Neutrino Physics & The ISS

Peter Dornan
Imperial College London

Why do Neutrino Physics?

- Least understood particle
- Beyond the Standard Model
  - A trivial Addition?
  - The Window on the Fundamental Theory?
- Ultimate theory must relate quarks & leptons
  - Cannot do this without a full understanding of the neutrino sector
  - Cannot do this with LHC or ILC

Neutrinos are BSM

- In the SM
  - Neutrinos are massless
  - Lepton Flavour is Conserved
  - Neutrino & antineutrino distinguished on the basis of helicity
- Neurtrino Oscillation shows
  - Neutrinos have mass
  - Lepton Flavour is not Conserved
  - Helicity cannot distinguish neutrinos from antineutrinos

A Minor Extension of the SM?

- Neutrinos are Dirac Particles
- Right handed Neutrinos exist
  - With no known interactions
    - Or very very weak ones
- Lepton Flavour is not respected
    - But overall lepton number is conserved
    - So Distinguish Neutrino and AntiNeutirno on the basis of Lepton Number
      - \- whatever it is
- Masses, Mixing Parameters - and CP Violation
  - \- just yet more parameters to feed into the theory

A Window on a Higher Theory?

- now we can speculate

- Neutrinos are Majorana States
  - Neutrino and anti neutrino are not distinct
  - Right handed neutrinos exist at very high masses - ~ unification scale
- Mixing angles - and probably masses – are related to those in the quark sector
- More forms of CP violation in the lepton area than the MNS phase
  - And this will solve the matter-antimatter mystery

Oscillation Parametrisation

- For oscillation must have two sets of eigenstates – flavour e-states and mass e-states

$$|\nu_\alpha\rangle = U_{MNS}|\nu_i\rangle \qquad \alpha = electron,\ muon,\ tau \qquad i = 1, 2, 3$$

Oscillation defined by

3 mixing angles, $\theta_{12}, \theta_{13}, \theta_{23}$

1 phase, δ

$$U = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{`atmospheric'}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}}_{\text{`cross/reactor'}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{`solar'}}$$

Oscillation Probability

- For just two state system

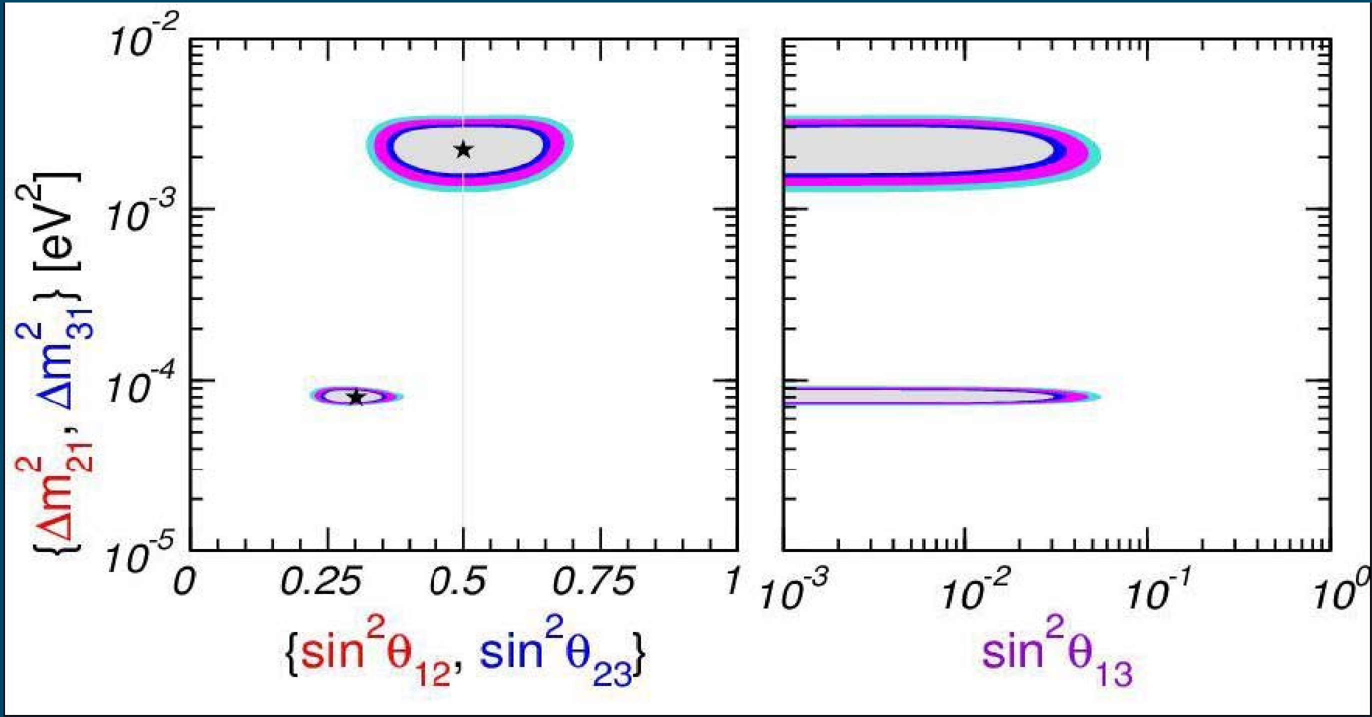
$$P_{\nu_\alpha \rightarrow \nu_\alpha} = 1 - \sin^2 2\theta_{ij} \sin^2\left(\frac{1.27\Delta m_{ij}^2 L}{E}\right)$$

Depends upon Mixing Angle, Mass Squared Difference, L/E

More Complex for a three state system
and additional complications if neutrinos pass through matter

Where are we?

from: Maltoni, Schwetz, Tortola, Valle ('04)



Unknown

Mass hierarchy, $m_2 > m_3$ or $m_2 < m_3$?

No information on CP violating phase δ

Unanswered – Oscillation Expts

- Is θ_{23} maximal?, How small is θ_{13}?
- CP Violation in the lepton sector?
- Mass hierarchy?
  - $m_3 <$ or $> m_2$
- CPT violation?
- The ultimate accuracy on the mixing angles and the mass differences
  - What accuracy is needed?
- (LSND? Sterile neutrino(s)?)

The Precision Era - after T2K and Nova

- Around 2012 - 2016
- We shall have good measurements of
  - θ_{12}, θ_{23}, Δm^2_{12}, Δm^2_{23}
- Probably have a measurement of θ_{13}
- Possibly know the mass hierarchy

- So can now plan for the ultimate neutrino measurements
  - Refine all parameters
  - Check consistency
  - Measure CP Violation
- This is the motivation for the ISS

The International Scoping Study (ISS)

International scoping study of a future Neutrino Factory and super-beam facility

- A One Year Study
  - Commenced NuFact05 – ended NuFact06
  - Final Report now in preparation
- Motivation
- Organisation
- Outcome
  - Physics Group
  - Accelerator Group
  - Detector Group
- The next step - IDS?

ISS: motivation

- Goal: Preparation for a design study leading to a conceptual design of a future neutrino facility

  - This will be a Significant *international* effort taking several years

  - Review physics case
    - ⇒ Critical comparison of options

  - Review options for accelerator complex:
    - Emphasis on the neutrino factory

  - Review options for neutrino-detection systems

ISS: organisation

Scoping study for a future neutrino complex
organisational chart

Programme Committee
Chair: Prof. P. Dornan (ICL)

Physics working group
Y. Nagashima (Osaka)

Council:
- *Y. Nagashima, chair*
- *Debbie Harris (FNAL)*
- *P. Hernandez (U.Valencia)*
- *S. King (Southampton)*
- *M. Lindner (TUM)*
- *K. Long (ICL)*
- *M. Mezzetto (INFN Padova)*
- *H. Murayama (LBL)*
- *L. Roberts (BU)*
- *O. Yasuda (TMU)*
- *W. Marciano (BNL)*
- *K.Nakamura (KEK)*

Accelerator working group
M. Zisman (LBNL)

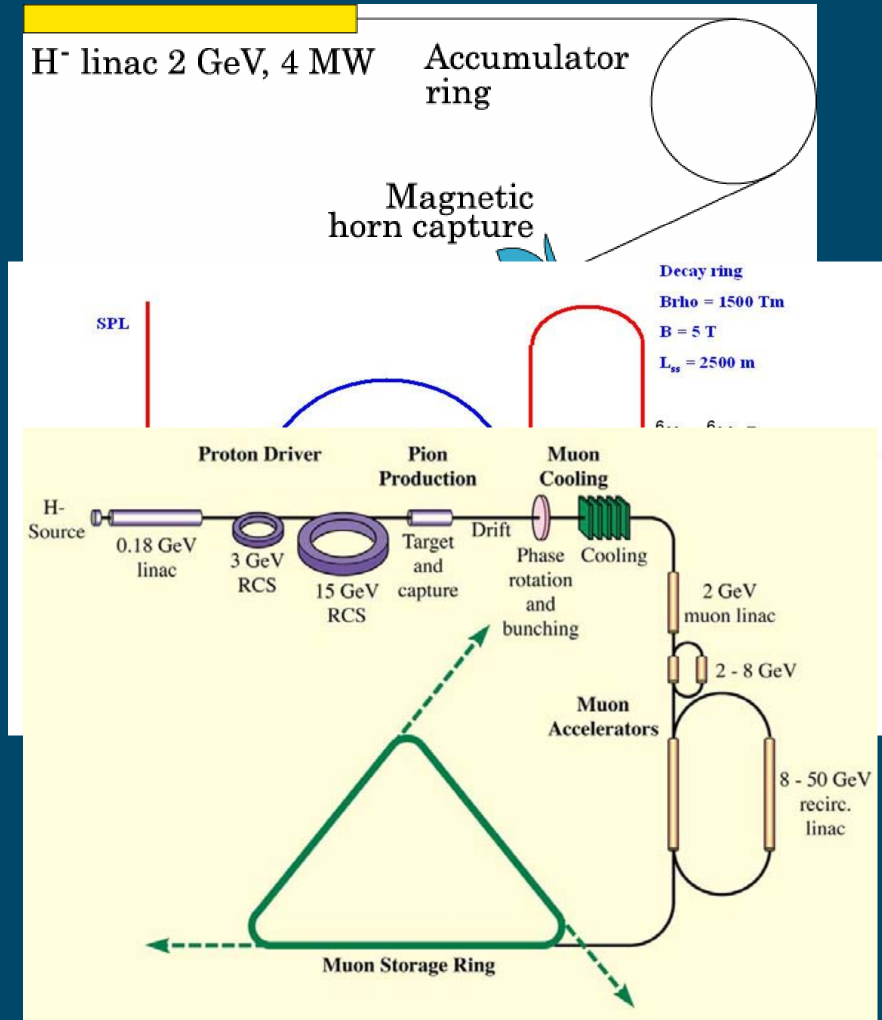
Council:
- *R. Fernow (BNL)*
- *Y. Mori (Kyoto)*
- *C. Prior (RAL/Oxford)*
- *R. Garoby (CERN)*
- *B. Palmer (BNL)*

Detector working group
A. Blondel (Geneva)

Council:
- *A. Bross (FNAL)*
- *K. Kaneyuki (Tokyo)*
- *P. Strolin (CERN)*
- *D. Wark (ICL, RAL)*
- *M. Mezzetto (INFN Padova)*
- *P. Soler (Glasgow)*
- *J.-E.Campagne (Orsay)*

Neutrino source – options:

- Second generation super-beam
  - CERN, FNAL, BNL, J-PARC II
- Bata-beam
- Neutrino Factory



Topics Covered in the ISS

- Accelerator
  - Mainly the Neutrino Factory Solution
    - Some consideration of superbeam where synergy exists
- Detector
  - All neutrino detectors
    - Appropriate for Superbeams, Beta beams and Neutrino factory
- Physics
  - The potential of superbeams, beta beams and neutrino factory with appropriate detectors

