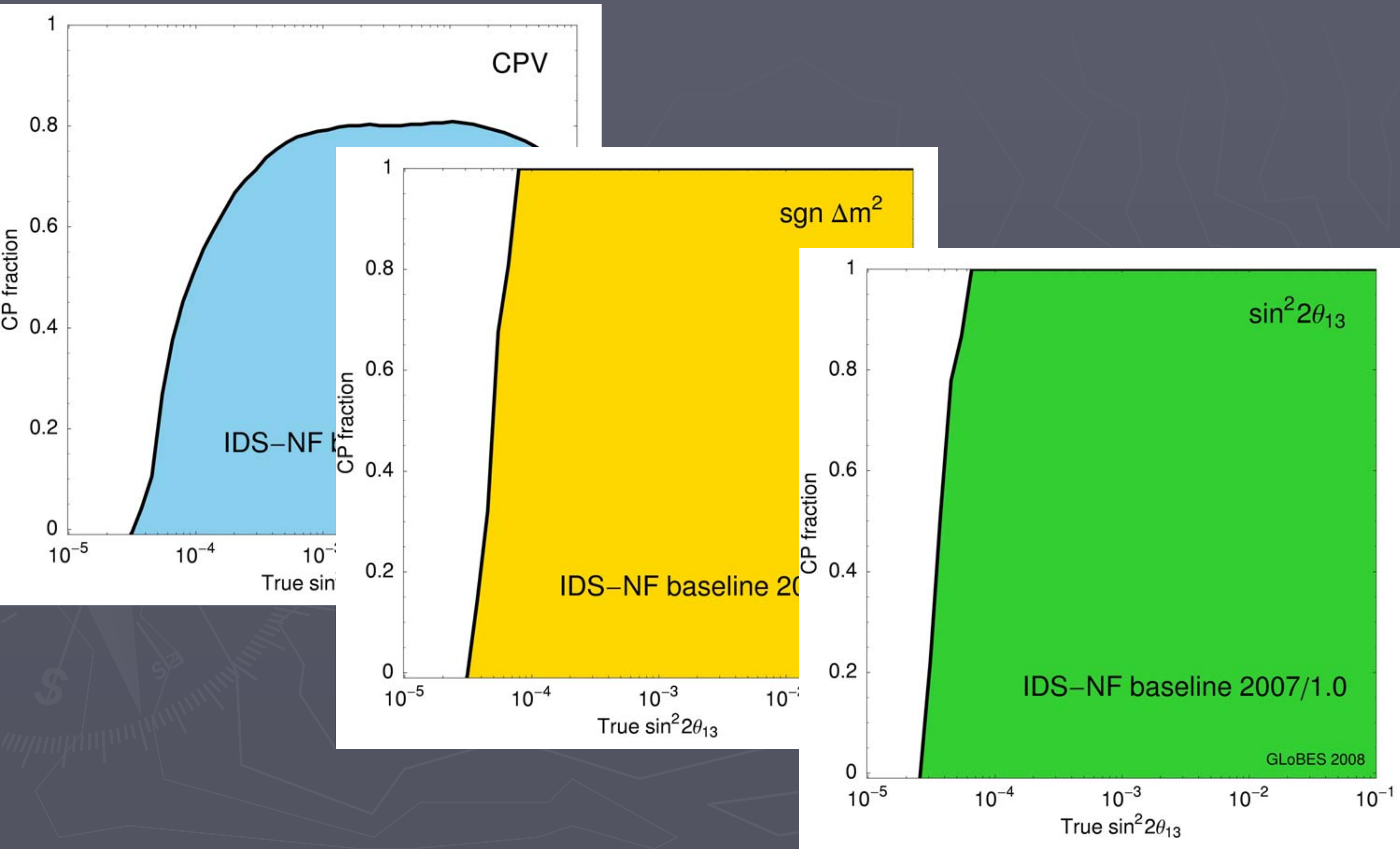
Performance of baseline Neutrino Factory



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IDS-NF: the next steps: Accelerator working group

