Neutrino Factory R&D

1.	Neutrino Factory Physics Case and R&D Organization	S.G.
2.	The R&D Program	Bob Palmer
3.	University Perspective (based on ICAR experience)	Chris White
4.	International Context & Future Plans	S.G.

Introduction

Neutrino Factories, in which an intense neutrino beam is generated by muons decaying in a long straight section within a muon storage ring, have caught the imagination of the neutrino community.

Neutrino Factories are considered the ultimate tool for studying neutrino oscillations … particularly if the parameter $\sin^2 2\theta_{13}$ turns out to be very small.

Neutrino factories require the development of a new very intense muon source. This is being pursued by the Muon Collaboration.

Neutrino Factory Recipe

1. Make as many charged pions as possible
   → INTENSE PROTON SOURCE (one or a few MW beam power)
   → Suitable for a Neutrino Superbeam built en route to a Neutrino Factory.

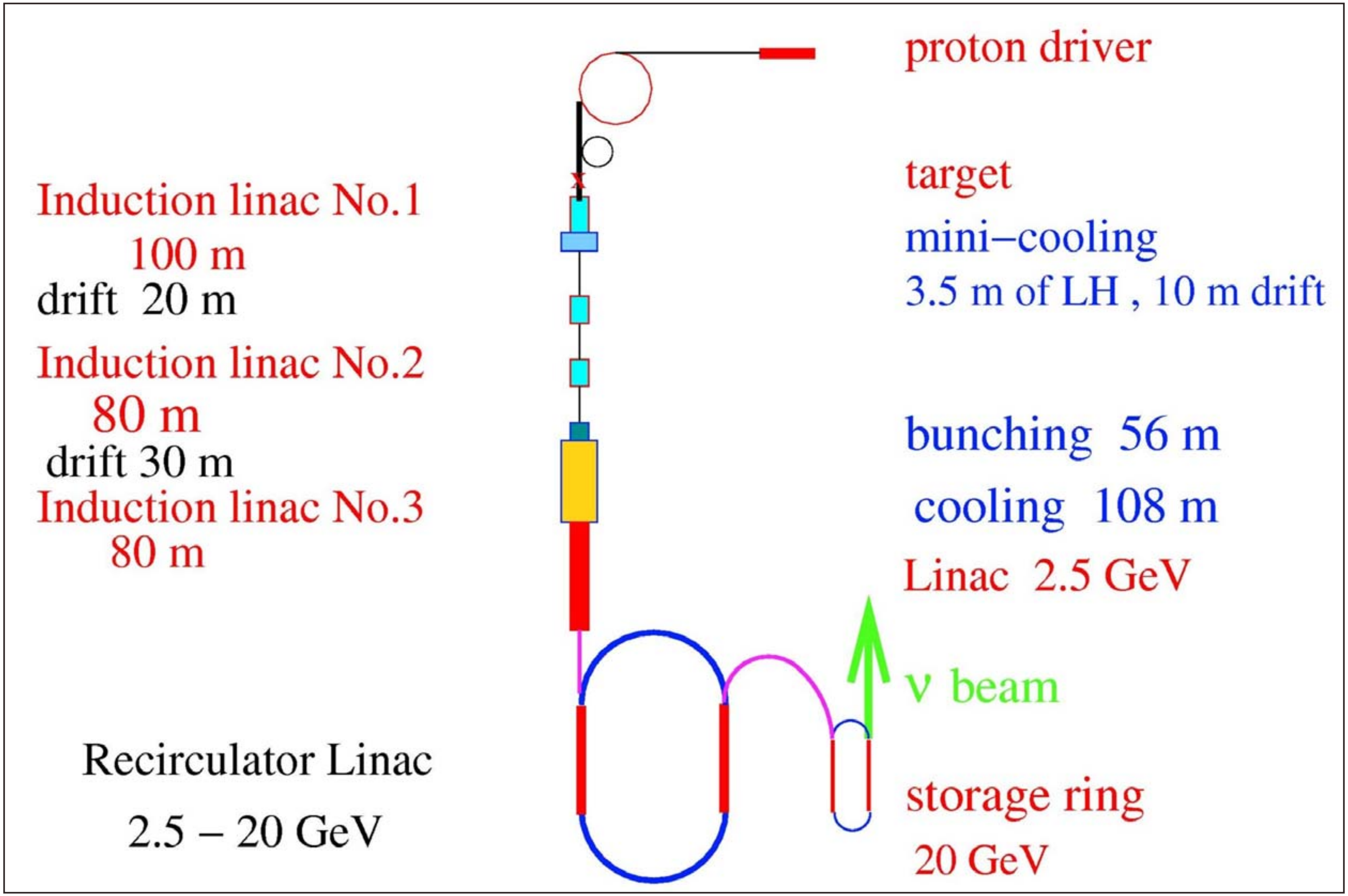
2. Capture as many charged pions as possible
   → Low energy pions (100 MeV – few hundred MeV)
   → Good pion capture scheme

3. Capture as many daughter muons as possible within an accelerator
   → Reduce muon energy spread and capture in bunches
   → Muon cooling (needs to be fast otherwise the muons decay)

4. Accelerate muons to energy of choice (20 GeV – 50 GeV)
   → Fast Acceleration System

5. Inject into storage ring with long straight sections.
   → Storage Ring
   (Muon decays in the straight sections create an intense neutrino beam)

