How Will We See Leptonic CP Violation?

D. Casper
University of California, Irvine

Outline

- Why is leptonic CP violation interesting?
- Solar and atmospheric neutrino oscillation
- Sub-dominant oscillation (θ_{13})
- CP violation in neutrino oscillation
  - Superbeams
  - Neutrino Factory
  - Betabeams
  - Monoenergetic beams
- Conclusion

Will We See Leptonic CP Violation?

- Matter asymmetry of the universe likely tied to CP-violation (and baryon number non-conservation)
  - A. Sakharov, 1967
- Hadronic CP violation seems too small to account for matter asymmetry
- Hadronic mixings and CP violation are small
  - Leptonic mixing angles are large…
  - …maybe leptonic CP violation is also large?

Leptogenesis in a Nutshell*

- See-Saw Mechanism provides a plausible explanation for observed neutrino masses
  - $m_\nu \sim m_{Dirac}/M$
  - For observed m_ν, $M \sim 10^{15}$ GeV
  - Right-handed neutrinos naturally lead to lepton number violation, and super-heavy neutrinos are ideal for generating lepton asymmetry (through CP-violating decay out of equilibrium)
- Lepton asymmetry can evolve into baryon asymmetry through sphaleron processes in Early Universe
- 10^{-3} eV < m_ν < 0.1 eV seems to lead to baryon asymmetry of the observed magnitude, independent of heavy neutrino abundance or pre-existing asymmetry

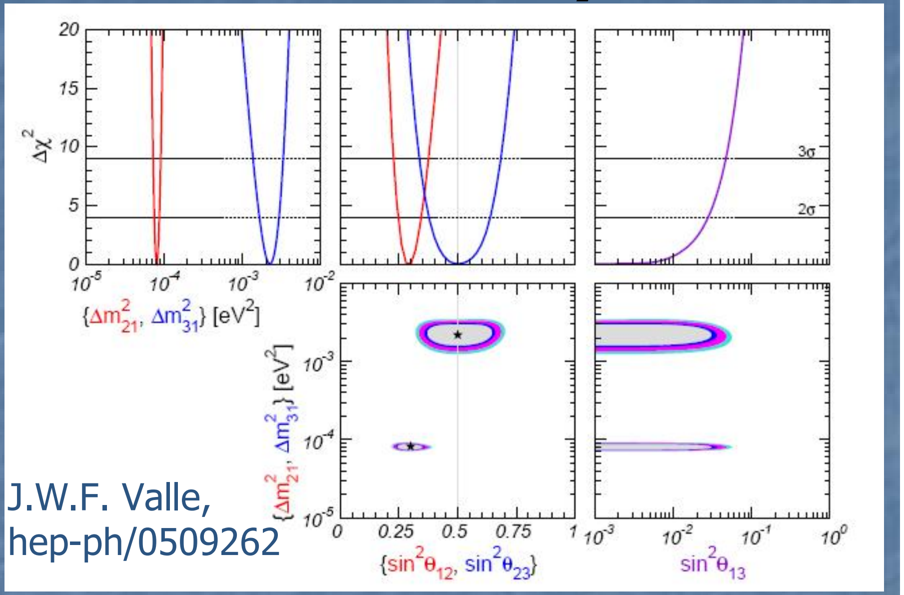
* See Buchmuller, Peccei and Yanagida, hep-ph/0502169

