Neutrino Factory & Muon Collider Collaboration

Muon Collaboration

1. Introduction – History & Organization
2. Neutrino Factory Physics Case

Steve Geer DOE Visit. 6th August 2003

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

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."

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).

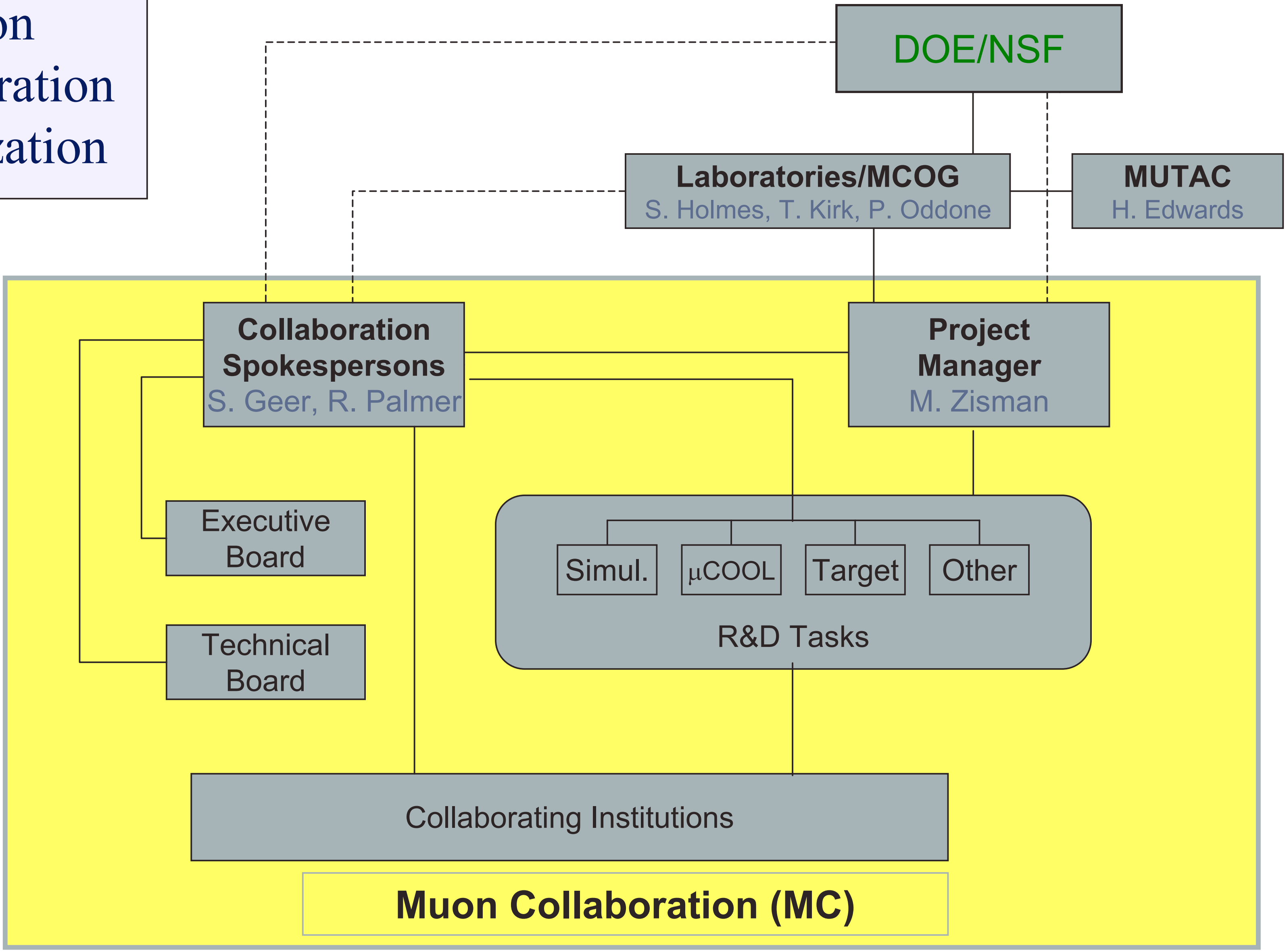
In May 1997, at its Orcas Island Meeting, the Muon Collaboration became a formal entity, with initially ~100 physicists and engineers participating. The collaboration subsequently requested funding support from the US DOE.