Neutrino Factory Design



Neutrino Factory Physics

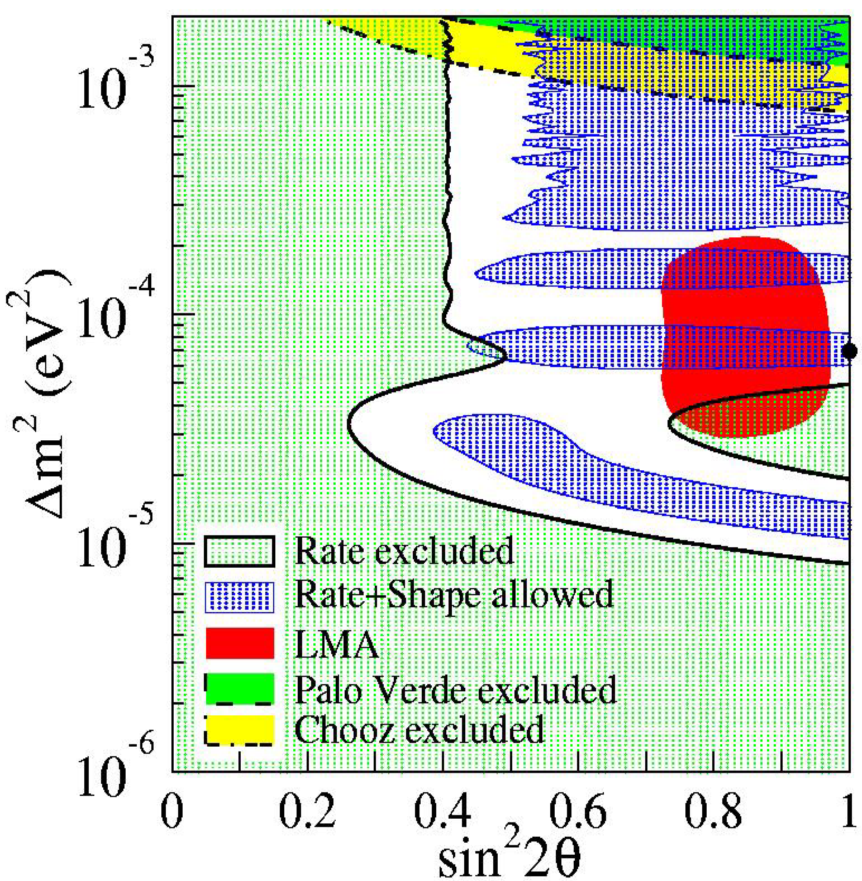
The focus of the Muon Collaboration on Neutrino Factories is driven by physics. In particular by:

1. The exciting evidence for neutrino oscillations with oscillation parameters that are within reach of future accelerator-based experiments.

2. An understanding of the accelerator-based experiments that are needed to fully exploit the initial discovery.

News since the HEPAP Subpanel Presentations

KamLAND



1. SNO has confirmed that the solar neutrino deficit is due to neutrino flavor transitions: Electron neutrinos disappear and the LMA solution is preferred.

2. K2K has confirmed that the atmospheric neutrino deficit is due to flavor transitions: Muon neutrinos disappear.

3. KamLAND has confirmed the LMA solution to the solar neutrino problem !

Implications

The solar- and atmospheric-neutrino measurements provide compelling evidence that neutrinos have mass & Lepton Flavor is not Conserved:

$\rightarrow$ Physics beyond the Standard Model

We know that all three known flavors (ν_e, ν_μ, ν_τ) participate in ν oscillations $\rightarrow$ an underlying 3×3 mixing matrix that can accommodate CP-Violation. The LMA solar solution implies that CP-Violation searches are within reach of laboratory neutrino oscillation experiments provided one unknown parameter ($\sin^2 2\theta_{13}$) is not very very tiny!

$\rightarrow$ Baryogenesis ?

$\rightarrow$ A new handle on Grand Unification

$\rightarrow$ A new handle on the physics of flavor

If there is a surprise, and 3 flavor mixing is not the whole story, the implications for our understanding of HEP will be profound.

What is Known :

Within the framework of three-flavor mixing neutrino oscillations are described by 3 mixing angles (θ_{12}, θ_{23}, θ_{13}), one complex phase (δ), and two independent mass splittings (Δm_{21}^2 , Δm_{32}^2).

We already know the approximate values of the parameters that describe the oscillations:

1. $\sin^2 2\theta_{23} \sim 1$ ($\geq$ 0.9 at 90% CL)
2. $|\Delta m_{32}^2| = |m_3^2 - m_2^2| \sim 2 \times 10^{-3}$ eV^2
3. $\Delta m_{21}^2 = m_2^2 - m_1^2 \sim (6 - 9) \times 10^{-5}$ eV^2 (at 2σ)
4. $\sin^2 2\theta_{12} \sim 0.87$
5. $\sin^2 2\theta_{13} < 0.14$ (at 2σ)

… but there is a lot we don't know ….

What is Not Known :

1. Does three-flavor mixing provide the right framework or are there contributions from: additional (sterile) neutrinos, neutrino decay, CPT-Violation, extra dimensions, …?

2. Is $\sin^2 2\theta_{13}$ small or tiny (or zero) ?

3. Is δ non-zero (Is there CP-violation in the lepton sector, and does it contribute significantly to Baryogenesis via Leptogenesis) ?