Important Caveat

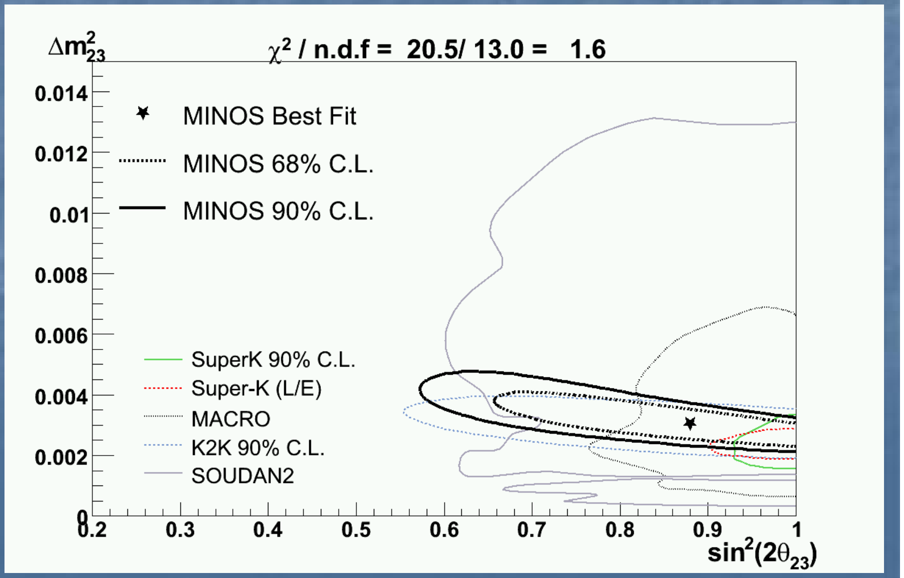
- In general, the observable CP violating phases (at low-energies) are not identical to those responsible for leptogenesis (at high energies)
  - Under certain special assumptions (consistent with what we know today) they can be directly related
- As experimentalists, we measure what we can, and leave the rest as an exercise for the reader…

Neutrino Oscillation Today

- Standard Model parameters:
  - MNS mixing matrix (θ_{12}, θ_{23}, θ_{13}, δ_{CP})
  - Neutrino mass splittings (Δm^2_{12}, Δm^2_{23})
- Solar/Reactor sector
  - θ_{12}, Δm^2_{12}
- Atmospheric/Accelerator
  - θ_{23}, Δm^2_{23}
- Non-standard/Sterile
  - θ_{i4}, etc
- Sub-dominant
  - θ_{13}