Meetings – an Intensive Year

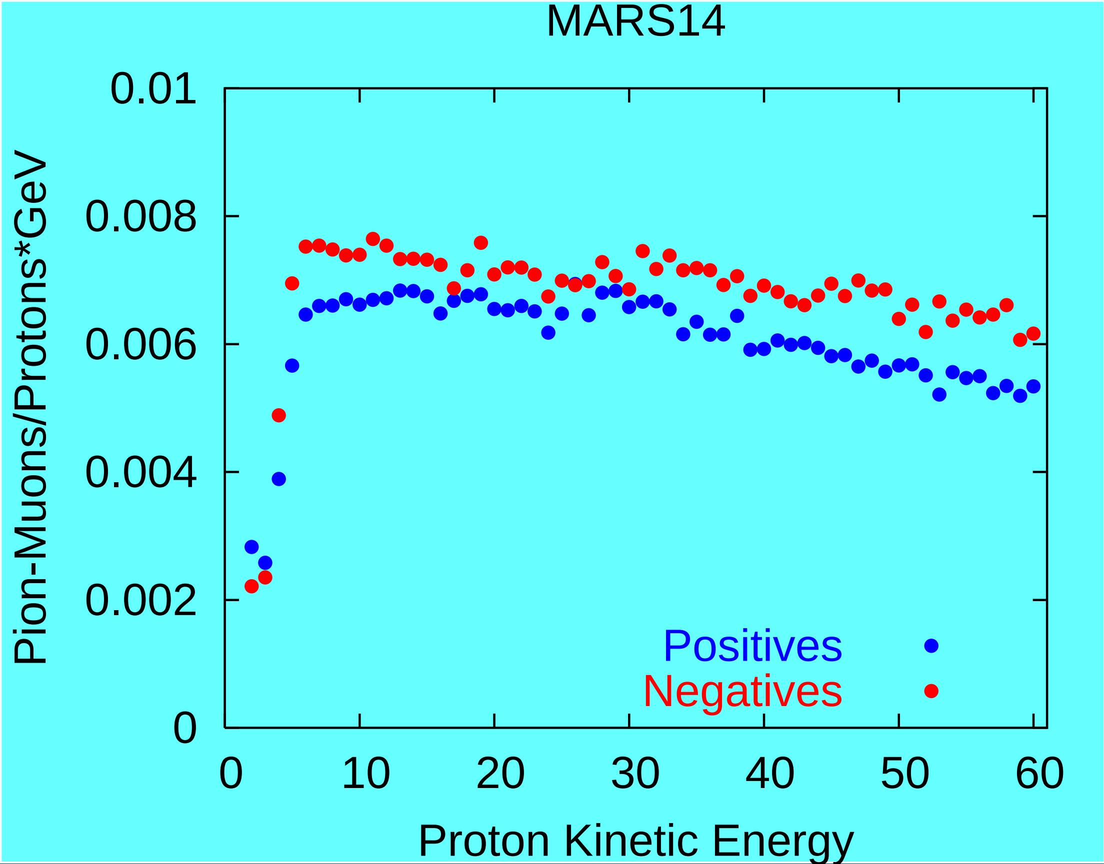
- Plenary meetings to date:
  - CERN: 22 – 24 September 2005
  - KEK: 23 – 26 January 2006
  - RAL: 24 – 27 April 2006
  - UC Irvine: 21 – 23 August 2006
- 8 Workshops:
  - Accelerator, Detector, Physics. Joint Physics/Detector
  - An amazing amount of work by many
- This very brief summary cannot do justice to it
- Here are just a few of the items I found particulalry interesting.
- Read the final report
  - Early next year

Accelerator Group

- A Baseline for the subsequent Design Study
  - Study alternative configurations; to arrive at baseline specifications
  - Develop tools required for end-to-end simulations
  - Identify Future R&D
- Subsystems & subgroups
  - Proton driver
  - Target and capture
  - Front end
    - Bunching and phase rotation
    - Cooling
  - Acceleration
  - Decay ring

Proton Driver - Optimum Energy

- Optimum Energy for high-Z targets broad, but drops at low energy



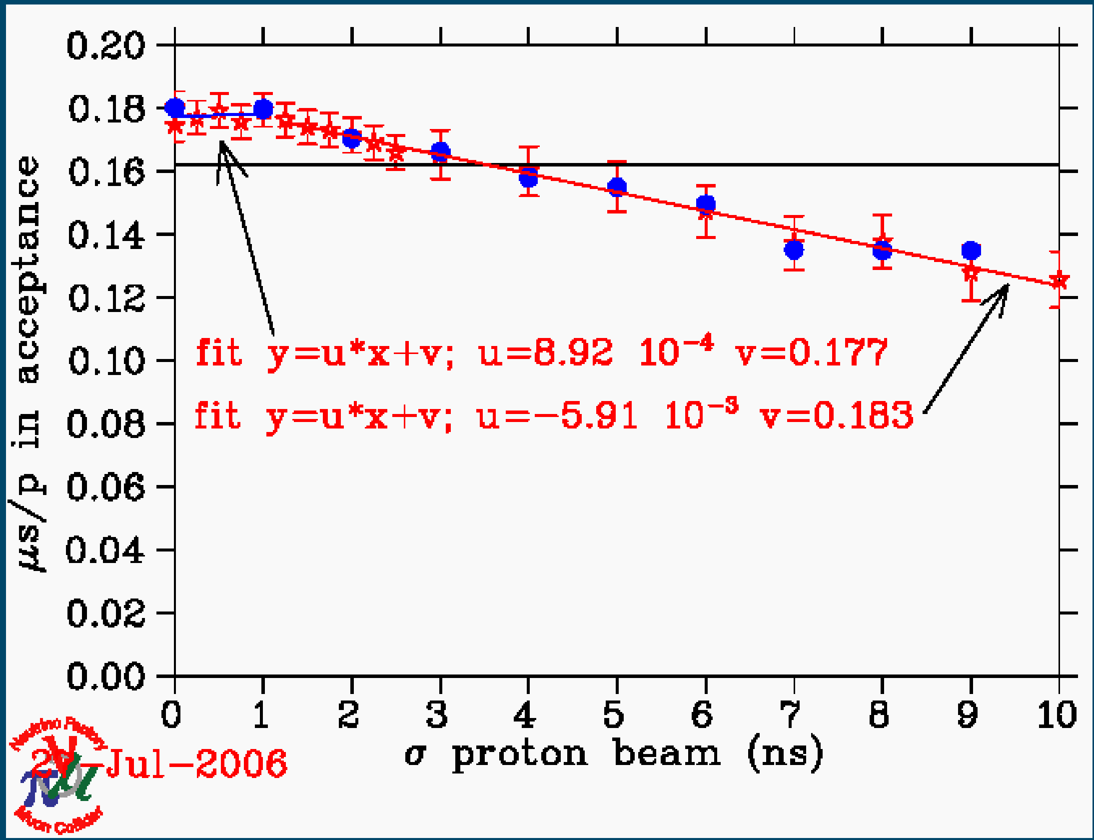
μ^-: 6 – 11 GeV

μ^+: 9 – 19 GeV

We adopted 10 ± 5 GeV as representative range

Bunch Length Dependence

- 1 ns is preferred, but 2-3 ns is acceptable
  - such short bunches harder to achieve at low beam energy



Proton Driver - Baseline

- Specify parameters, not design
  - implicitly assumes liquid-metal target

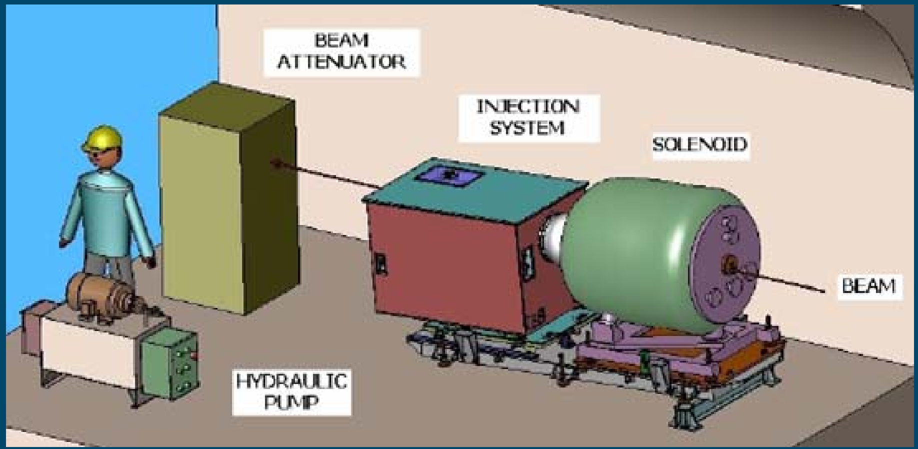
Parameter	Value
Energy (GeV)	10 ± 5
Beam power (MW)	4
Repetition rate (Hz)	≈50
No. of bunch trains	3,5[a)]
Bunch length, rms (ns)	2 ± 1
Beam duration[b)] (μs)	≈40

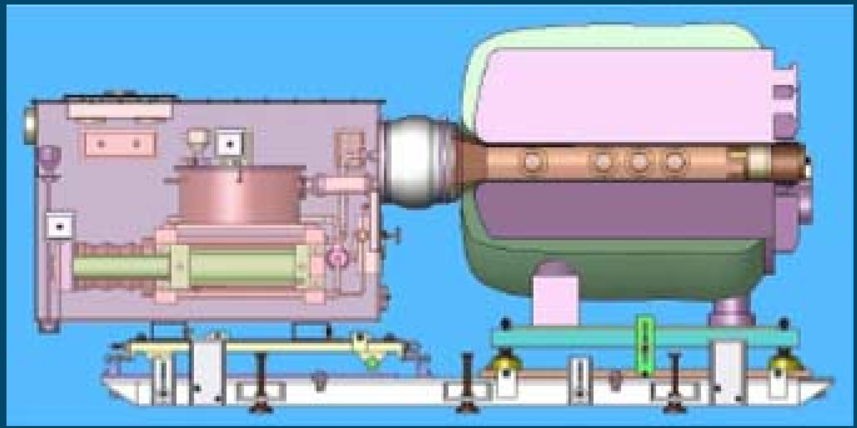
[a)] Values ranging from 1–5 possibly acceptable.

[b)] Maximum spill duration for liquid-metal target.

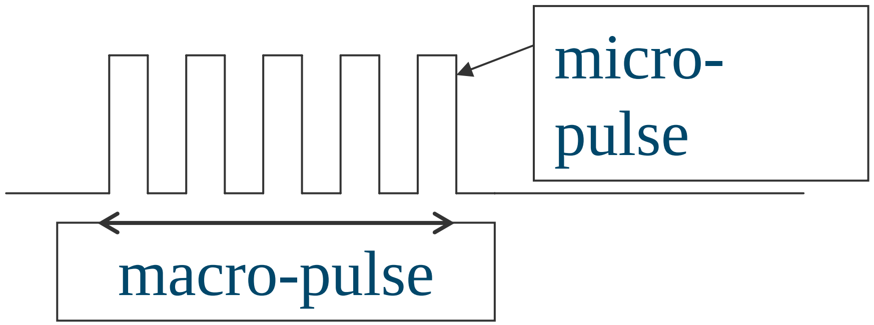
Target and capture

- MERIT experiment at CERN
  - High-power liquid-mercury jet target engineering demonstration





Influences on the Targetry choice



the proton driver

To reduce space charge it is best to have many and long micro-pulses, long macro-pulses and a high repetition rate.

the front end

Need a micro-pulse of ~<3 ns for phase rotation.
The beryllium windows will not stand a pulse longer than 160 μs.

the storage ring

Should not exceed ~4 micro-pulses to limit the size of the storage ring.

Solid Targets

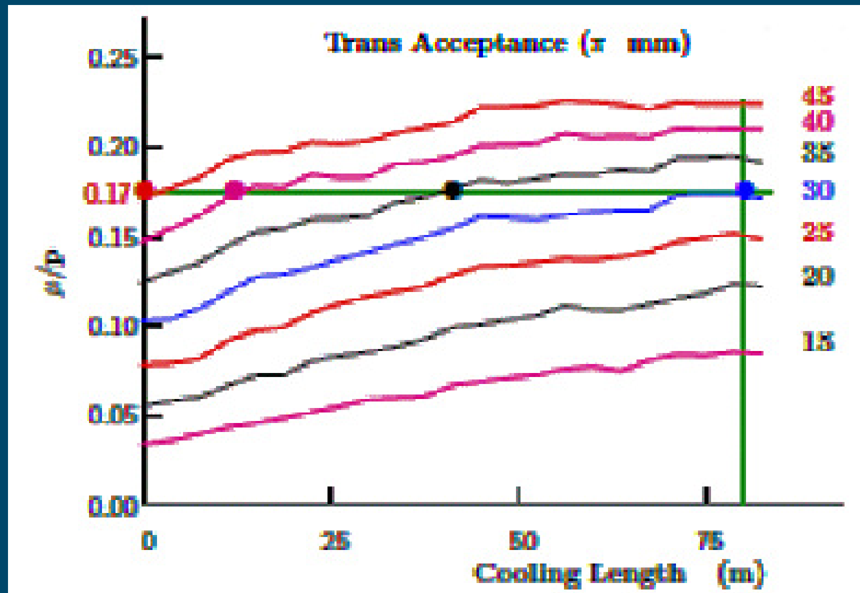
Prefer dc rather than pulsed beams to avoid thermal shock.