4. What is the sign of $\Delta m_{32}{}^2$ (pattern of neutrino masses) ?

5. Is $\sin^2 2\theta_{23}$ maximal (= 1) ?

The answers to these questions may lead us towards an understanding of the origin of flavor … but getting the answers will require the right tools.

Beam Properties at a Neutrino Factory

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \rightarrow 50\% \; \nu_e \, , \; 50\% \; \bar{\nu}_\mu$$

$$\mu^- \rightarrow e^- \, \bar{\nu}_e \, \nu_\mu \rightarrow 50\% \; \bar{\nu}_e \, , \; 50\% \; \nu_\mu$$

Decay kinematics well known → minimal systematic uncertainties in:

1. Spectrum
2. Flux
3. Comparison of neutrino with antineutrino results

… but, most important, there are ν_e as well as ν_μ in the initial beam.

Electron Neutrinos & Wrong-Sign Muons

The primary motivation for interest in neutrino factories is that they provide electron neutrinos (antineutrinos) in addition to muon anti-neutrinos (neutrinos). This enables a sensitive search for $\nu_e \rightarrow \nu_\mu$ oscillations.

$$\begin{array}{l} \mu^+ \rightarrow e^+\ \nu_e\ \bar{\nu}_\mu \overset{CC}{\Rightarrow} \mu^+ \\ \qquad\qquad\quad\ \downarrow \\ \qquad\qquad\quad\ \nu_\mu \underset{CC}{\Rightarrow} \mu^- \end{array}$$

$\nu_e \rightarrow \nu_\mu$ oscillations at a neutrino factory result in the appearance of a "wrong-sign" muon … one with opposite charge to those stored in the ring:

Backgrounds to the detection of a wrong-sign muon are expected to be at the 10^{-4} level $\Rightarrow$ background-free $\nu_e \rightarrow \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Signal and Background

Note: backgrounds for $\nu_e \rightarrow \nu_\mu$ measurements (wrong-sign muon appearance) are much easier to suppress than backgrounds to $\nu_\mu \rightarrow \nu_e$ measurements (electron appearance).

Many groups have calculated signal & background rates. Recent example
Hubner, Lindner & Winter; hep-ph/0204352

JPARC-SK:	Beam = 0.75 MW, M_{fid} = 22.5 kt, T = 5 yrs
JPARC-HK:	Beam = 4 MW, M_{fid} = 1000 kt, T = 8 yrs
NUFACT:	Beam = 2.6×10^{20} decays/yr, M_{fid} = 100 kt, T = 8 yrs

$\Delta m_{32}^2 = 0.003\ \mathrm{eV}^2$, $\Delta m_{21}^2 = 3.7\times10^{-5}\ \mathrm{eV}^2$, $\sin^2 2\theta_{23} = 1$, $\sin^2 2\theta_{13} = 0.1$, $\sin^2 2\theta_{12} = 0.8$, $\delta = 0$

	Superbeams		Neutrino Factory
	JPARC-SK	JPARC-HK	
Signal	140	13000	65000
Background	23	2200	180
S/B	6		360

Correlations & Ambiguities

If the LMA solar solution is confirmed, extracting precise & unambiguous values for all of the three-flavor oscillation parameters (Δm_{32}^2, Δm_{21}^2, $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{12}$, $\delta = 0$) will be challenging :

$$
\begin{aligned}
P(\nu_e \to \nu_\mu) \approx\; & \sin^2 2\theta_{13} \sin^2\theta_{23} \frac{\sin^2((1-\hat{A})\Delta)}{(1-\hat{A})^2} \\
& \pm \sin\delta_{CP}\; \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \frac{\sin(\hat{A}\Delta)\sin((1-\hat{A})\Delta)}{\hat{A}(1-\hat{A})} \\
& + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2}
\end{aligned}
$$

Fits prone to correlations between the parameters & to degenerate (false) solutions

Oscillation Measurements at a Neutrino Factory

There is a wealth of information that can be used at a neutrino factory. Oscillation parameters can be extracted using events tagged by:

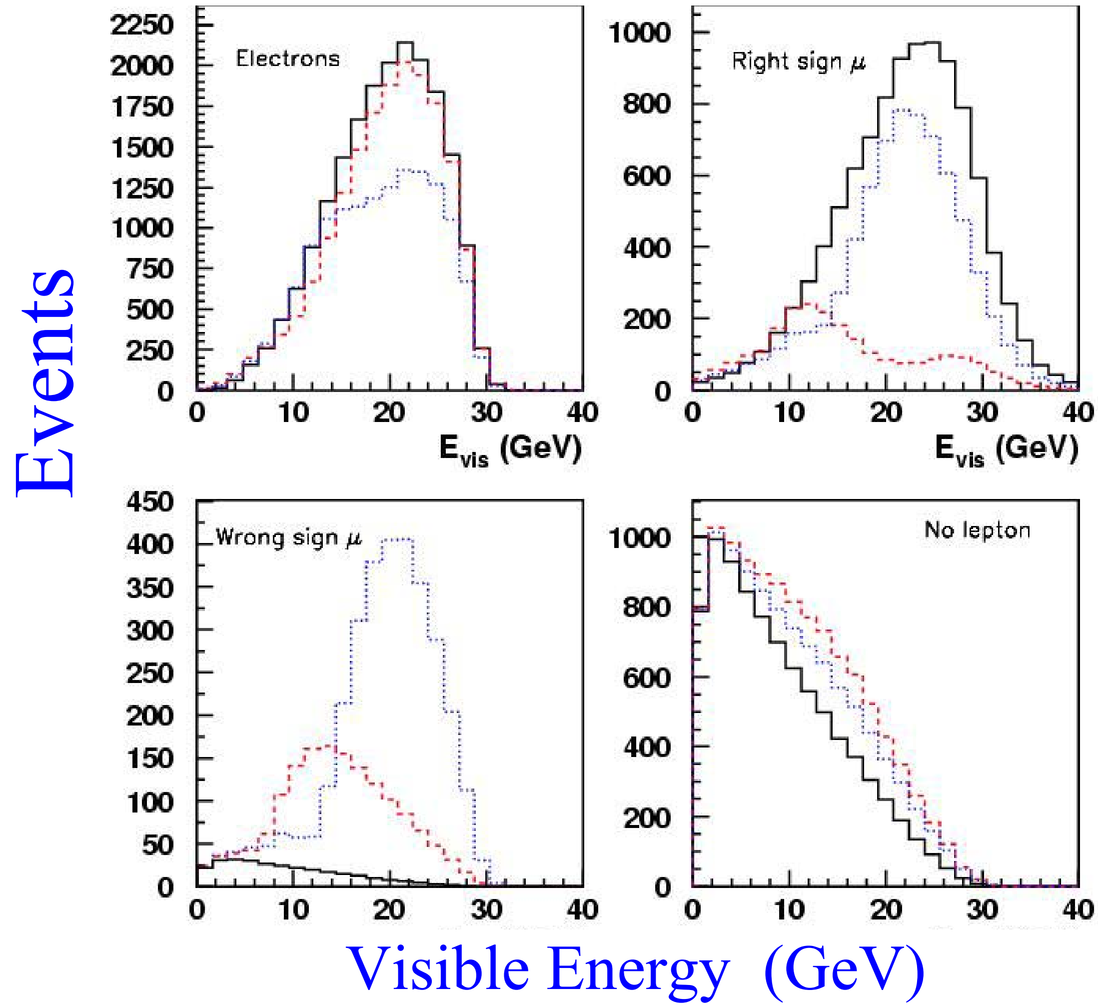
a) right-sign muons
b) wrong-sign muons
c) electrons/positrons
d) positive τ-leptons
e) negative τ -leptons
f) no leptons

×2 (μ^+ stored and μ^- stored)

The distributions are sensitive to the oscillation parameters

Bueno, Campanelli, Rubbia; hep-ph/00050007

Simulated distributions for a 10kt LAr detector at L = 7400 km from a 30 GeV nu-factory with 10^{21} μ^+ decays.



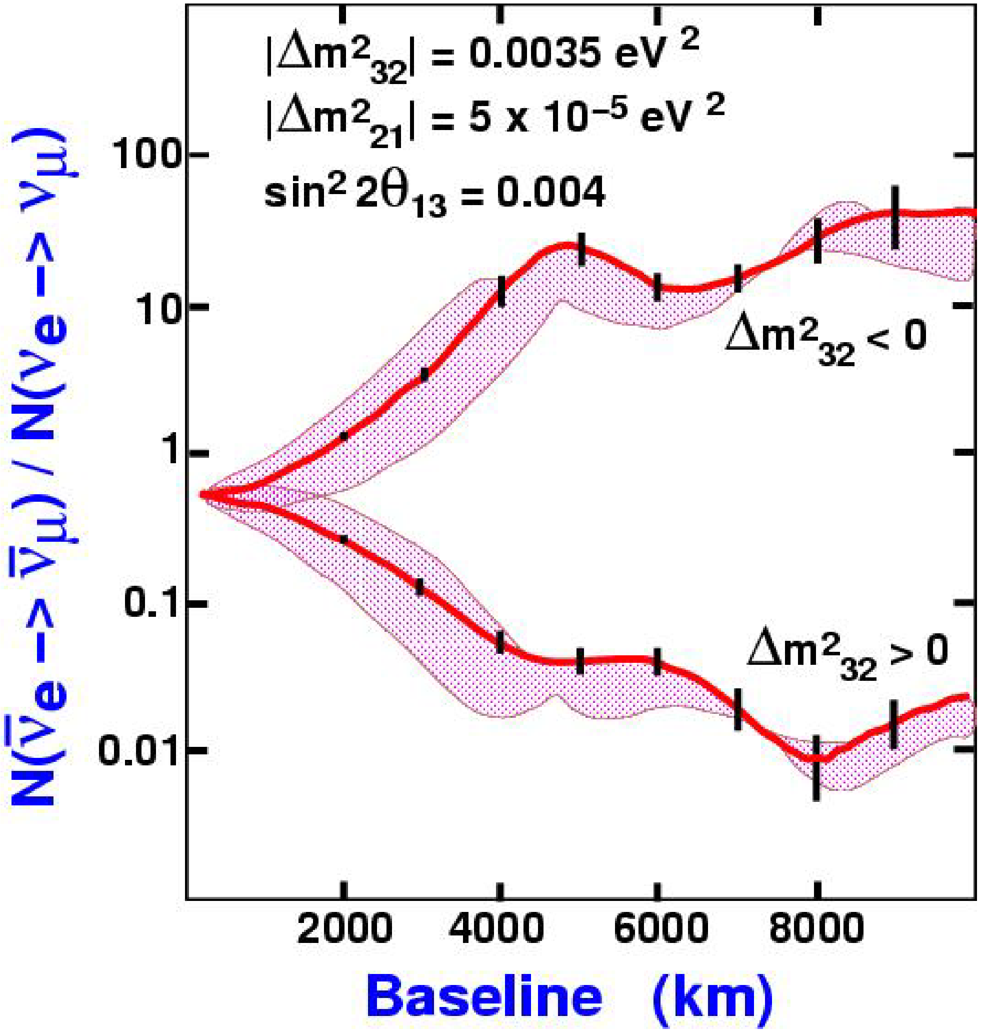
CP-Violation & the pattern of neutrino masses