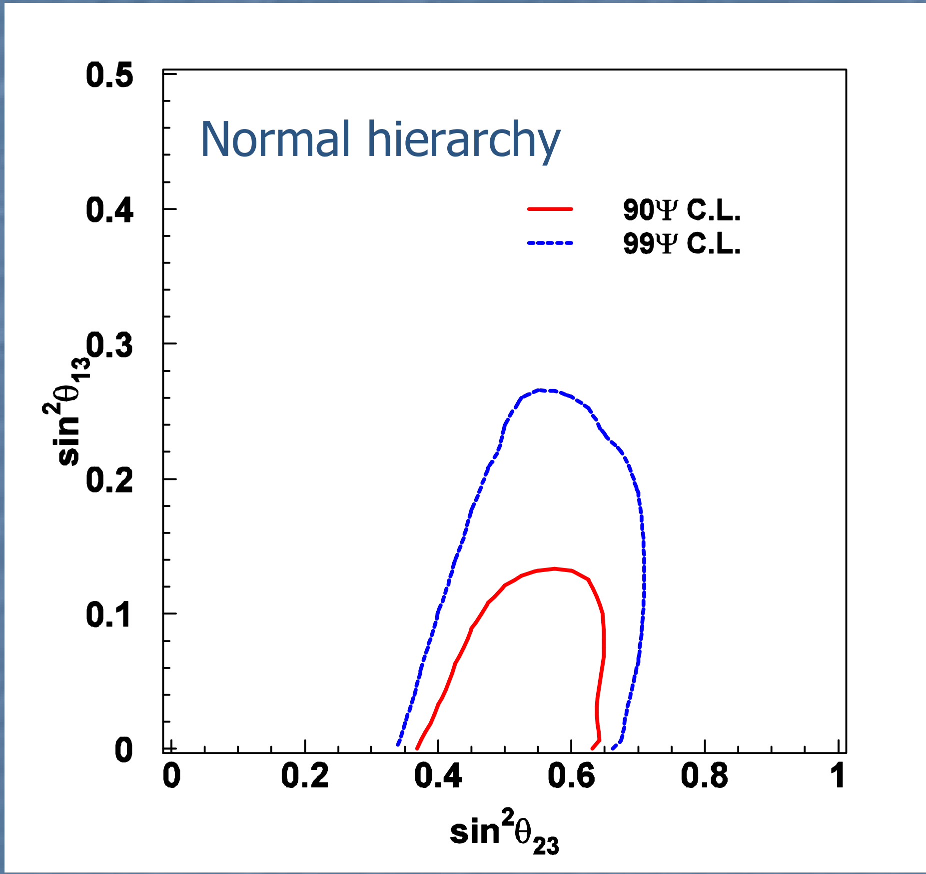
J.W.F. Valle, hep-ph/0509262

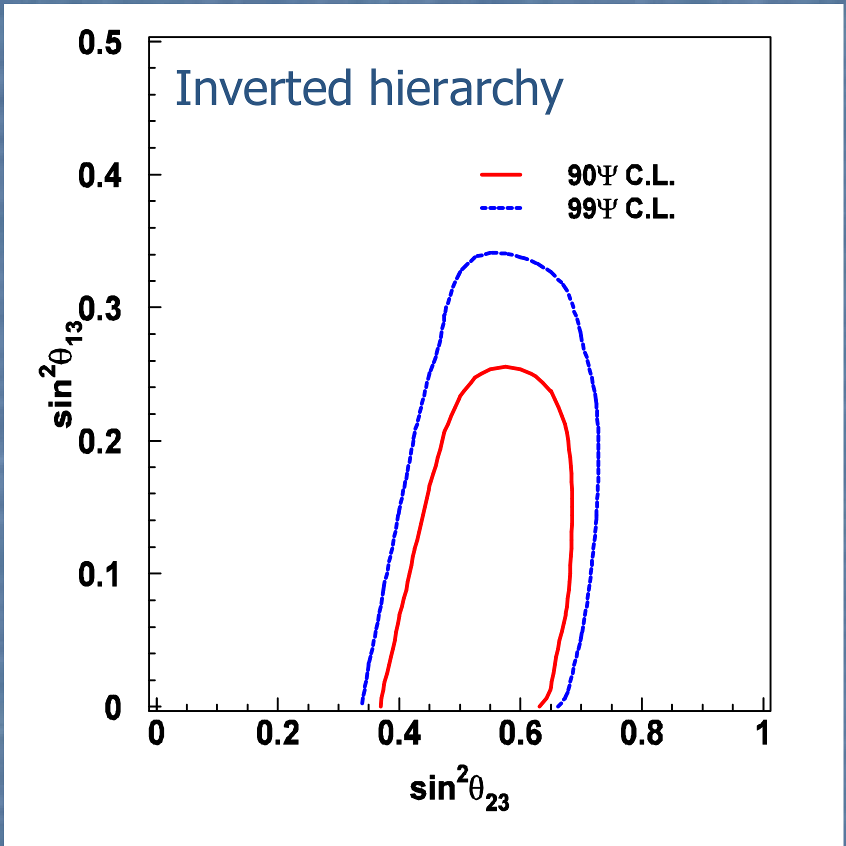


The Prerequisite: θ_{13}

- CP violation in neutrino oscillation requires three-flavor mixing
  - All three mixing angles enter the CP-violating term
  - All angles must be non-zero
  - Only observable in appearance experiments
- θ_{12} and θ_{23} are large (good!)
- Observing leptonic CP violation requires observing non-zero θ_{13}
- Show & Tell, part I…