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.

Muon Collaboration Organization



DOE/NSF

Laboratories/MCOG
S. Holmes, T. Kirk, P. Oddone

MUTAC
H. Edwards

Collaboration Spokespersons
S. Geer, R. Palmer

Project Manager
M. Zisman

Executive Board

Technical Board

R&D Tasks

Collaborating Institutions

Muon Collaboration (MC)

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)	

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

HEPAP Subpanel Report in 2002

Accelerator R&D

"We give such high priority to accelerator R&D because it is absolutely critical to the future of our field. ... As particle physics becomes increasingly international, it is imperative that the United States participates broadly in the global R&D program."

Neutrino Factory & Muon Collider R&D

"We support the decision to concentrate on intense neutrino sources, and recommend continued R&D near the present level of 8M$ per year. This level of support is well below what is required to make an aggressive attack on all of the technological problems on the path to a neutrino factory."

Neutrino Factory Physics

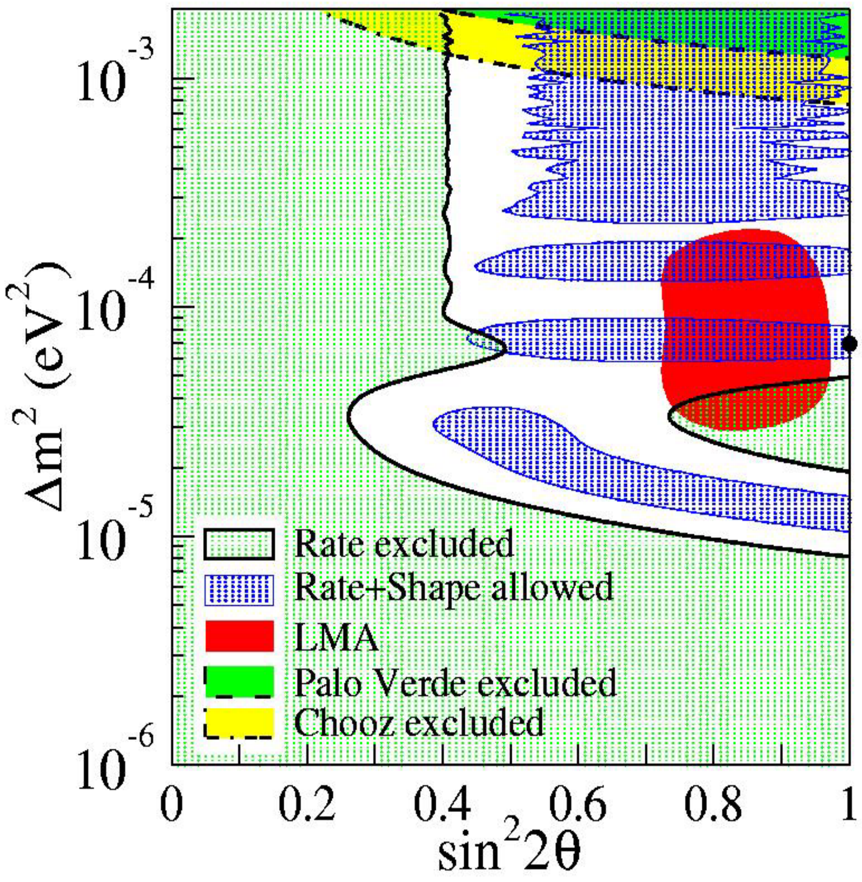
The focus of the Muon Collaboration on Neutrino Factories is driven by physics. In particular by:

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:

→ Physics beyond the Standard Model

We know that all three known flavors (ν_e, ν_μ, ν_τ) participate in ν oscillations → 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!