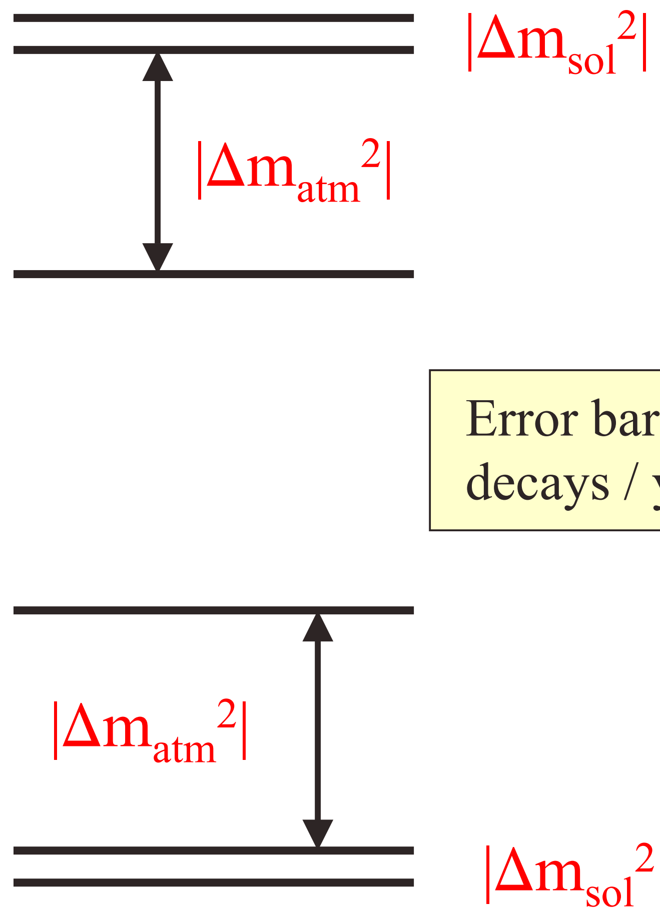
The signature for CP violation would be an inequality between $P(\nu_e \leftrightarrow \nu_\mu)$ and $P(\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu) \rightarrow$ Measure wrong-sign muon rates for μ^+ and μ^- running.

If the baseline is a few $\times$ 1000 km, matter effects can also produce an inequality between $P(\overline{\nu}_e \leftrightarrow \overline{\nu}_\mu)$ and $P(\nu_e \leftrightarrow \nu_\mu)$ which depends upon the sign of $\Delta m_{32}^2 \rightarrow$ the pattern of neutrino masses.

CP-Violation & the pattern on neutrino masses - 2

Barger, Geer, Raja, Whisnant, PRD 62, 073002
S. Geer, hep-ph/0008155





Error bars $\rightarrow 2 \times 10^{20}$ decays / yr for 5 years

Impact of Two Baselines on the $\sin^2 2\theta_{13}$, sign Δm^2_{32} & Maximal-CPV Sensitivity