Jet Targets

Because the jet breaks up after the beam hits, the macro-pulse length should not be too long, ~<50 μs.
Pulse repetition rates greater than 50 Hz will make re-establishment of the jet difficult

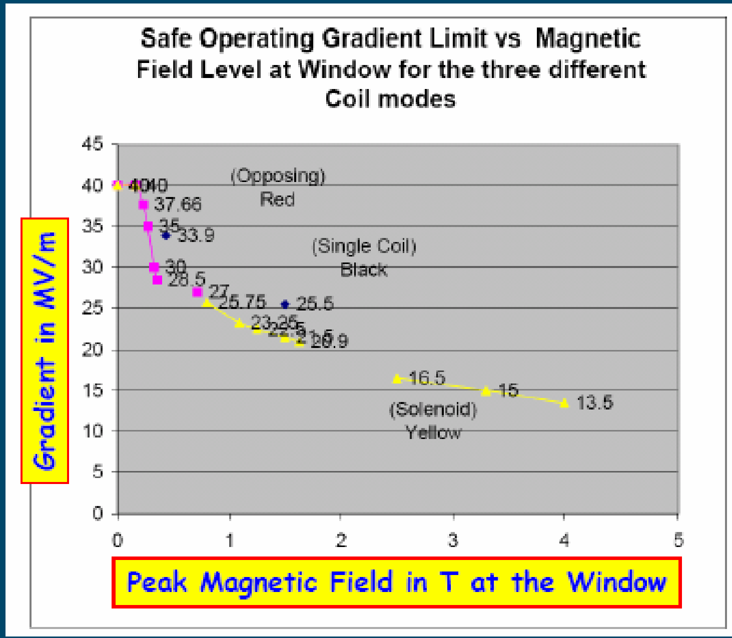
Cooling v Acceptance

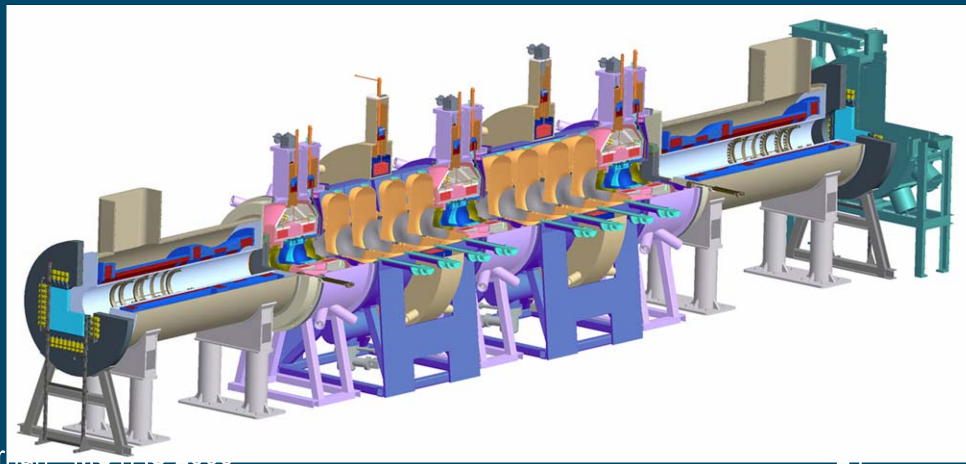
- Trade-off
  - increasing from 30 to 35 π mm-rad halves the required length of cooling channel
    - at 45 π mm-rad, no cooling needed
- Unlikely that A > 30 π mm-rad is practical
- Cooling Necessary



Cooling: hardware R&D programme

- Complementary programmes:
  - MuCool:
    - Design, prototype, and test – using an intense proton beam – cooling channel components
  - MICE:
    - Design, construct, commission, and operate – in a muon beam – a section of cooling channel and measure its performance in a variety of modes
- Both programmes well advanced



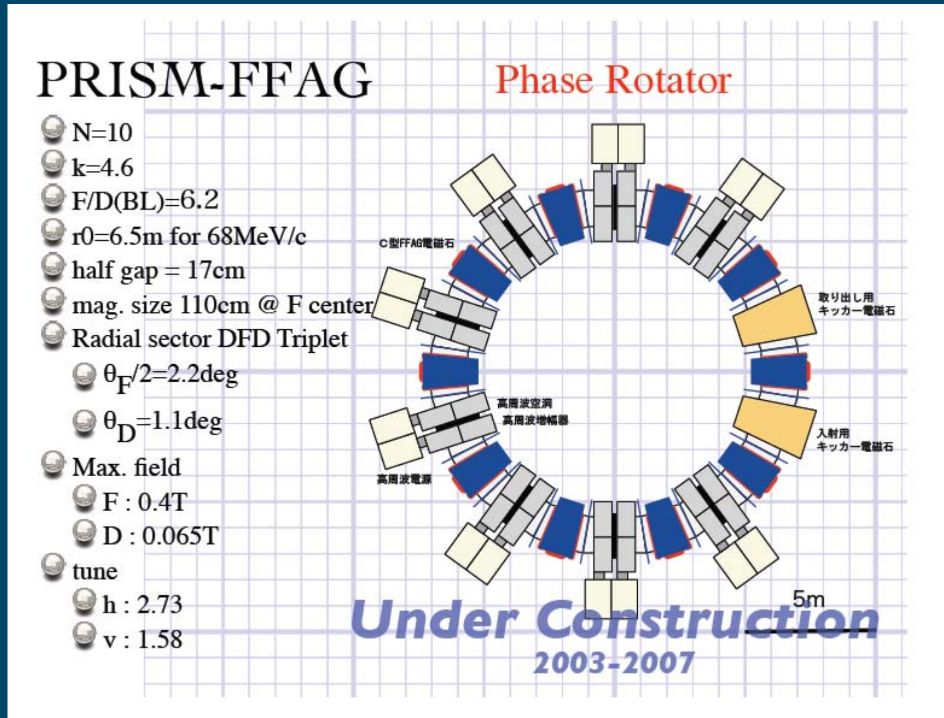


Baseline(2)

- Target
  - assume liquid target; Hg, look at Pb-Bi also
- Front End
  - bunching and phase rotation
    - use U.S. Study 2a configuration
  - cooling
    - include linear cooling channel in baseline - as being tested with MICE
  - keep both signs of muons
    - “waste not, want not”

Acceleration - FFAG development

- Increasing effort on scaling and non-scaling FFAG
- PRISM: Phase rotated intense muon source
  - Under construction in Osaka
    Commissioning 2007
  - Proof of principle 'non-scaling' FFAGDecay ring

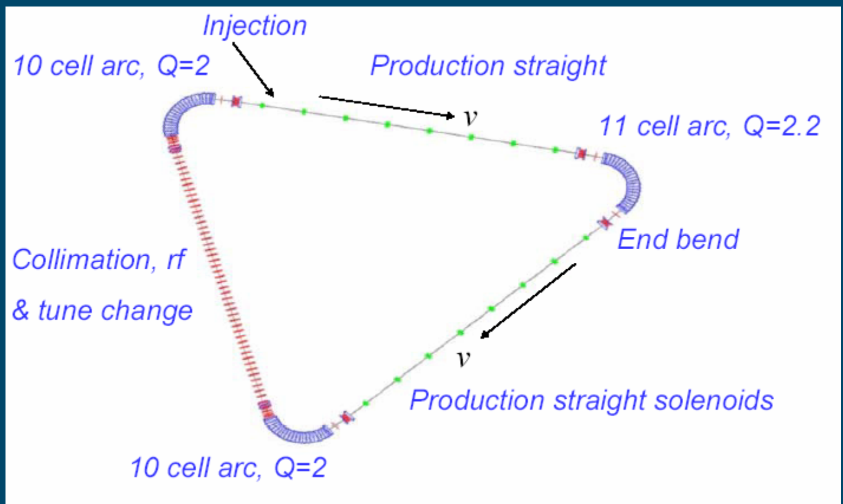


EMMA :Electron model of muon acceleration

Muon Decay Rings

Triangle rings would be stacked side by side in tunnel

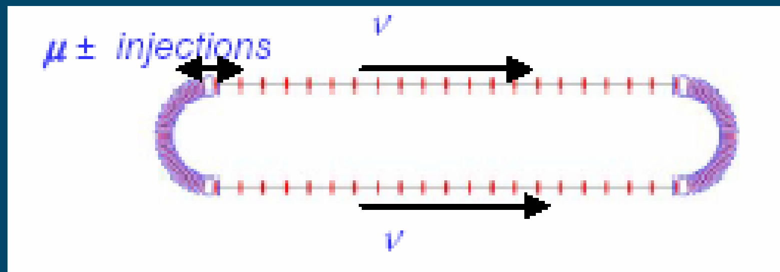
- one ring stores μ+ and one ring stores μ–
  - permits illuminating two detectors with (interleaved) neutrinos and antineutrinos simultaneously



Racetrack rings have two long straight sections that can be aimed at a single detector site

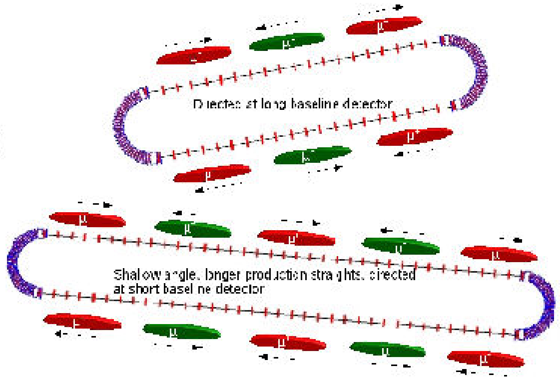
- could alternate storing μ+ and μ– in one ring, or store both together
- second ring,

More flexibility than triangle case, but probably more expensive



DECAY RINGS

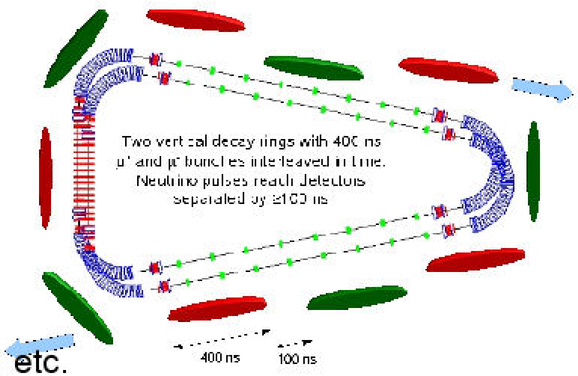
Working hypothesis :



- Compare alternatives and trade-offs, racetrack and triangular
- Implications of final energy (20 GeV, 50 GeV) on design
- Allow 3 π cm stored emittance
- Assume both signs muons $\rightarrow$ one or two rings.
- Consider double baseline
- Radiation issues at $10^{21}\mu/10^7$s

Goal : decide on racetrack versus triangle

Some fundamental criteria considered at the present stage :

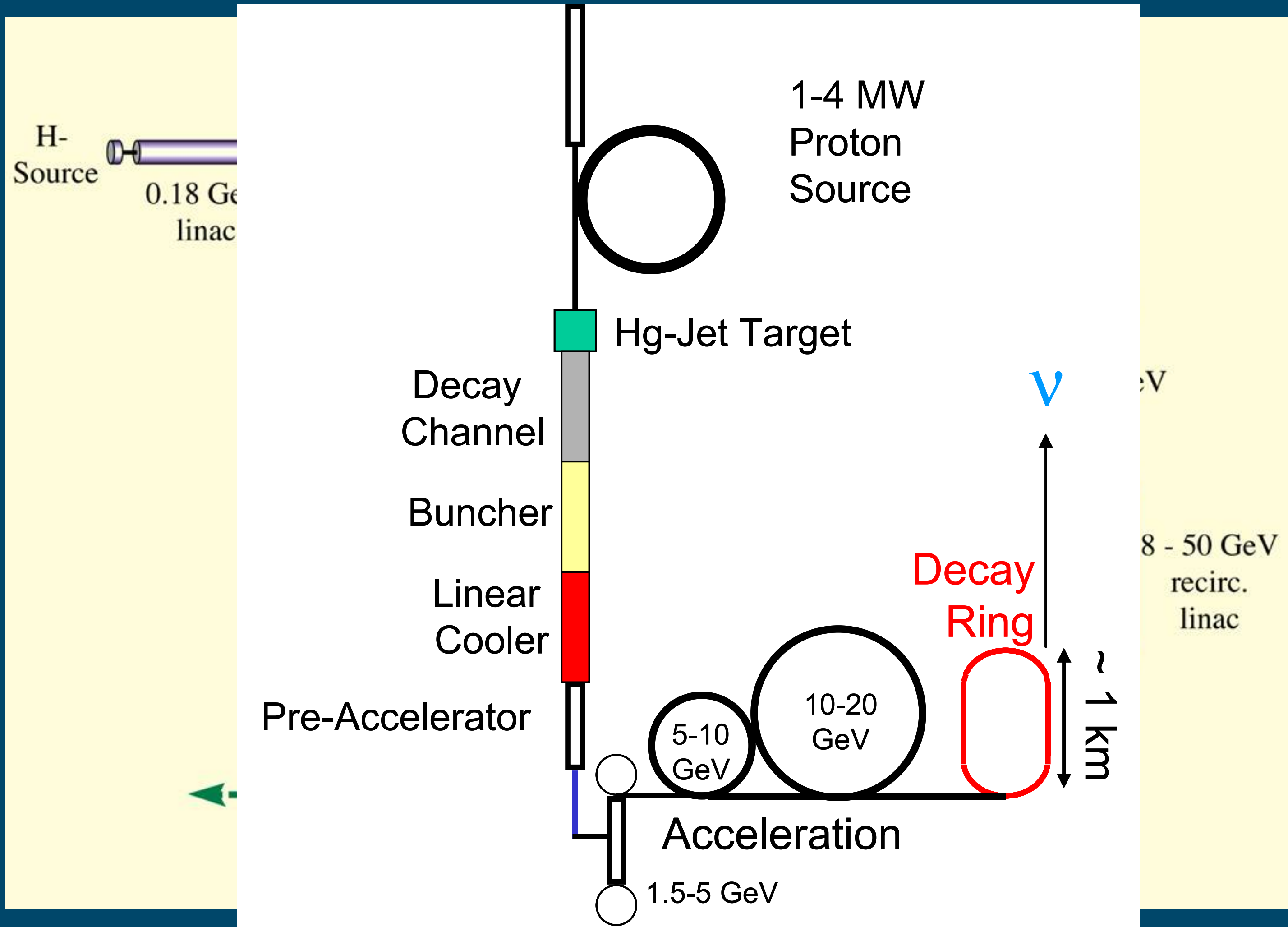


- Efficiency
- Number of rings, number of tunnels, for two detectors
- Constraint of geometry on baseline angles.
  Flexibility in choice of site
- Construction - 10-15 degs. to horizontal / near vertical
- Total depth ($\approx 0.25 - 0.3\mathcal{C}$)
- Muon bunch structure - impact on efficiency, ring geometry, etc.
- RF requirements
- Apertures and fields needed