→ Baryogenesis ?
→ A new handle on Grand Unification
→ 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 $\nu_e \to \nu_\mu$ oscillations.

$$\begin{tikzcd}
\mu^+ \arrow[r] & e^+ & \nu_e \arrow[d] & \bar{\nu}_\mu \arrow[r, Rightarrow, "\mathrm{CC}"] & \mu^+ \\
 & & \nu_\mu \arrow[rr, Rightarrow, "\mathrm{CC}"'] & & \mu^-
\end{tikzcd}$$

$\nu_e \to \nu_\mu$ 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 ⇒ background-free $\nu_e \to \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

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:

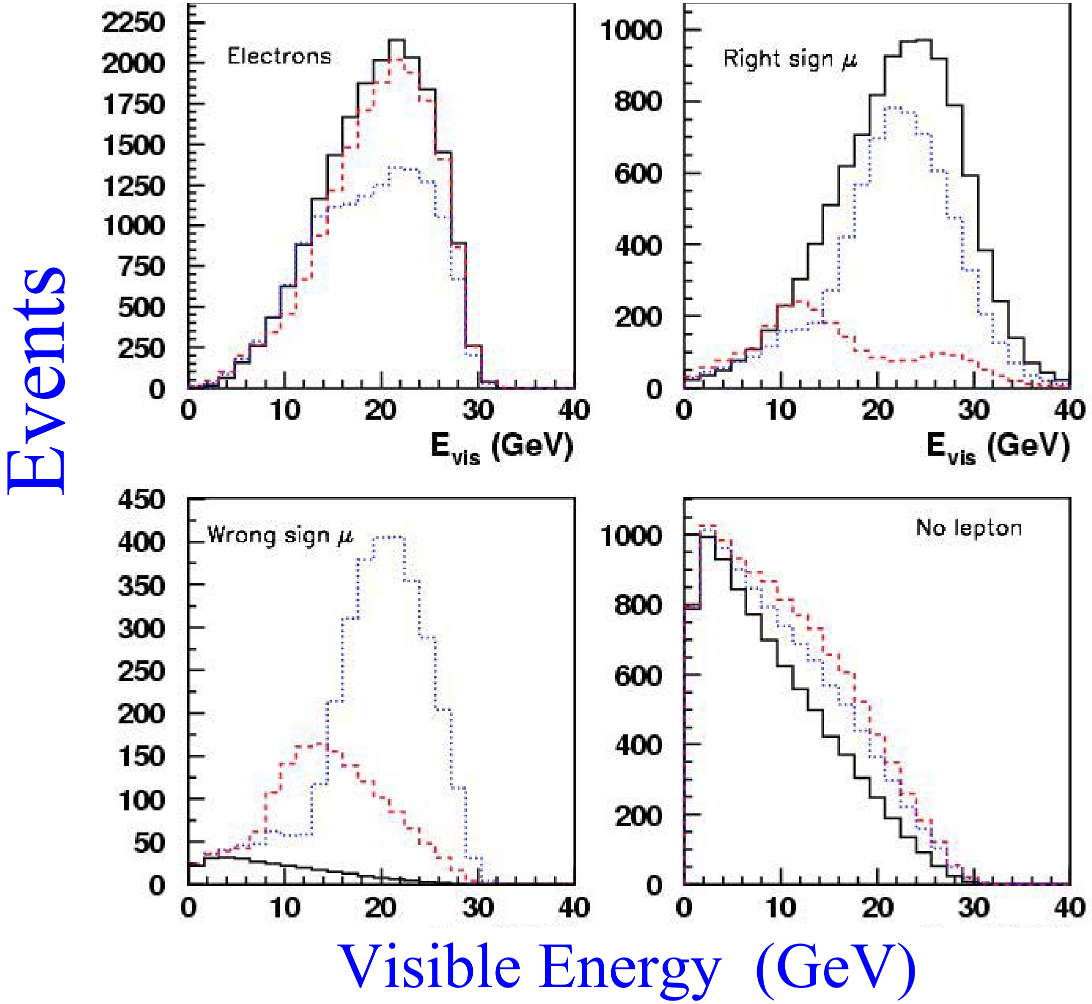
a) right-sign muons
b) wrong-sign muons
c) electrons/positrons
d) positive τ-leptons
e) negative τ -leptons
f) no leptons

×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.