The Search for θ_{13}: Atmospheric

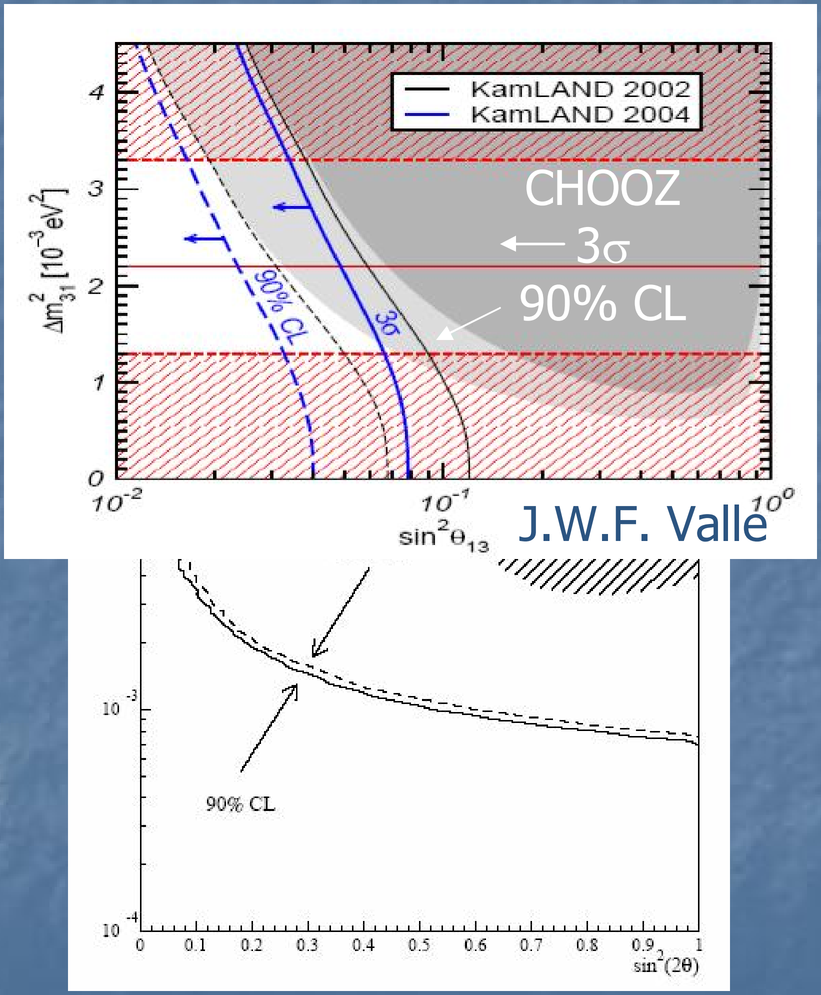




Super-Kamiokande three-flavor analysis
(Little prospect of reaching significantly beyond CHOOZ)

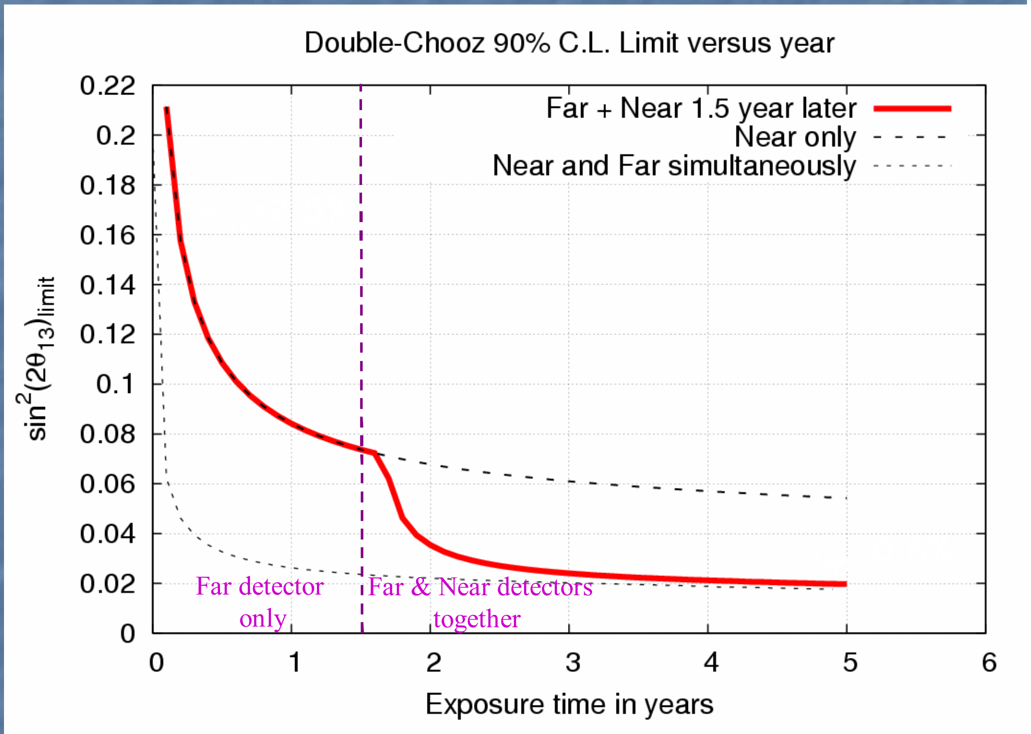
Search for θ_{13}: CHOOZ/KAMLAND

- CHOOZ reactor experiment final results (1999)
  - Limit on θ_{13} ~ 11°
- KAMLAND-2004 data is competitive with CHOOZ
  - Particularly for small mass differences