Baseline (3)

- Acceleration
  - used mixed system
    - linac, dog-bone RLA(s), FFAGs
      - transition energies between subsystems still being debated
- Decay Ring
  - adopt racetrack
    - keep alive triangle as alternative
      - depends on choice of source and baselines
    - energy 20 to 40 GeV
      - 50 GeV okay for ring, but implies more acceleration than presently planned

Old Baseline
Current Baseline



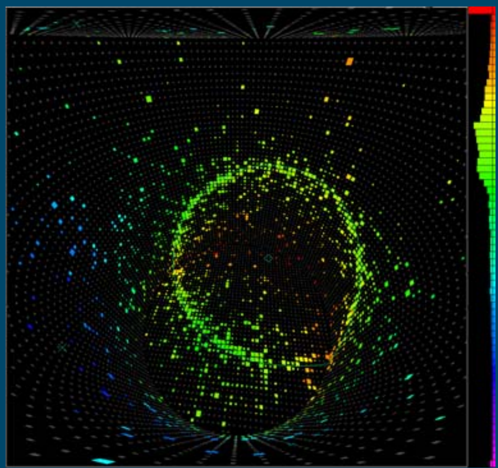
Detector Group

- Detectors studied
  - Water Cerenkov
  - Magnetised Segmented Detectors
    - Iron / Scintillator sandwich (MINOS like)
    - Totally Active Scintillating Detector (Minerva like)
  - Liquid Argon TPC
  - Hybrid Emulsion Detectors
  - Beam Diagnostic Devices
  - Near Detector

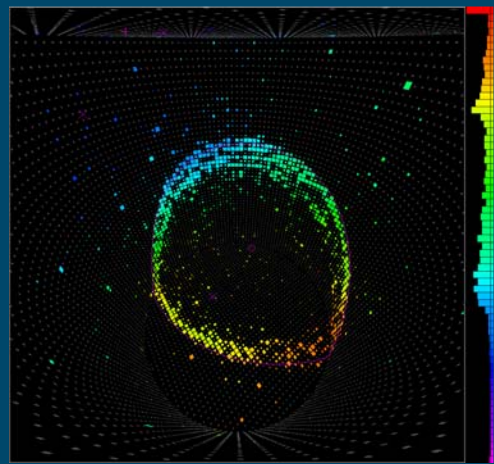
Water Cerenkov

- Suitable for low energy neutrino detection (~ 0.2-1 GeV)
- Excellent $\nu_\mu - \nu_e$ separation

Electron-like



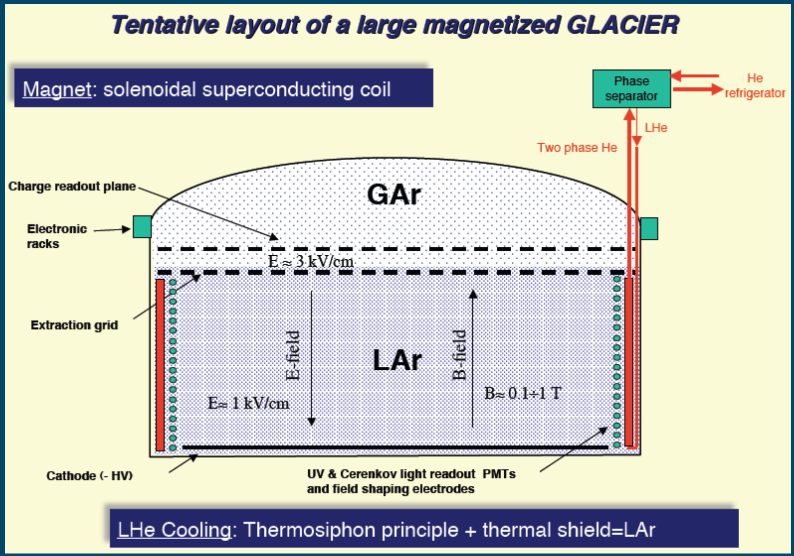
Muon-like

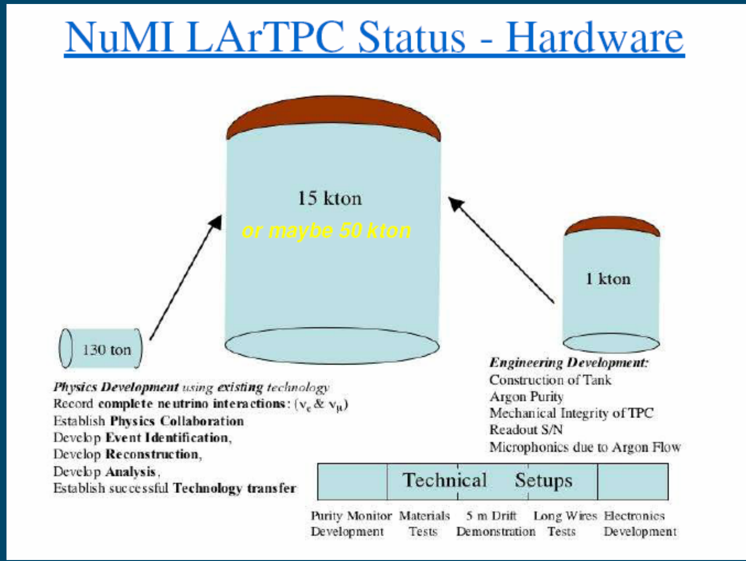


- Impossible to put a magnetic field around it, so not suitable for neutrino factory.
- Baseline for low energy beta-beams or super-beams

Liquid argon

- Detector concepts

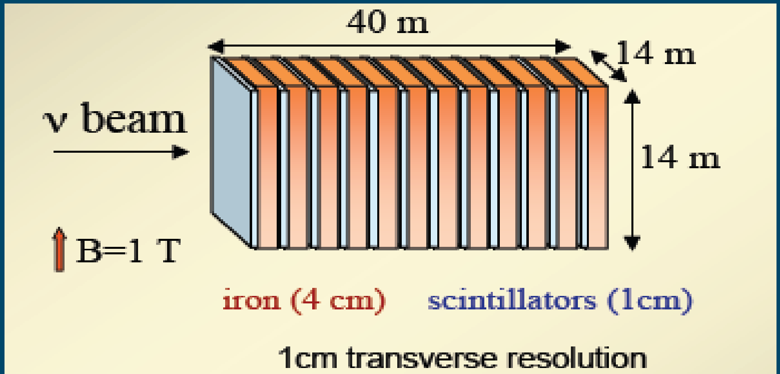




- Various configurations being studied in ISS:
  - Glacier
  - T2K-LAr (near det.)
  - NuMI LArTPC

Magnetised Segmented Detectors

- Golden channel signature: "wrong-sign" muons in magnetised calorimeter



9xMINOS (5.4 kT)

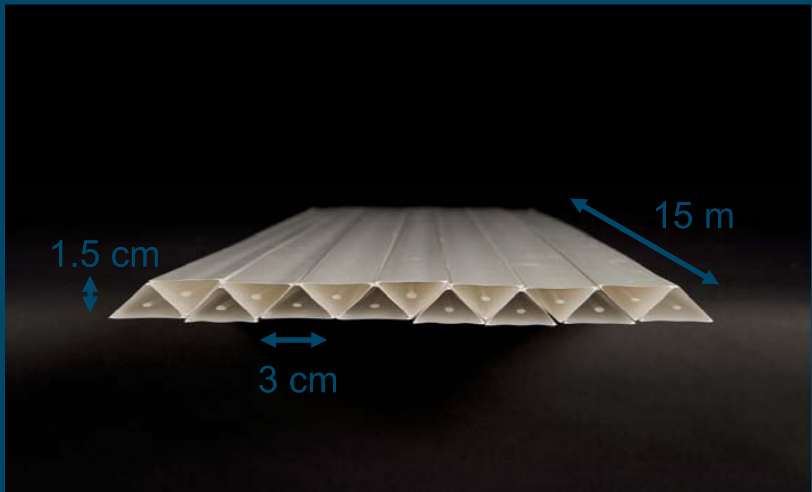
- Baseline technology for a far detector at a neutrino factory
- Issues: electron ID, segmentation, readout technology (RPC or scintillator?) – need R&D to resolve these
- Technology is well understood, R&D needed to determine details, natural progression from MINOS
- Magnetisation of volume seems to be most challenging problem
- A ~100 kton detector with a B-field of 1.4 T is feasible (Nelson)

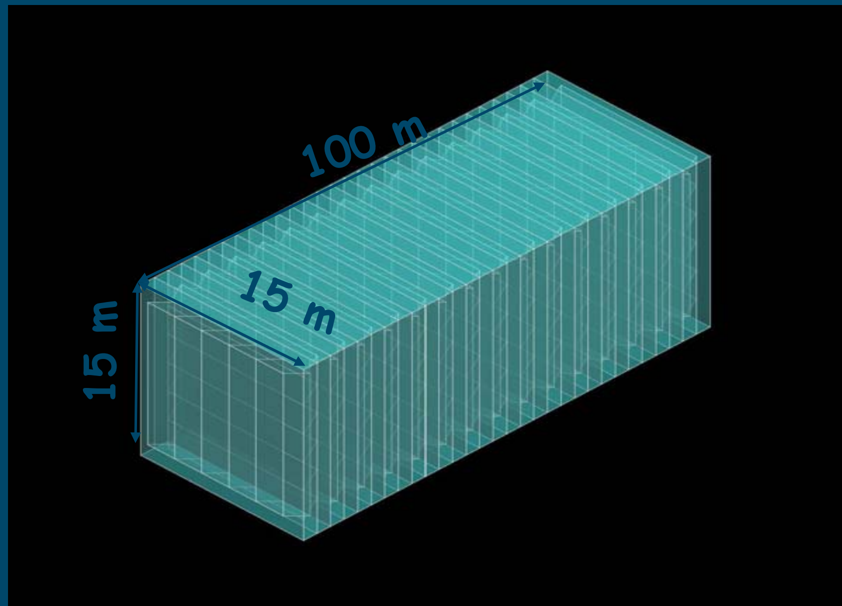
Totally Active Segmented Detector

Simulation of a Totally Active Scintillating Detector (TASD) using Nova and Minerva concepts with Geant4

Ellis, Bross

- 3333 Modules (X and Y plane)
- Each plane contains 1000 slabs
- Total: 6.7M channels

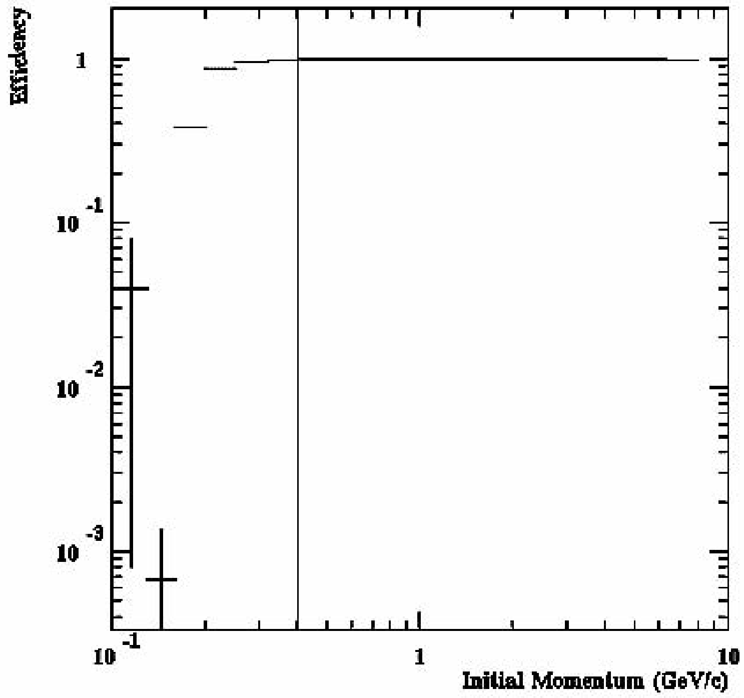




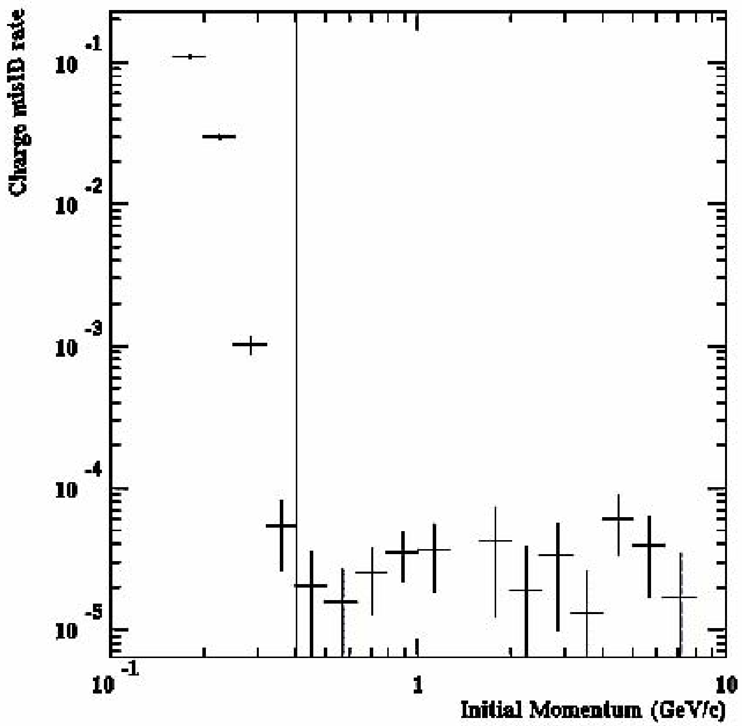
- Momenta between 100 MeV/c to 15 GeV/c
- Magnetic field considered: 0.5 T
- Reconstructed position resolution ~ 4.5 mm