Huber & Winter, hep-ph/0301257

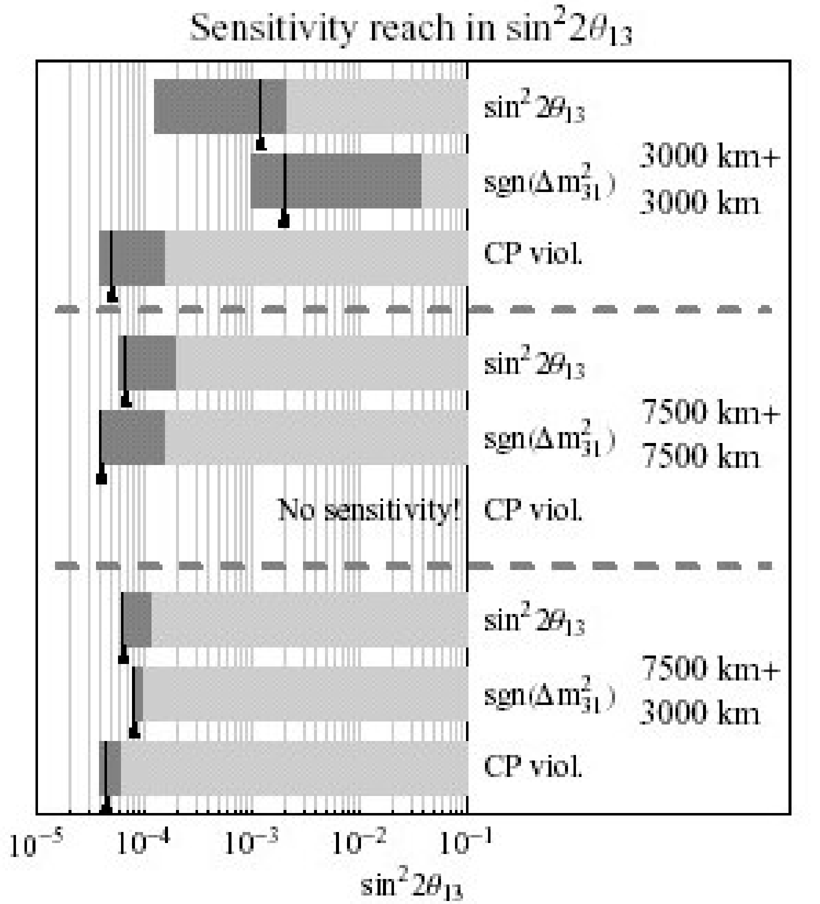


FIG. 3: The sensitivity reaches as functions of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ itself, the sign of $\Delta m^2_{31} > 0$, and (maximal) CP violation $\delta_{CP} = \pi/2$ for each of the indicated baseline-combinations. The bars show the ranges in $\sin^2 2\theta_{13}$ where sensitivity to the corresponding quantity can be achieved at the 3σ confidence level. The dark bars mark the variations in the sensitivity limits by allowing the true value of Δm^2_{21} vary in the 3σ LMA-allowed range given in Ref. [19] and others ($\Delta m^2_{21} \sim 4 \cdot 10^{-5}\,\mathrm{eV}^2 - 3 \cdot 10^{-4}\,\mathrm{eV}^2$). The arrows/lines correspond to the LMA best-fit value.

With two carefully chosen baselines, the correlations & ambiguities can be overcome at a Neutrino Factory.

The calculated $\sin^2 2\theta_{13}$ reach (3σ) is below 10^{-4} for all three physics goals (measuring $\sin^2 2\theta_{13}$, determining the mass hierarchy, & observing maximal CPV) !!

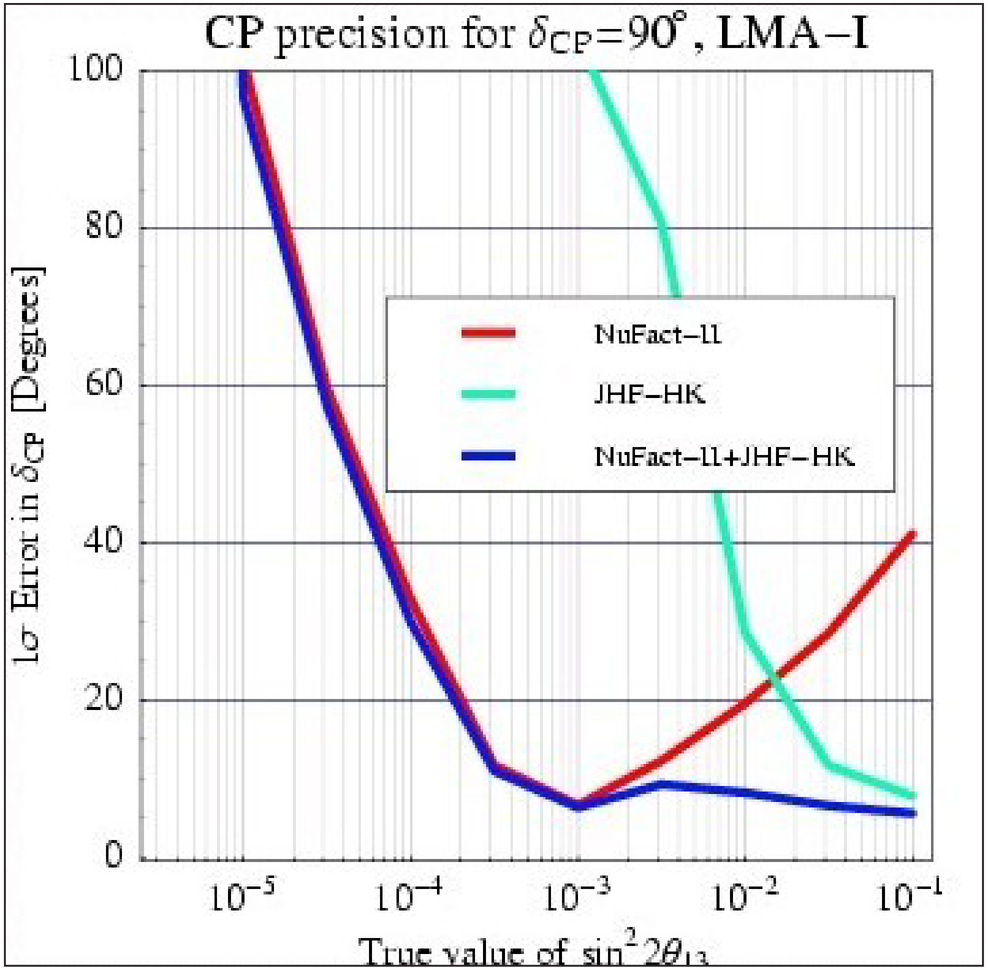
For the right baseline choice, the physics reach is not sensitive to Δm^2_{21} (variation within dark grey bands).

The calculations are for a 50 GeV Neutrino Factory.

Sensitivity to Non-Maximal CP-Violation

The impact of ambiguities correlations has now been studied by several groups $\rightarrow$ can be overcome at a Neutrino Factory by exploiting two baselines <u>or</u> a very long baseline together with the $\nu_e \rightarrow \nu_\tau$ mode (unique for Neutrino Factories).