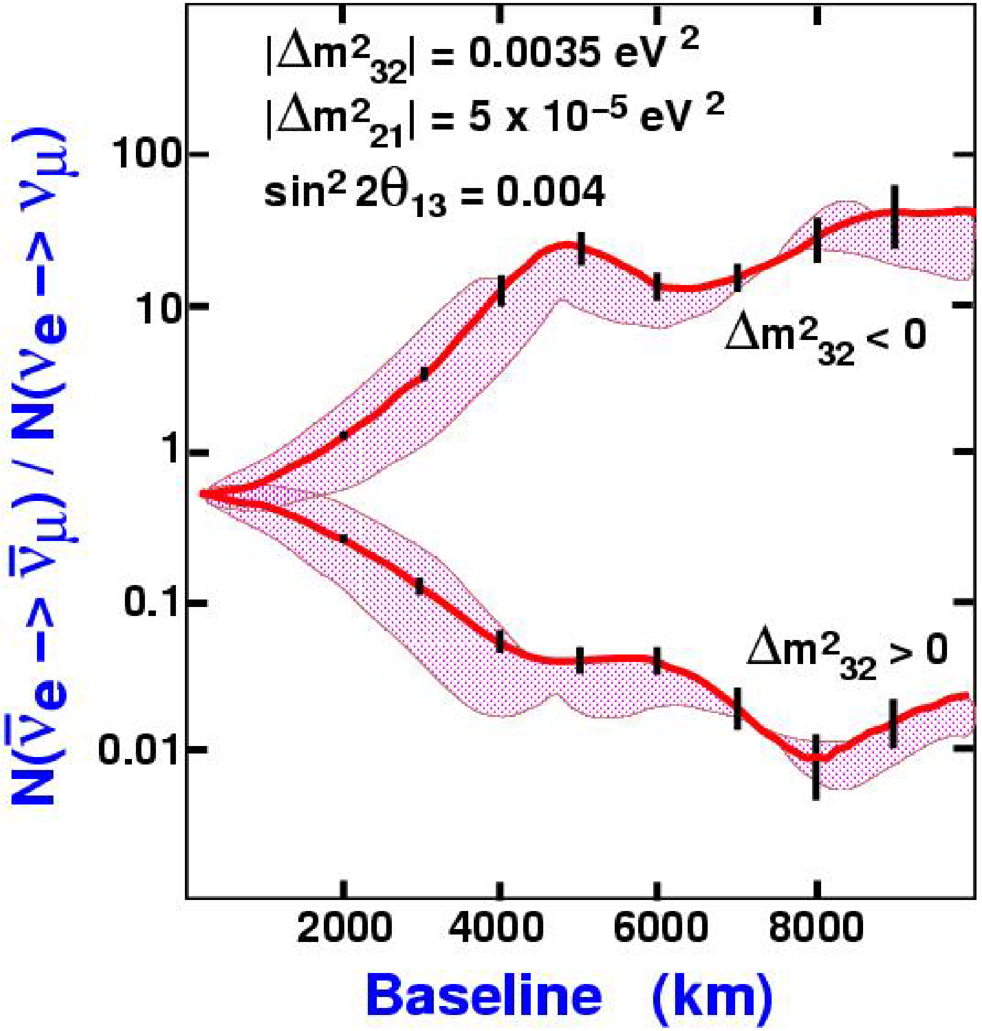
CP-Violation & the pattern of neutrino masses