TASD – Low Mom Performance

Muon reconstructed efficiency



Muon charge mis-ID rate



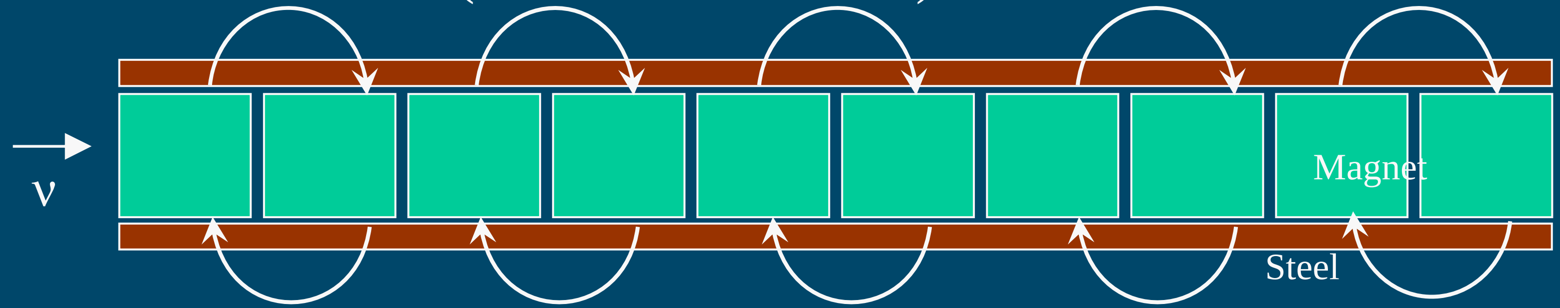
Large Magnetic Volumes

Possible magnet schemes for MSD Camilleri, Bross, Strolin

10 solenoids next to each other. Horizontal field perpendicular to beam

Each: 750 turns, 4500 amps, 0.2 Tesla. 42 MJoules .

Total: 420 MJoules (CMS: 2700 MJoules)



15 m x 15 m x 15m solenoid modules; B = 0.5 T

Warm coil magnets:

- Total cost: \$5m x 10 = \$50M
- Problem: operational cost (>\$13M/year with factor of 3 uncertainty)

Superconducting coil magnet cost extrapolation formulas:

- **Use stored energy – 14M\$/module**
- **Use magnetic volume – 60M\$/module**
- **GEM magnet extrapolation – 69 M\$/module**

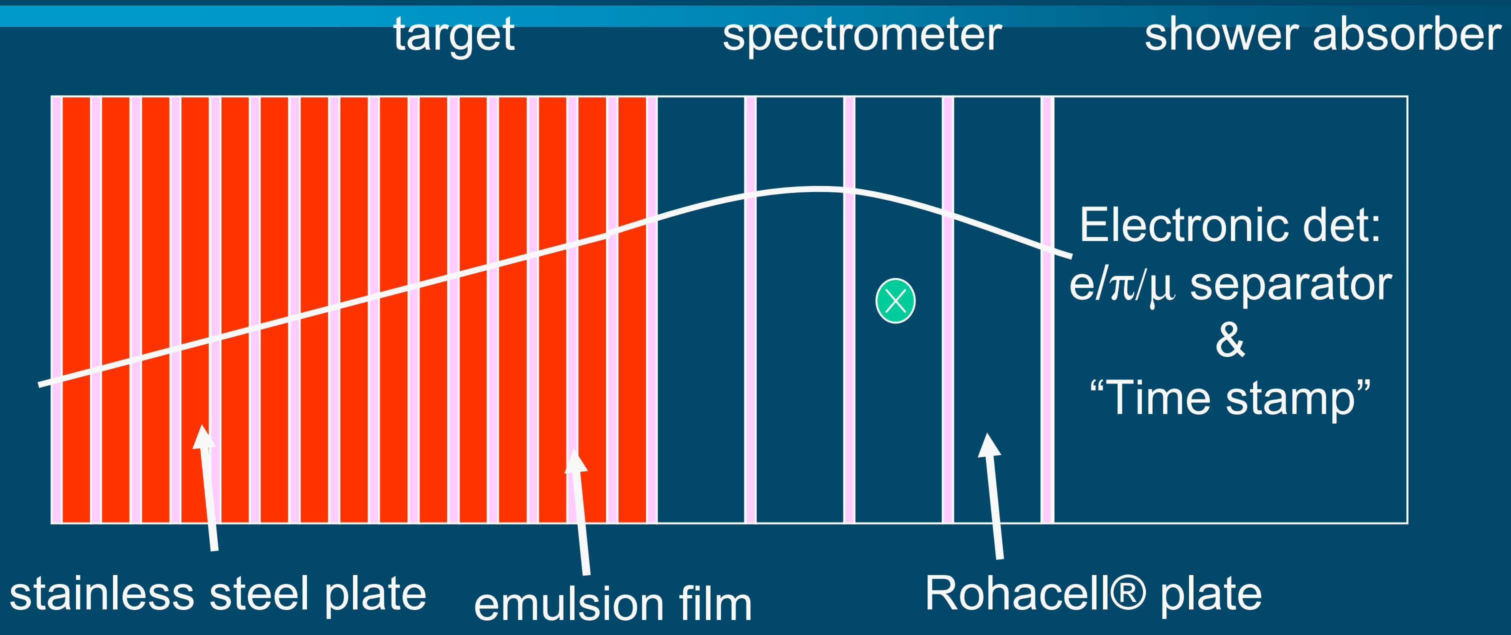
x10 modules!

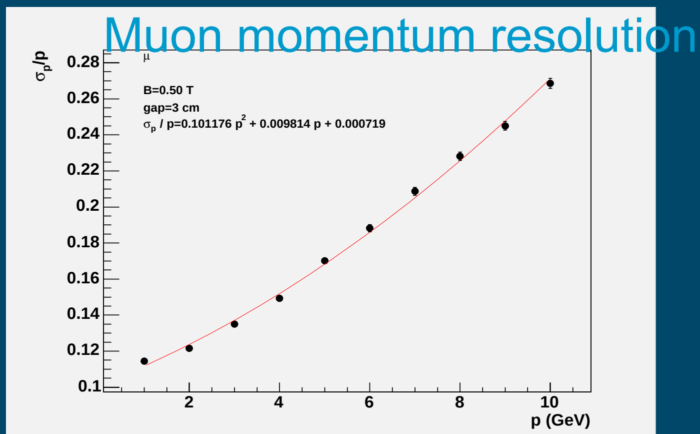
High T_c Magnet Possibilities

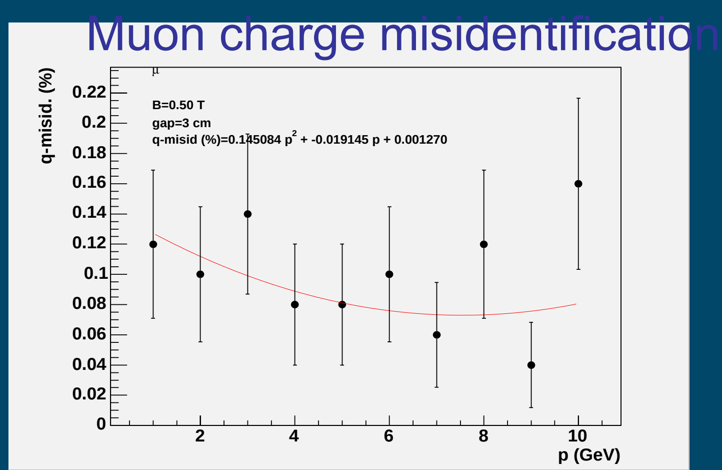
- Recently announced cable has 3X the current carrying capability at somewhat smaller cost.
  - So the 200X cost (over conventional SC) is now maybe 60.

- So look closer (with thanks to Bob Palmer)
  - Assume
    - Operation at 35K
      - Still allows for foam insulated cryostat (no vacuum loading)
      - Higher current carrying capacity
  - Superconductor cost for 30,000 m^3 (USD) (newly announced cable)
    - $50M
  - Foam Insulated vessel (based on GLACIER studies)
    - $50M
  - Engineering (WAG)
    - $50M
- $150M
- Exciting Future Possibility - Needs to be Followed

Magnetised Emulsion Detectors

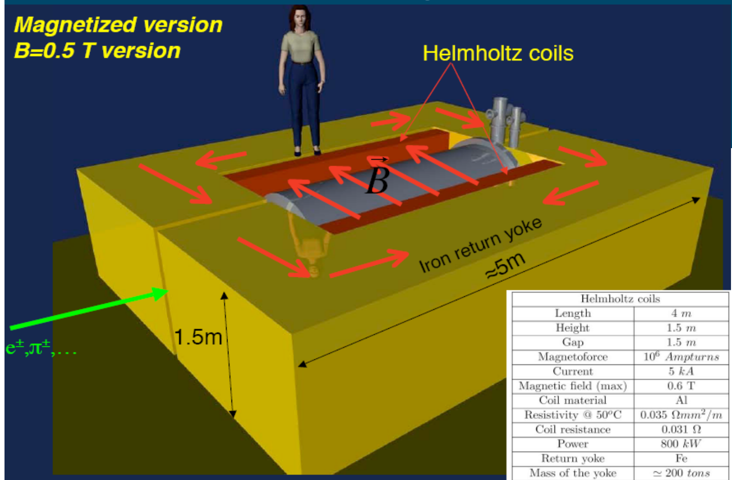






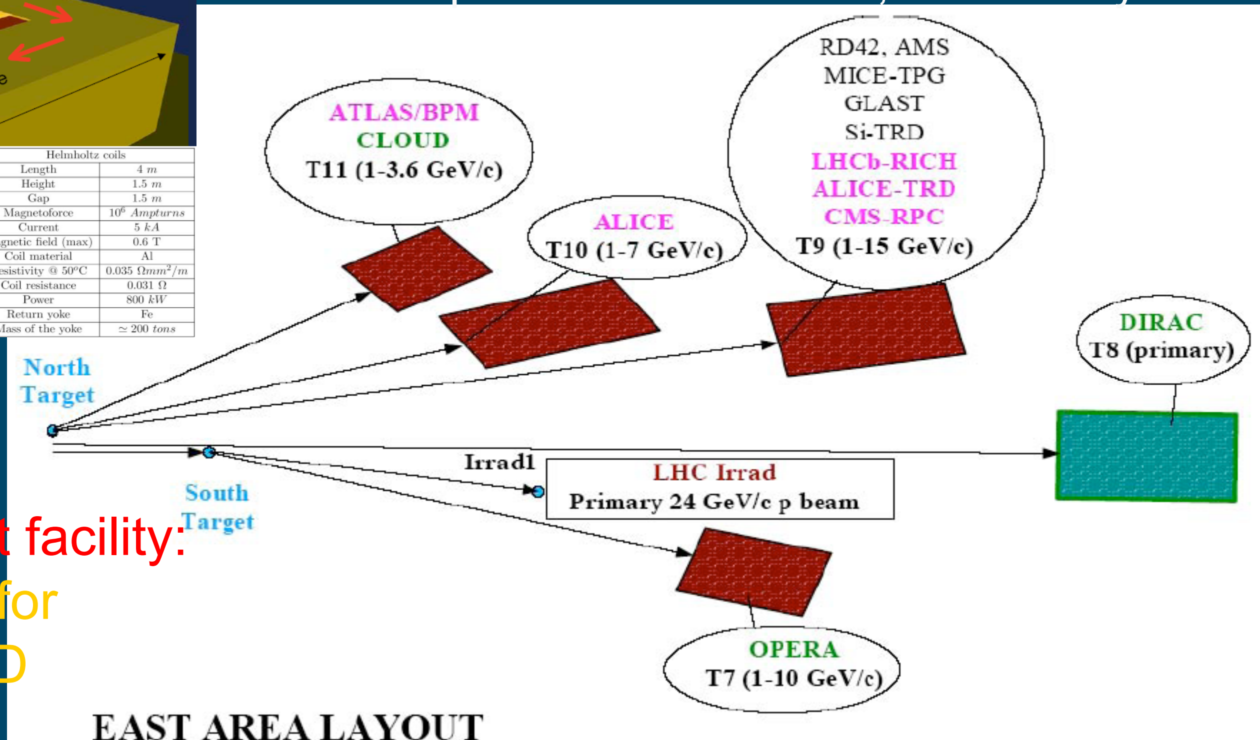
A Neutrino Detector Facility at CERN?