Huber, Lindner & Winter; hep-ph/0204352



Will be able to see a signal for $\sin^2 2\theta_{13}$ as small as a $\sim 10^{-4}$!

Neutrino Interaction Experiment Reasons to Build a Neutrino Factory

50 GeV ν-Fact: $10^6 – 10^7$ events/kg/year

Broad program – many experiments

1. Precise σ(ν) measurements
2. Structure Functions (no nuclear corrections) → individual quark flavor parton distributions
3. Precise α_s measurements (from non-singlet str. Fus.)
4. Study of nuclear effects (e.g. shadowing)for, separately, valence & sea quarks
5. Spin structure functions
6. Single tagged charm mesons & baryons(1 ton detector → 10^8 flavor tagged charm hadrons/year) → D^0-$\overline{D}^0$ mixing
7. Electroweak tests → $\sin^2\theta_W$ & $\sigma(\nu-e^-)$
8. Exotic interaction search (clean initial state)
9. Neutral heavy leptons (10-100 MeV/c^2)
10. Anomalous ν interactions in EM fields

Muon Collaboration

Muon Collaboration Goals

The collaboration is governed by a charter which defines its goals and organization. The goals are defined :-

"To study and develop the theoretical tools and the software simulation tools, and to carry out R&D on the unique hardware, required for the design of Neutrino Factories and Muon Colliders."

Collaboration Organization

The Muon Collaboration consists of particle physicists and accelerator scientists from Universities and Laboratories.

The Collaboration is organized very much like a particle physics collaboration. This is a new way to conduct accelerator R&D … it provides a good framework for University particle physicists to participate effectively in accelerator R&D.

Muon Collaboration Institutions

Muon Collaboration

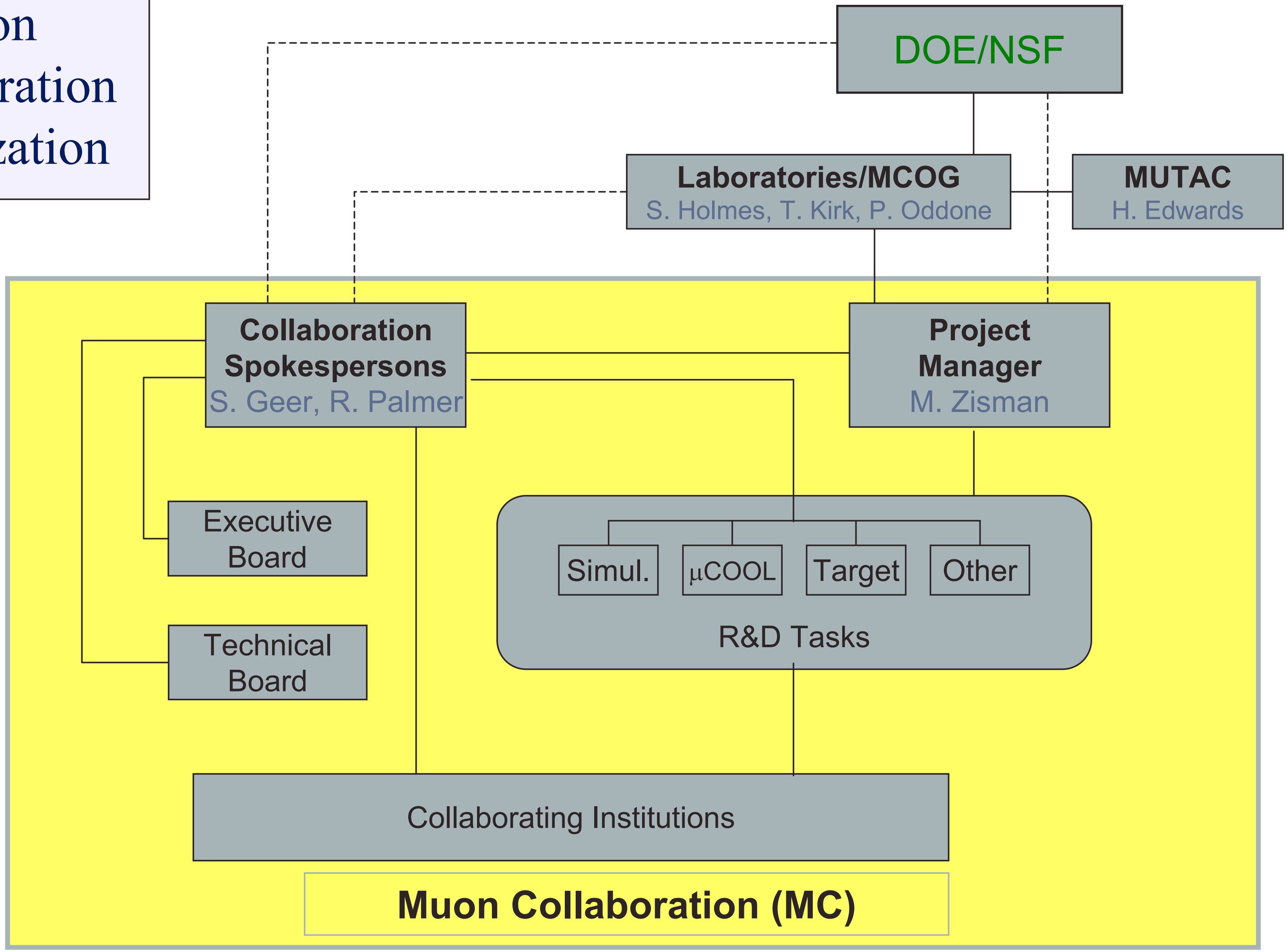
130 Scientists & Engineers from 37 Institutions