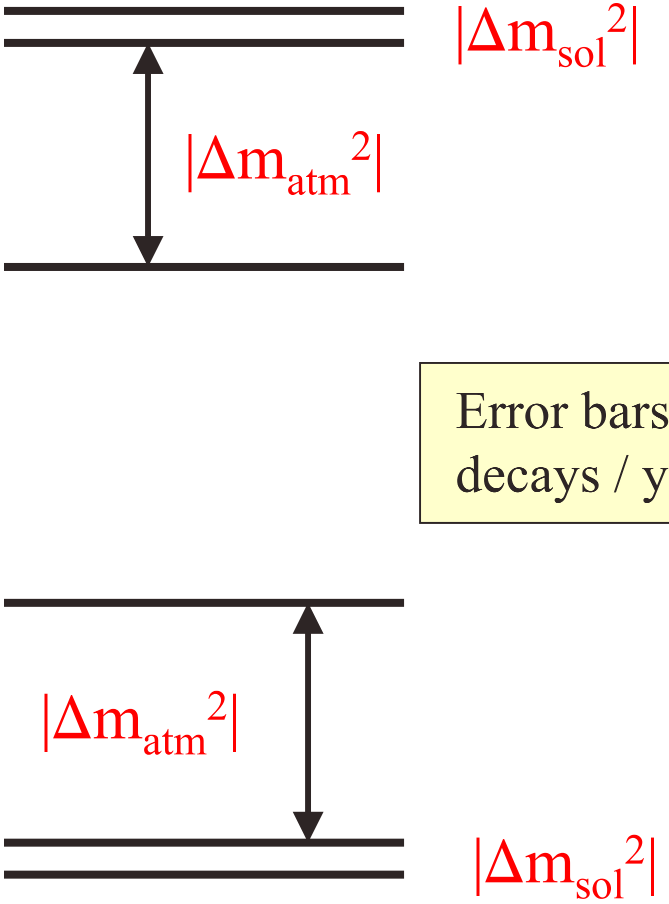
The signature for CP violation would be an inequality between $P(\nu_e \leftrightarrow \nu_\mu)$ and $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu)$ → Measure wrong-sign muon rates for μ^+ and μ^- running.

If the baseline is a few × 1000 km, matter effects can also produce an inequality between $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu)$ and $P(\nu_e \leftrightarrow \nu_\mu)$ which depends upon the sign of Δm_{32}^2 → 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 → 2×10^{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