- Request test beam in East Area at the CERN PS, with a fixed dipole magnet for dedicated Neutrino Detector R&D



Helmholtz coils	
Length	4 m
Height	1.5 m
Gap	1.5 m
Magnetoforce	10^6 $Ampturns$
Current	5 kA
Magnetic field (max)	0.6 T
Coil material	Al
Resistivity @ 50°C	0.035 $\Omega mm^2/m$
Coil resistance	0.031 Ω
Power	800 kW
Return yoke	Fe
Mass of the yoke	$\simeq$ 200 $tons$

Liquid Argon tests, beam telescopes for silicon pixel and SciFi tests, calorimetry …



Need very low intensity ≈ 1000 /spill

Neutrino detector test facility: community resource for neutrino detector R&D

Matter Effects - Reducing the Systematic Uncertainty

Geophysicist Recommendations

Recommendations

Best profiles:

- Western Europe to Eastern US
- Atlantic Islands (Canaries, Maderia, Azores) to Portugal, western Spain, France, southern Ireland, western England

Avoid:

- Alps
- central Europe
- thick crust (e.g. Fenoscandia)
- Europe to Japan

Can probably reduce systematic to <2%
Such a study, in collaboration with geophysicists will be needed for candidate LBL sites

Detector Baseline

beam	Far detector	R&D needed
sub-GeV BB and SB (MEMPHYS, T2K)	Megaton WC	photosensors! cavern and infrastructure
few GeV BB and SB (off axis NUMI, high γ BB, WBB)	<u>no established baseline</u> TASD (NOvA-like) or Liquid Argon TPC or Megaton WC	photosensors and detectors long drifts, long wires, LEMs
Neutrino Factory (20-50 GeV, 2500-7000km)	~100kton magnetized iron calorimeter (golden) + ~10 kton non-magnetic ECC (silver)	straight forward from MINOS simulation+physics studies ibid vs OPERA

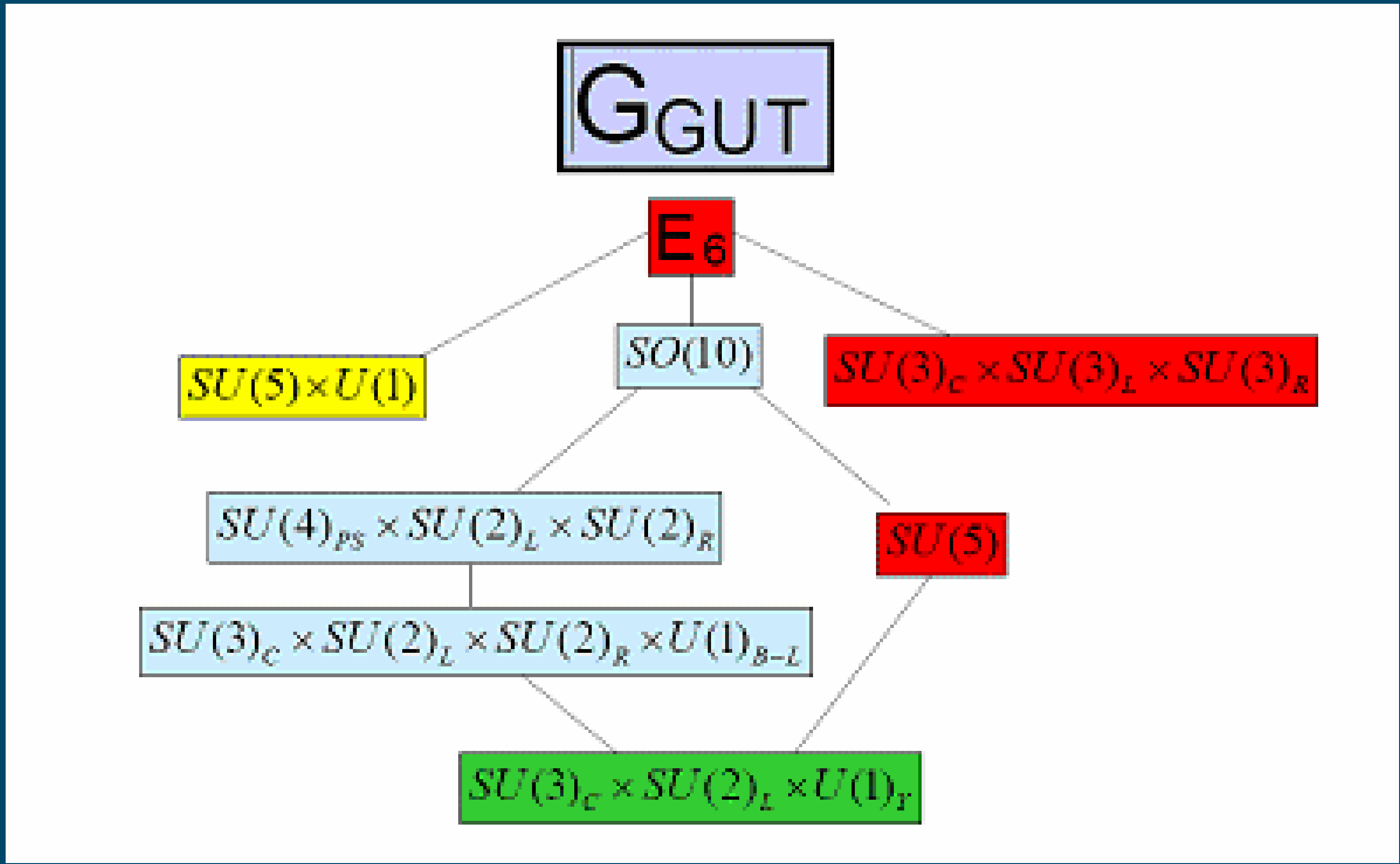
Beyond the Baseline

beam	Far detector	R&D needed
sub-GeV BB and SB (MEMPHYS, T2K)	Liquid Argon TPC (100kton)	clarify what is the advantage wrt WC?
few GeV BB and SB (off axis NUMI, high γ BB)	no established baseline	
Neutrino Factory (20-50 GeV, 2500-7000km)	platinum detectors! large coil around TASD Larg ECC	engineering study for magnet! simulations and physics evaluation; photosensors, long drift, etc…

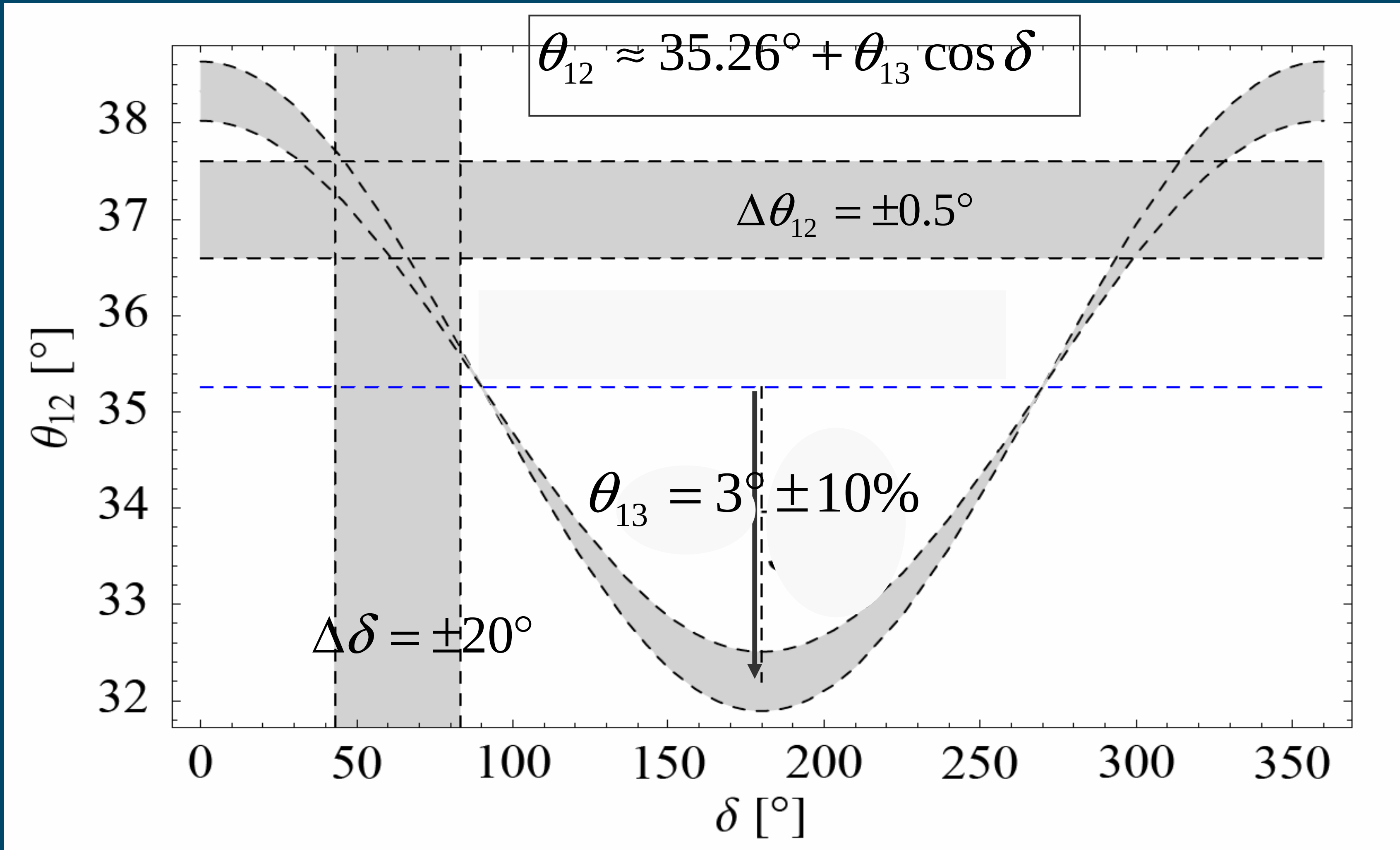
Physics Group

- Theory subgroup
  - Justification for high-precision, high-sensitivity neutrino-oscillation programme
- Phenomenological subgroup
  - Review models purporting to describe neutrino oscillations and identify measurables that distinguish between them
- Experimental subgroup
  - Use realistic assumptions on the performance of accelerator and detector to:
    - Evaluate performance of the super-beam, beta-beam and Neutrino Factory alone or in combination
- Muon physics subgroup
  - Lepton-flavour violating processes – clear synergy with neutrino oscillations

Relating Quarks to Leptons



A Possible Neutrino Sum Rule



Exerimental SubGroup

- Optimise performance of Neutrino Factory as a function of Muon ring energy and the baseline (L/E nbut doesn’t scale)
- Aim to use realistic assumptions on the performance of accelerator and detector
- Evaluate relative performance of the super-beam, beta-beam and Neutrino Factory alone or in combination

Neutrino Factory Performance

$\mu^+ \to e^+ \nu_e \overline{\nu}_\mu$	$\mu^- \to e^- \overline{\nu}_e$	
$\overline{\nu}_\mu \to \bar{\nu}_\mu$	$\nu_\mu \to \nu_\mu$	disappearance
$\overline{\nu}_\mu \to \bar{\nu}_e$	$\nu_\mu \to \nu_e$	appearance (challenging) **"platinum"**
$\overline{\nu}_\mu \to \bar{\nu}_\tau$	$\nu_\mu \to \nu_\tau$	appearance (atm. oscillation)
$\nu_e \to \nu_e$	$\bar{\nu}_e \to \bar{\nu}_e$	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