S.Berg, M.Medahi, Y.Mori, C.Prior, J.Pozimski

- Proton driver:
  - Lattice design and simulation for proton driver
    - Description of the facility
- Target:
  - Analysis of MERIT data:
    - To determine maximum length of bunch train
  - Start on consideration of target infrastructure
- Front end:
  - Review impact of interaction of magnetic field and accelerating gradient with a view to reviewing layout;
  - Revise baseline cooling-channel design if required
- Acceleration:
  - Definition of lattice for normal and superconducting linac, RLAs
    - Tracking through portions of lattice to determine output distributions
  - Definition of lattice for non-scaling FFAG
    - Tracking to study output distortion and to analyse emittance growth
- Storage ring:
  - Study of transfer lines and tracking in idealised lattice to study emittance growth, losses, and fluxes

http://www.cap.bnl.gov/mumu/project/IDS/workplan.html

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IDS-NF: the next steps: Detector working group

A.Bross, A.Cervera, N.Mondal, P.Soler

- Work towards full simulation/reconstruction of MIND:
  - Goals:
    - For E_ν < 10 GeV demonstrate:
      - Backgrounds below 10^{-3}
      - Efficiency can be increased with respect to present analysis
  - Determine:
    - Signal and background efficiencies as a function of energy
    - Energy resolution as a function of energy
  - Begin optimisation:
    - Identify key parameters
  - Initial study of pattern recognition for muon identification
  - Include full set of physics processes:
    - Quasi-elastic, resonance production
- Beyond the baseline:
  - If energy threshold could be reduced it might be possible to achieve as good (or better?) performance at lower muon energy
    - Crucial issue is magnetisation of massive detector with no iron
      - See talk by Sasha Zlobin

Beam Diagnostics and Near Detector aims

- Beam diagnostics (needed for flux measurement)
  - Number of muon decays
  - Measurement of divergence
  - Measurement of Muon polarization
- Near detector measurements needed for neutrino oscillation systematics:
  - Flux control for the long baseline search.
  - Measurement of charm background
  - Cross-section measurements: DIS, QES, RES scattering
- Other near detector neutrino physics (electroweak and QCD):
  - $\sin^2\theta_W$ - $\delta\sin^2\theta_W \sim 0.0001$
  - Unpolarised Parton Distribution Functions, nuclear effects
  - Polarised Parton Distribution Functions – polarised target
  - Lambda (Λ) polarisation
  - α_S from xF_3 - $\delta\alpha_S \sim 0.003$
  - Charm production: $|V_{cd}|$ and $|V_{cs}|$, CP violation from $D^0/\bar{D}^0$ mixing
  - Beyond SM searches
  - …

Near Detector Conclusions

- Near Detector considerations: optimisation design
  - Vertex detector: Choice of Pixels; eg. Hybrid pixels, Monolithic Active Pixels (MAPS), DEPFET; or silicon strips
  - Tracker: scintillating fibres, gaseous trackers (TPC, Drift chambers, …)
  - Other sub-detectors: PID, muon ID, calorimeter, …
- Tasks:
  - Simulation of near detector and optimisation of layout: could benefit from common software framework for Far Detector
  - Flux determination with inverse muon decays, etc.
  - Analysis of charm using near detector
  - Determination of systematic error from near/far extrapolation
  - Expectation of cross-section measurements
  - Test beam activities to validate technology (eg. vertex detectors)
  - Construction of beam diagnostic prototypes
  - Other physics studies: PDFs, etc. (engage with theory community for interesting measurements)

IDS-NF: the next steps: Physics & Performance Eval. Grp.

- IDS baseline:
  - Recompute performance plots for new baseline
  - Figures for other parameters (such as θ_{23})
- Specific physics questions concerning the IDS baseline setup:
  - Review physics case for the silver channel
  - Physics case for a higher muon energy (such as from NSI)
  - Detector mass/useful muon decay splitting between shorter and longer baseline?
  - Useful muon decay splitting between neutrinos/antineutrinos?
  - Simultaneous two-baseline optimization for the IDS-NF baseline setup
  - What is the reason for the worse CPV sensitivity for large θ_{13} compared to earlier setups?
  - Detailed study of systematics
- Investigate ideas beyond the baseline, such as the low energy Neutrino Factory

A.Donini, P.Huber, S.Pascoli, W.Winter

Conclusions

- Closing out the ISS:
  - Publish the reports and the Executive Summary
- The IDS-NF has started:
  - The ISS baseline has been adopted by the IDS-NF
  - First steps along the work plan have been defined
- There is a lot to do:
  - Carry out the first steps
  - Make it possible for others to join the effort
  - Lay the foundations for the crucial engineering work

FNAL: 10–12Jun08: Plenary meeting #2