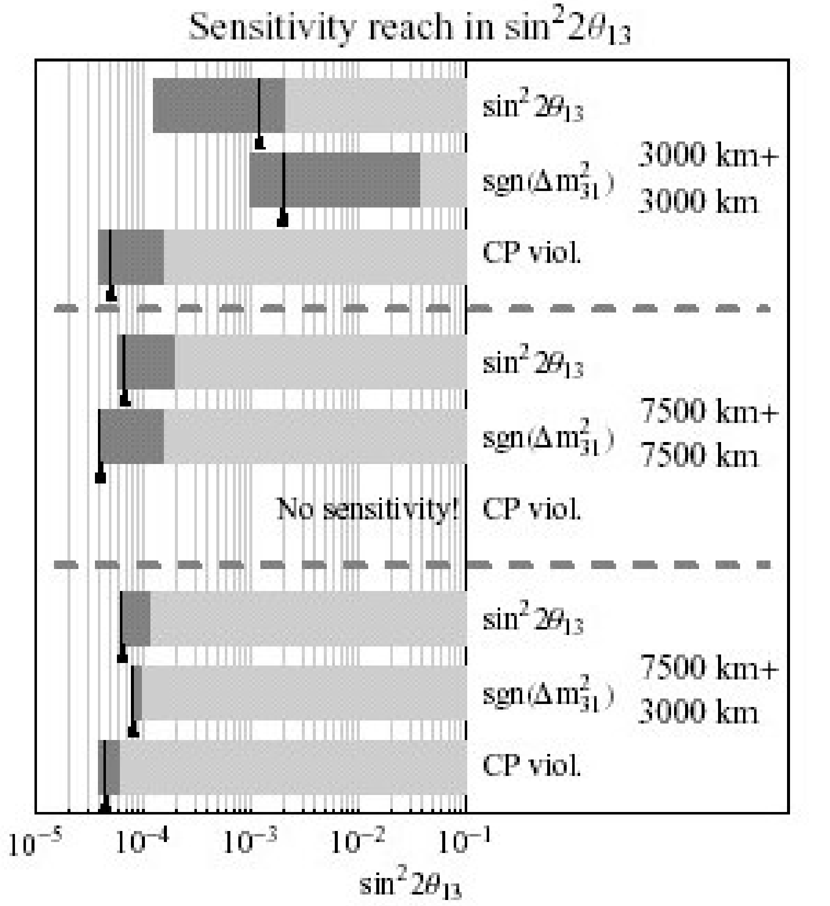


FIG. 3: The sensitivity reaches as functions of $\sin^2 2\theta_{13}$ for $\sin^2 2\theta_{13}$ itself, the sign of $\Delta m^2_{31} > 0$, and (maximal) CP violation $\delta_{CP} = \pi/2$ for each of the indicated baseline-combinations. The bars show the ranges in $\sin^2 2\theta_{13}$ where sensitivity 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.

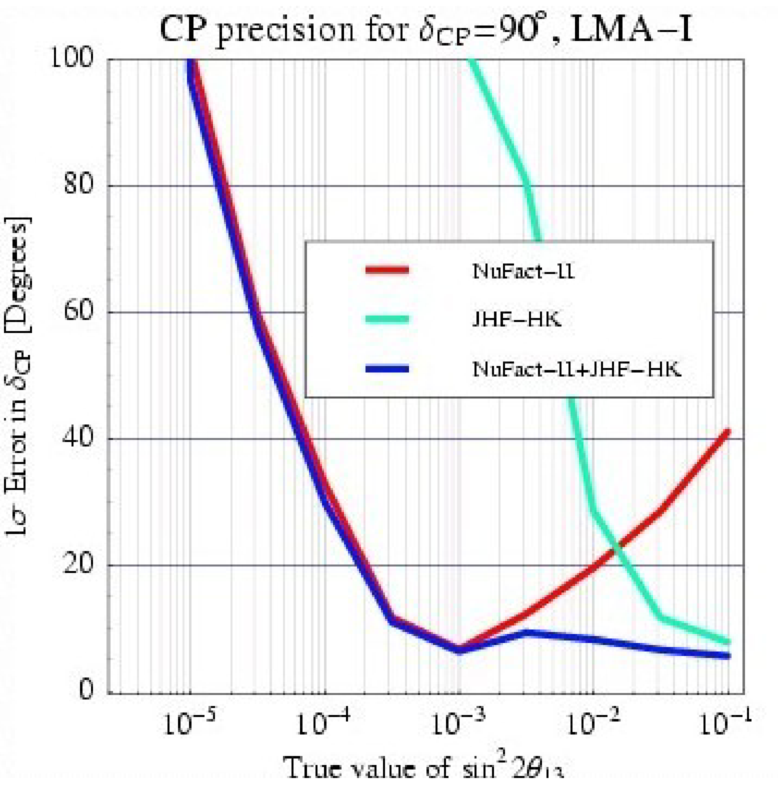
The calculated $\sin^2 2\theta_{13}$ reach (3σ) is below 10^{-4} for all three physics goals (measuring $\sin^2 2\theta_{13}$, determining the mass hierarchy, & observing maximal CPV) !!