6 US Labs
ANL
BNL
FNAL
LBNL
Oak Ridge Nat. Lab.
Thomas Jefferson Lab.

17 US Universities
Columbia Univ.
Cornell Univ.
IIT
Indiana Univ.
Michigan State Univ.
NIU
Northwestern Univ.
Princeton Univ.
UC-Berkeley
UC-Davis
UCLA
UC - Riverside
Univ. Chicago
U. Illinois, Urbana-Champaign
Univ. of Iowa
Univ. Mississippi
Univ. Wisconsin

14 Foreign Institutes
BINP
CERN
DESY
Imperial College, London
INFN - LNF
JINR, Dubna
Karlsruhe
KEK
Kernfysisch Versneller Instit.
Osaka Univ.
Oxford Univ.
Pohang Univ.
RAL
Tel Aviv Univ.

Muon Collaboration Organization



Organization

http://www.cap.bnl.gov/mumu/mu_home_page.html

Muon Collaboration (~130 members)

S. Geer	(FNAL)	Co-Spokesperson.
R. Palmer	(BNL)	Co-Spokesperson
M. Zisman	(LBNL)	Project Manager

Muon Collab. Oversight Group (MCOG)

T. Kirk	(BNL)	Contact
S. Holmes	(FNAL)	
P. Oddone	(LBNL)	

Muon Technical Advisory Committee (MUTAC)

H. Edwards	(FNAL)	Chair
M. Breidenbach	(SLAC)	
G. Dugan	(Cornell)	
M. Harrison	(BNL)	
J. Hastings	(BNL)	
Y.-K. Kim	(LBNL)	
C. Leemann	(Jefferson)	
J. Lykken	(FNAL)	
A. McInturff	(LBNL)	
U. Ratzinger	(GSI)	
R. Ruth	(SLAC)	
K. Yokoya	(KEK)	

Summary - 1

1. Neutrino oscillations are exciting
   - Physics beyond the Standard Model
   - Physics of GUTs
   - Origin of flavor ?
   - CP violation and Baryogenesis

2. Now that the LMA solution is confirmed, we know that unambiguously determining all the oscillation parameters will be a challenge
   - LMA solution will enable us to learn more (CP- Violation ?), but also makes parameter extraction more complicated.

3. Neutrino Factories have the right characteristics to do the job:
   (i) high statistics and low background rates,
   (ii) low systematics (for neutrino-antineutrino comparisons in particular),
   (iii) high energy neutrinos that permit very long baselines (seems to be important to resolve degenerate solutions)
   (iv) both muon- and electron- neutrinos & antineutrinos → large variety of measurements to help fully determine all the oscillation parameters.

Summary - 2

1. We believe the Muon Collaboration is making good technical progress:
   - Bob Palmer's Talk
   - MUTAC and MCOG Assessment (summary talk at end)

2. We understand that cost optimization is important, and we believe the Muon Collaboration is making good progress towards cost optimization:
   - Bob Palmer's Talk

3. We understand that International Collaboration is important, and we believe we are making good progress:
   - Summary talk at end

4. We are trying to pursue accelerator R&D in a new collaborative way … much like a traditional particle physics collaboration (Universities & Laboratories, particle physicists and accelerator scientists) – and we believe we are succeeding.

History - 1

The Muon Collaboration began as an informal group of ~100 people investigating the feasibility of building a high energy Muon Collider → Snowmass 1996 "Muon Collider Feasibility Study Report" (BNL-52503; FNAL-Conf-96/092, LBNL-38946; 480 pages).

In May 1997, at its Orcas Island Meeting, the Muon Collaboration became a formal entity, with initially ~100 physicists and engineers participating. The collaboration subsequently requested funding support.

The collaboration embarked on three areas of intensive activity:

1. Theory and design simulations
2. Targetry R&D
3. Cooling channel R&D

The Collaboration negotiated an oversight and review structure with the DOE and the Laboratory Directors, and received its first significant funding in Spring 1998.

History - 2

By Summer 1999 the Muon Collaboration had investigated low energy Muon Colliders (Higgs Factories: Phys. Rev. ST. Accel Beams 2, 081001 (1999)), High Energy Muon Colliders (Snowmass Report), and Neutrino Factories.

The first MUTAC review (1999) recommended that the Muon Collaboration focus on one of these, and conduct an end-to-end technical study. The Collaboration chose to focus on Neutrino Factories.

In the Fall of 1999 the Fermilab Director sponsored the first 6 Month Neutrino Factory Feasibility Study (~1M$ of engineering) → Neutrino Factories are Feasible but require an aggressive component R&D program. However, the study 1 design failed the initial intensity goal by a factor of a few. Report completed Spring 2000: http://www.fnal.gov/projects/muon_collider/nu-factory/

In the Summer of 2000 the BNL Directorate sponsored a 9 Month Neutrino Factory Study 2 (~1M$ of engineering) . The main goal was to exploit what was learnt in Study 1, and improve the design to achieve the intensity goal. This goal was achieved. Report completed Spring 2001: http://www.cap.bnl.gov/mumu/studyii/FS2-report.html