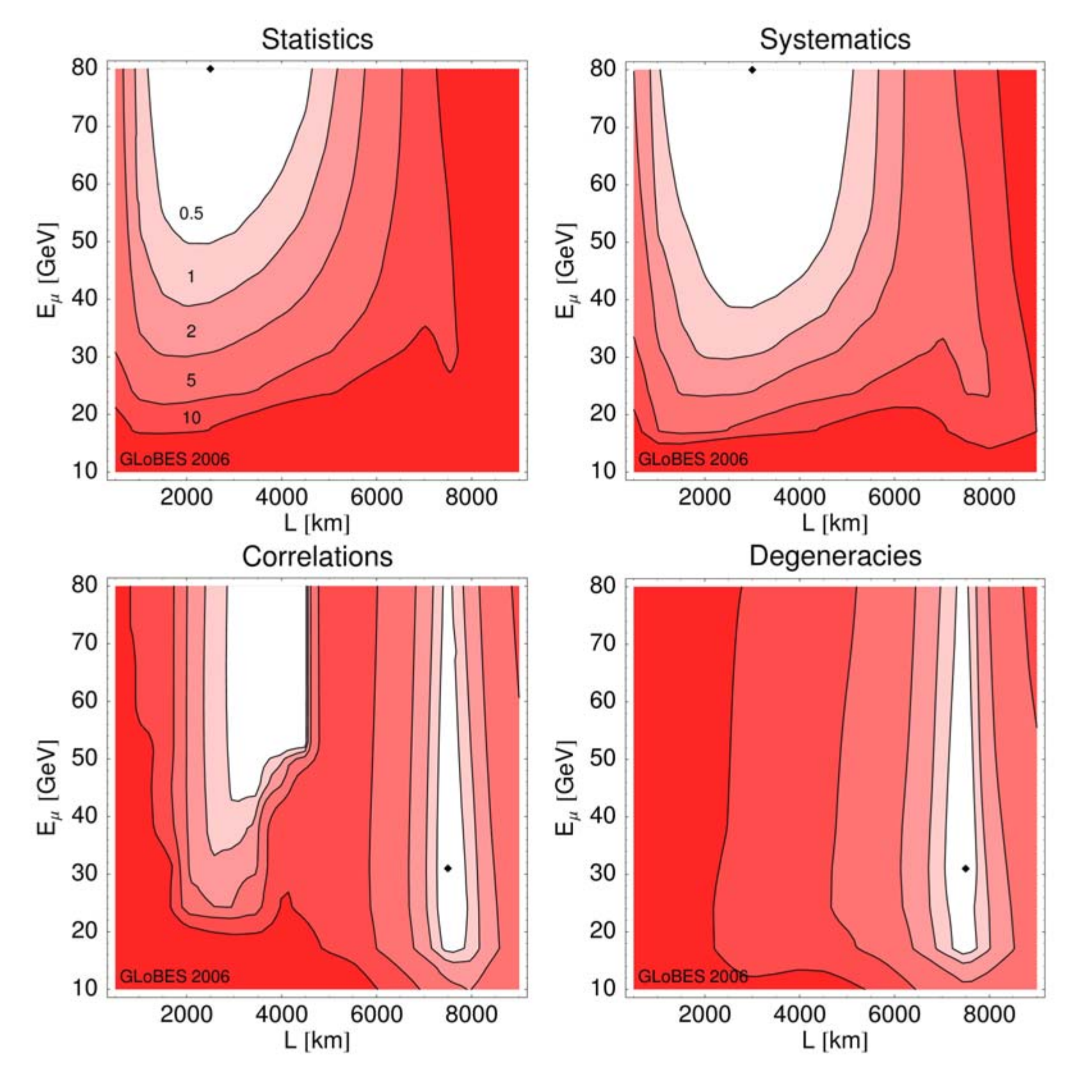
- **Reference Neutrino Factory:**
  - 10^{21} useful decays/yr; exposure '5 plus 5' years
  - 50kTonne magnetised iron detector (MID) with MINOS performance
  - Backgrounds (for golden channel):
    - Right-sign muons
    - Charm decays
  - $E_{res} \sim 0.15 * E_\nu$
  - variable E_ν bins, efficiency and migration matrices

"Golden"

Optimisation of Muon energy & Baseline

P. Huber, M. Lindner M. Rolinec W. Winter, A. Donini, et al.

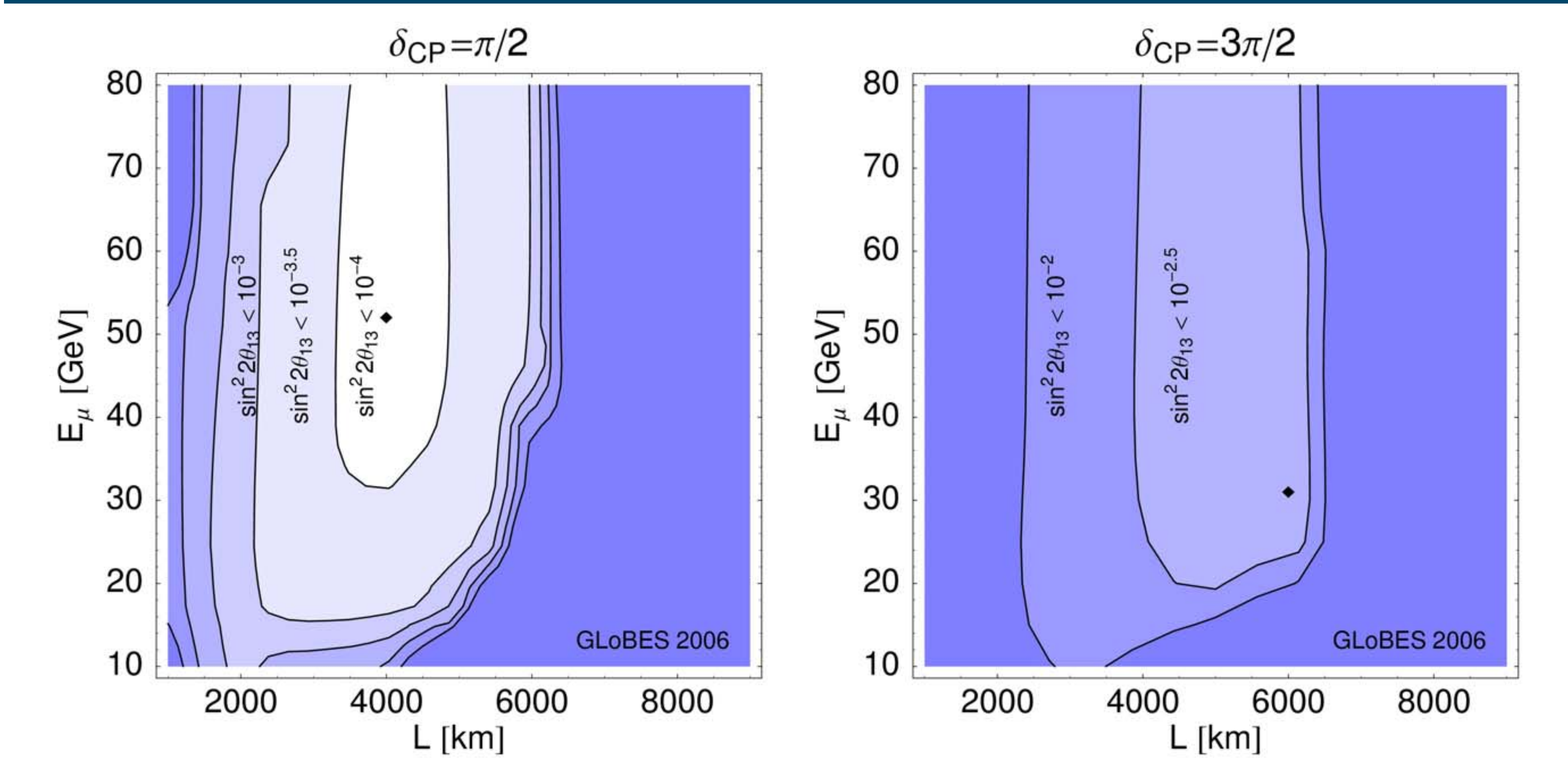
NuFact - $\sin^2 2\theta_{13}$ sensitivity



Magic baseline (7500 km) good degeneracy solver

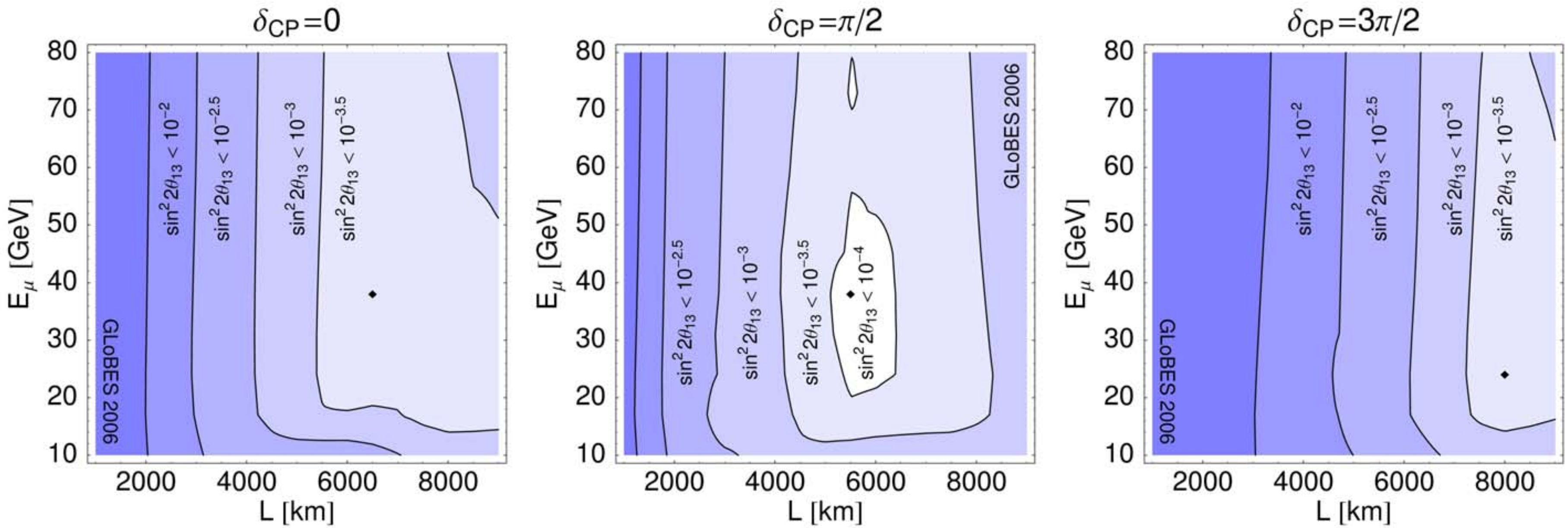
Stored muon energy > 20 GeV

NuFact - **CP sensitivity**



Baseline: 3000 – 5000 km
Stored-muon energy > 30 GeV

NuFact - Mass Hierarchy sensitivity



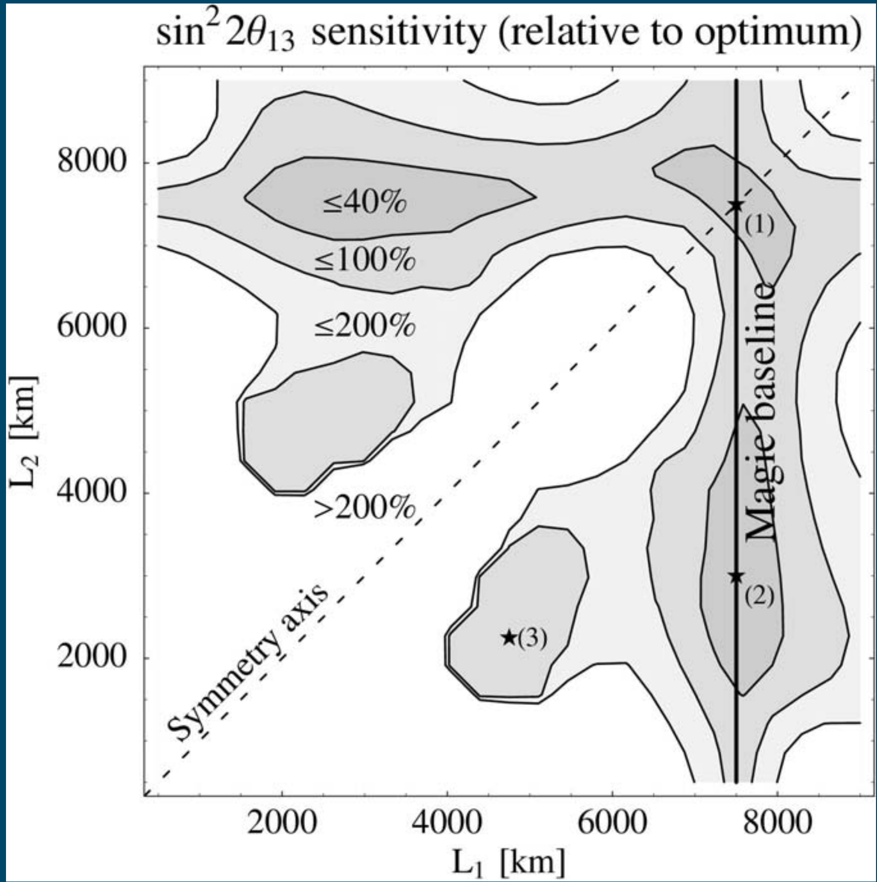
Baseline: ~7500 km
Stored muon energy 20 – 50 GeV

NuFact - Multiple baselines:

- Performance for two 25kT detectors relative to the performance for one 50 kT detector at the magic baseline

Stored muon energy 50 GeV

Second detector at ~3000 km preferred as it has sensitivity to CP violation



Comparisons - Superbeams

- ‘SPL‘ CERN → Frejus:
  - 10 year exposure, on-axis beam
  - E(p) = 2.2/3.5 GeV, E(ν) ~0.3 GeV
  - Baseline ~130 km
- ‘T2HK’ J-PARC → HyperKamiokande:
  - 10 year exposure off-axis beam
  - E(p) = 50 GeV, E(ν) ~0.6 GeV
  - Baseline ~295 km
- ‘WBB’ BNL → Henderson/Homestake
  - E(p) = 24 GeV, E(ν) 0 - 6 GeV
  - Baseline: 2500 km
- FNAL → Henderson/Homestake
  - E(p) = 120 GeV, E(ν) 0 - 10 GeV
  - Baseline: 1250 km