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

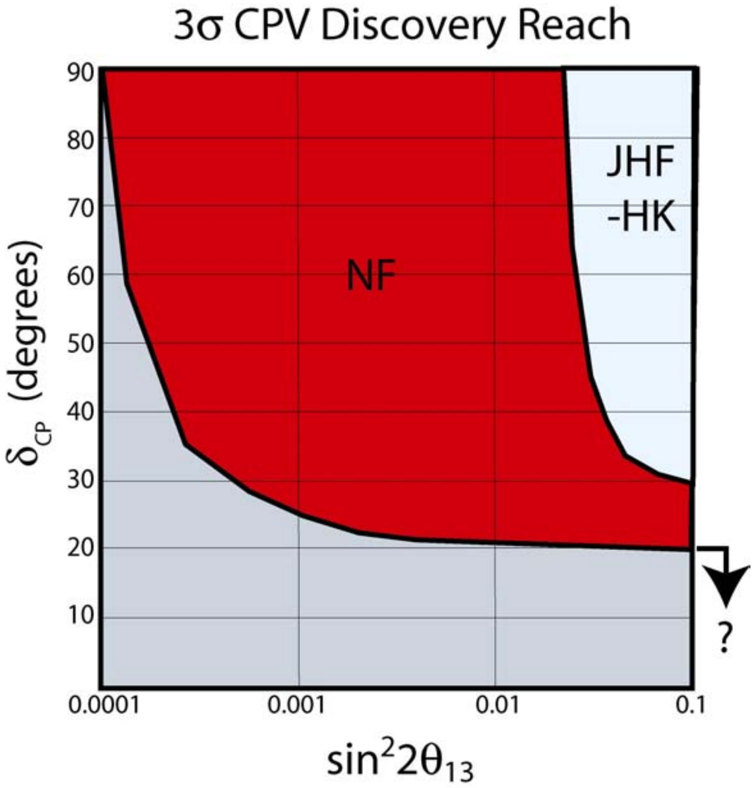
The calculations are for a 50 GeV Neutrino Factory.

Sensitivity to Non-Maximal CP-Violation

The impact of ambiguities correlations has now been studied by several groups → can be overcome at a Neutrino Factory by exploiting two baselines or 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 ~ 10^{-4} !

Oscillation Physics Reasons to Build a Neutrino Factory

Case 1: θ_{13} very small ($\sin^2 2\theta_{13} < 0.01$). A Neutrino Factory is the only known way to make real progress → measure θ_{13}, determine the mass ν hierarchy & search for CP-Violation down to $\sin^2 2\theta_{13} = O(10^{-4})$.

Case 2: θ_{13} not very small ($\sin^2 2\theta_{13} > 0.01$). If CP-Violation is observed at Superbeams → hope that ideas that lead to "the standard model of neutrino masses" will emerge. A Neutrino Factory would very likely provide the extra flexibility and precision to test these ideas. If CP-Violation is not observed at Superbeams (δ_{CP} too small), a Neutrino Factory would extend the search.

Case 3: A surprise (more than 3-flavor mixing). The phenomenological framework will be complicated, and the physics probably profound. A Neutrino Factory will be in great demand !