Comparisons - Beta beams

- Low γ: $\gamma = 100$ and $L = 130$ km
  - High flux (~10^{18} decays per year) and high flux (10^{19} dpy)
- High γ: $\gamma = 350$ and $L = 700$ km
  - High flux (~10^{18} decays per year) and high flux (10^{19} dpy)
  - Also Beta beam abd superbeam combination

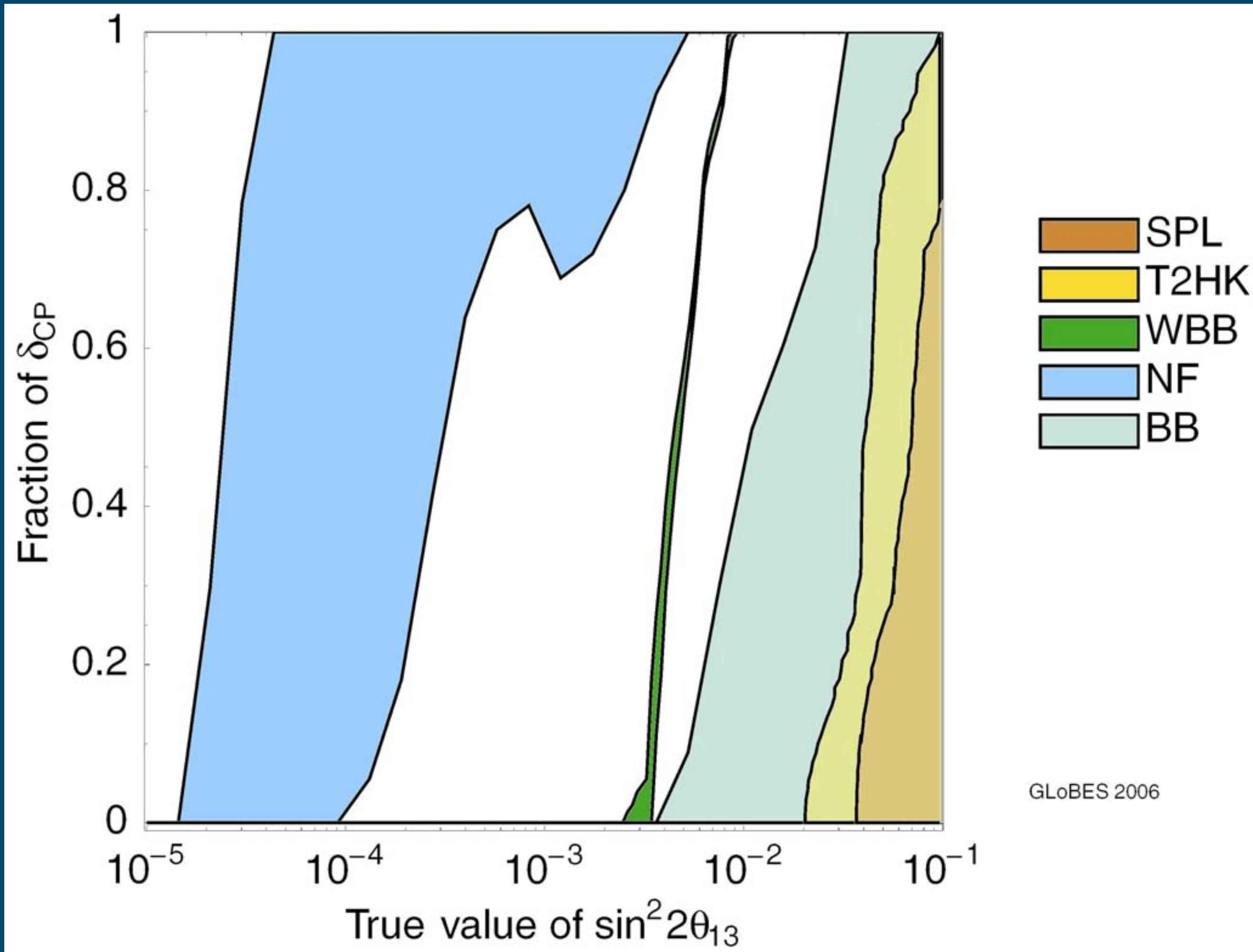
Comparisons - Neutrino Factory

- 10^{21} useful decays/yr; exposure ‘5 plus 5’ years

- Basic. One 50kTonne magnetised iron detector with MINOS performance
  - $E_{res} \sim 0.15 * E_{\nu}$ = 50 GeV
  - Baseline = 4000 km, E_{μ} = 50 GeV

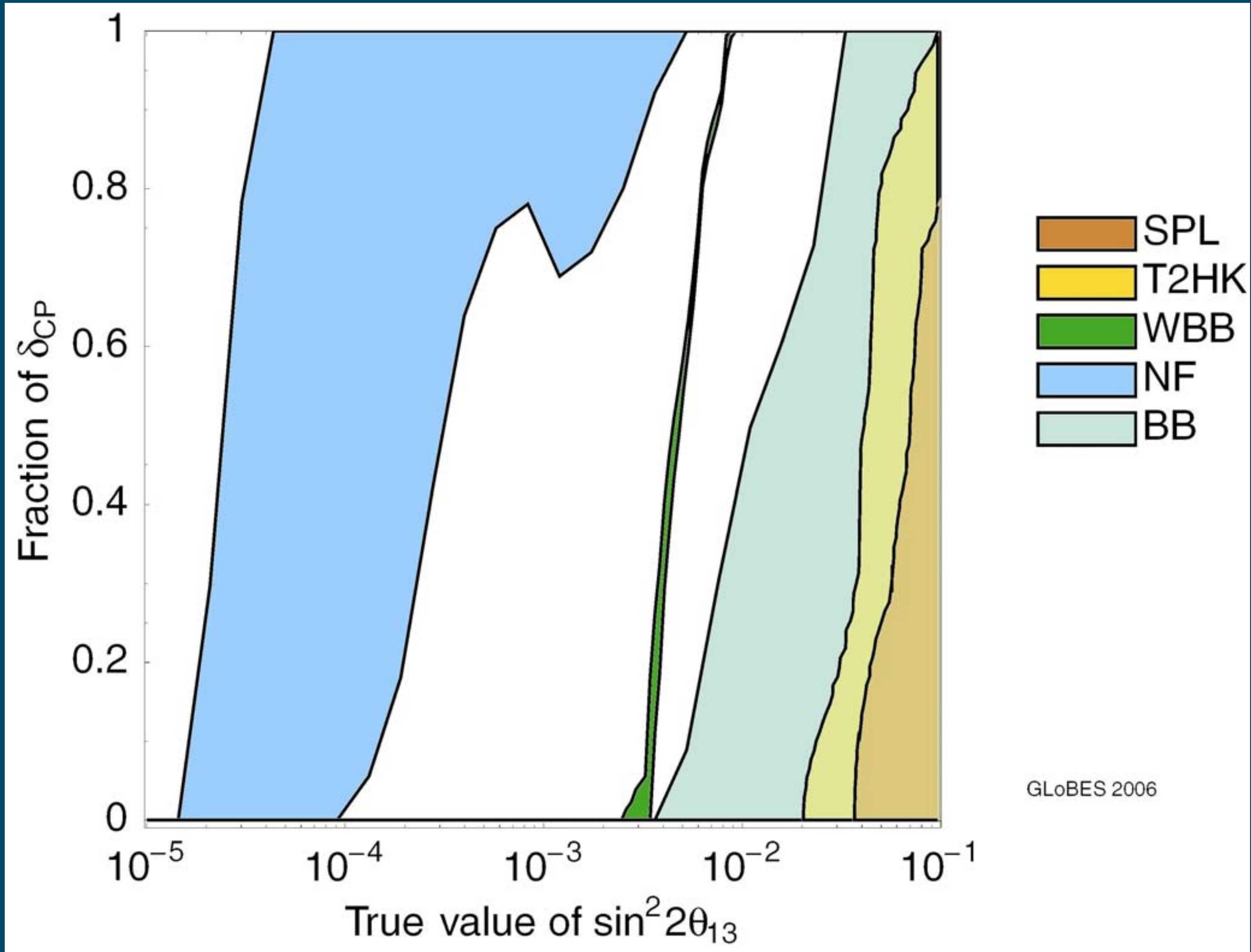
- Enhanced. Two 50kTonne magnetised iron detectors - Lower energy threshold:
  - Efficiency reaches plateau at 50% by 1 GeV
  - Better energy resolution: $E_{res} \sim [0.15 \times E_{\nu}^{0.5} + 0.085]$ GeV
  - Baselines 4000 and 7500 km, E_{μ} = 20 GeV

For θ_{13}

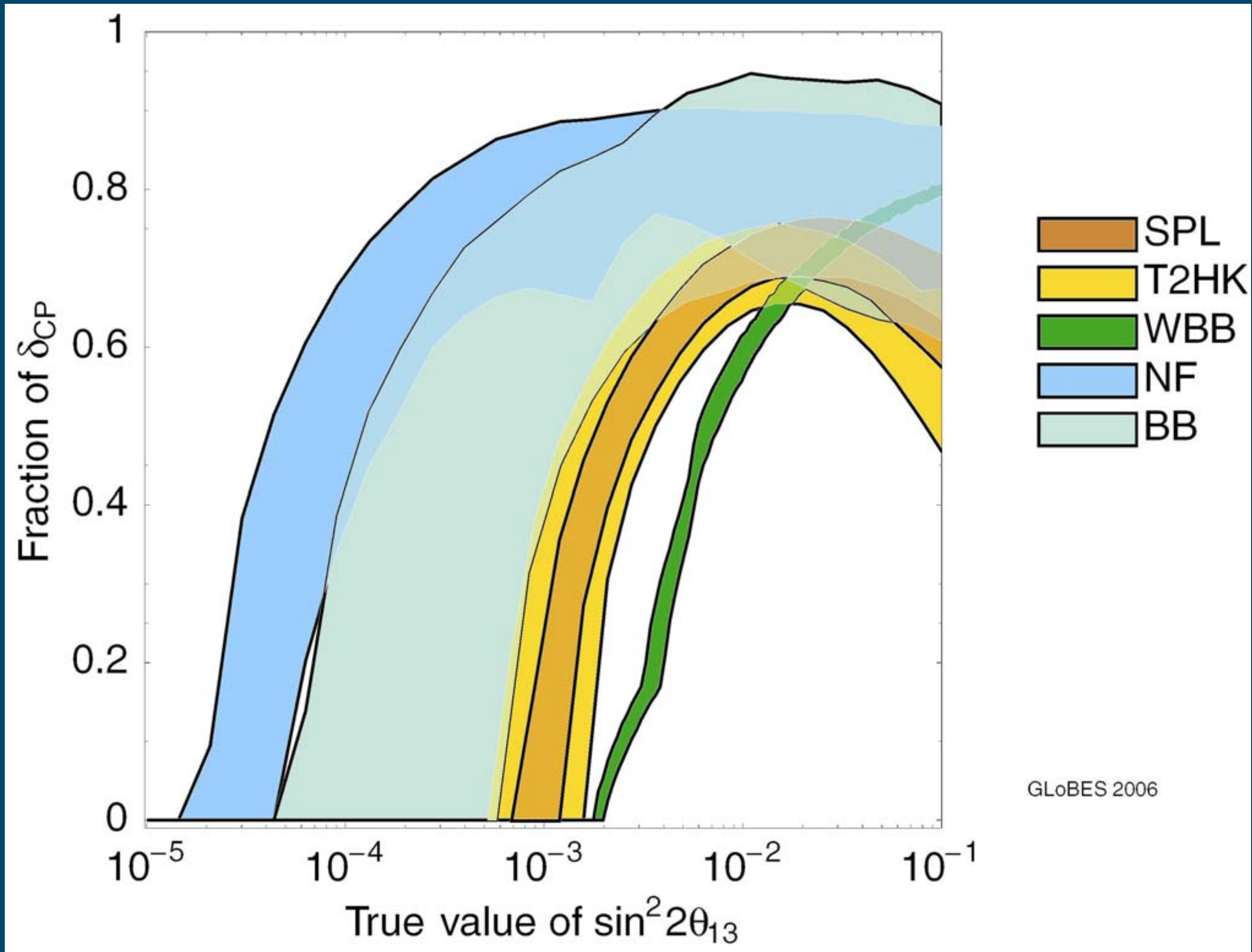


Fraction of δ_{CP}
1
0.8
0.6
0.4
0.2
0
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
True value of $\sin^2 2\theta_{13}$
SPL
T2HK
WBB
NF
BB
GLoBES 2006

For the Mass Hierarchy



For CP violation



Summary

- Compelling case for precision neutrino programme
- Extensive performance evaluation of super-beam, beta-beam, and Neutrino Factory options is needed
  - Large θ_{13}:
    - Comparable sensitivity
      - ⇒ need to include cost and schedule considerations in evaluating optimum
  - Intermediate θ_{13}:
    - Neutrino Factory better, beta beam competitive
      - ⇒ need to include cost and schedule considerations in evaluating optimum
  - Low θ_{13}:
    - With present assumptions Neutrino Factory out-performs other options
      - ⇒ need to include cost and schedule considerations in evaluating optimum

Future

Clear motivation to move from ISS phase to full 'Design Study' phase

With Programmes to Optimise the performance of

Superbeams

Betabeams

Neutrino Factory

So that the best decision for construction is taken in ~2012

As required by the 'European Strategy for Particle Physics'