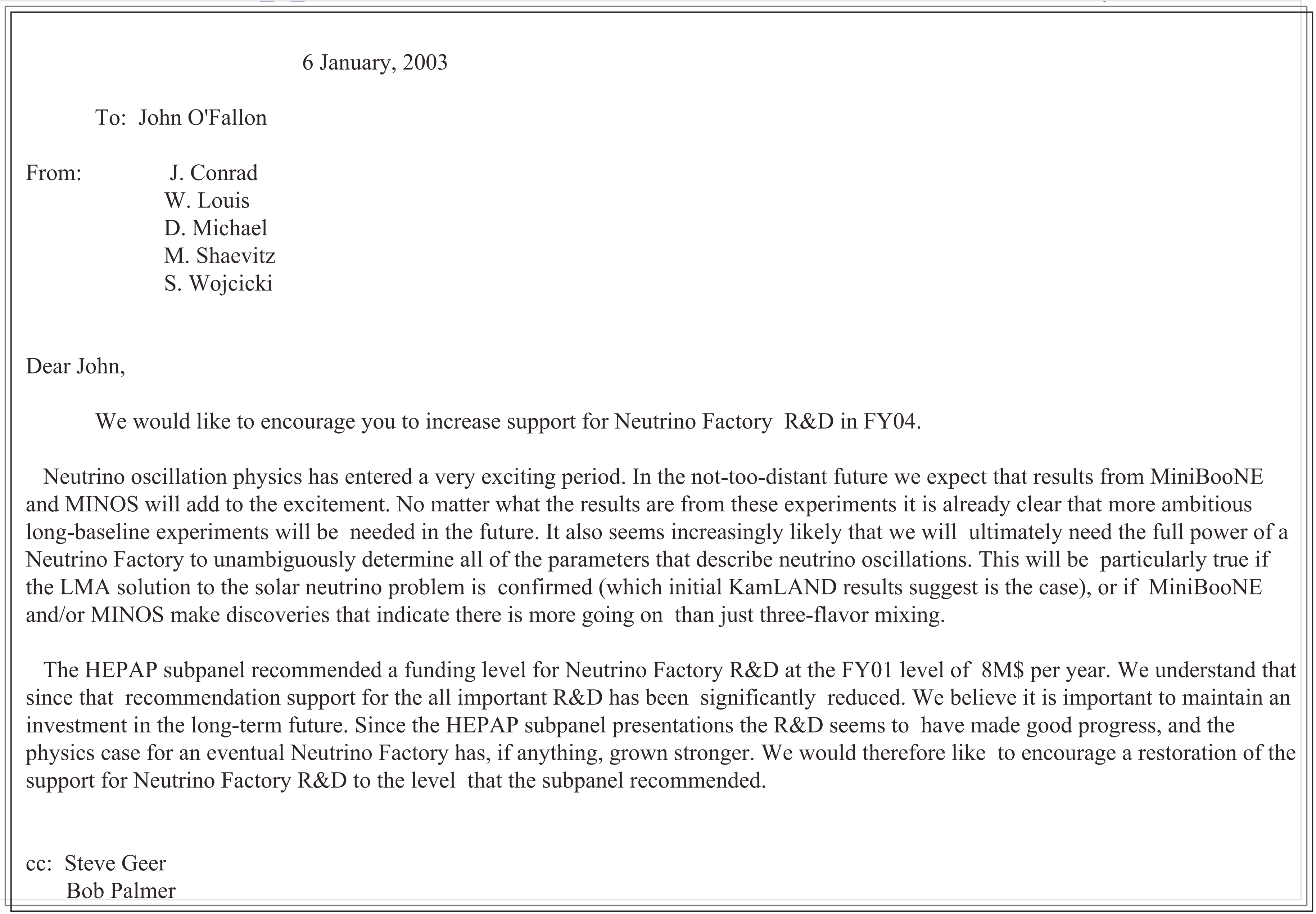
Neutrino Interaction Experiment Reasons to Build a Neutrino Factory

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

Support from the neutrino community



6 January, 2003

To: John O'Fallon

From:
J. Conrad
W. Louis
D. Michael
M. Shaevitz
S. Wojcicki

Dear John,

We would like to encourage you to increase support for Neutrino Factory R&D in FY04.

Neutrino oscillation physics has entered a very exciting period. In the not-too-distant future we expect that results from MiniBooNE and MINOS will add to the excitement. No matter what the results are from these experiments it is already clear that more ambitious long-baseline experiments will be needed in the future. It also seems increasingly likely that we will ultimately need the full power of a Neutrino Factory to unambiguously determine all of the parameters that describe neutrino oscillations. This will be particularly true if the LMA solution to the solar neutrino problem is confirmed (which initial KamLAND results suggest is the case), or if MiniBooNE and/or MINOS make discoveries that indicate there is more going on than just three-flavor mixing.

The HEPAP subpanel recommended a funding level for Neutrino Factory R&D at the FY01 level of 8M$ per year. We understand that since that recommendation support for the all important R&D has been significantly reduced. We believe it is important to maintain an investment in the long-term future. Since the HEPAP subpanel presentations the R&D seems to have made good progress, and the physics case for an eventual Neutrino Factory has, if anything, grown stronger. We would therefore like to encourage a restoration of the support for Neutrino Factory R&D to the level that the subpanel recommended.

cc: Steve Geer
Bob Palmer

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:
    - Mike Zisman'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 this end:
    - Bob Palmer's Talk

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

4. We badly need more funds – hope there will be some discussion at the end.