The Search for θ_{13}: Reactors

- Several reactor experiments proposed to search for θ_{13}:
  - Double CHOOZ
  - Daya Bay
  - Braidwood
- All hope to improve on CHOOZ (disappearance) sensitivity
- Typical sensitivities: $\sin^2 2\theta_{13} \sim 0.02\text{-}0.03$
  - Double CHOOZ hopes to reach this by December 2010
- No sensitivity to δ…

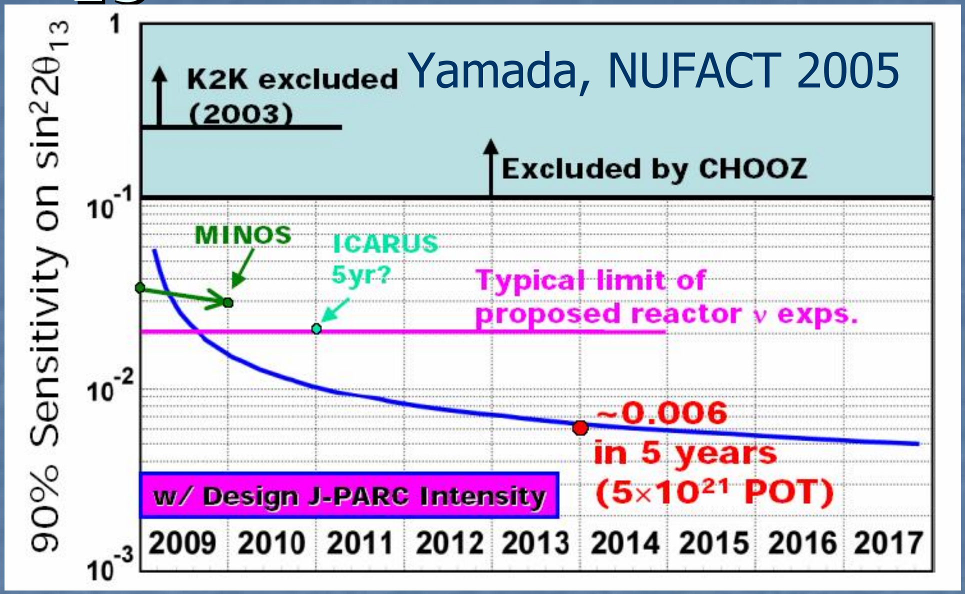


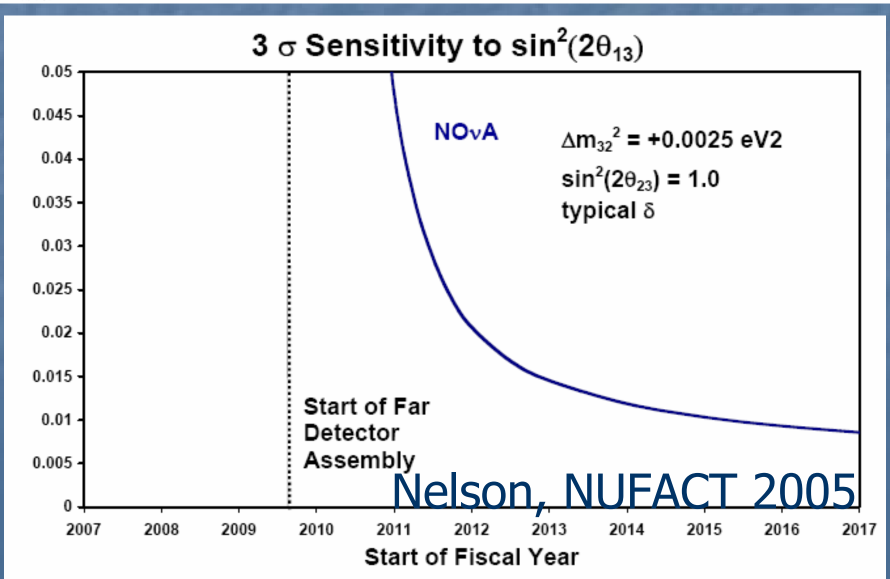
05/2007 05/2008 05/2009 05/2010

Dazeley, NUFACT 2005

The Search for θ_{13}: Superbeams

- Exploit off-axis "trick" to create narrow-band beam without losing signal
- T2K
  - Approved
  - Funded in Japan
  - Beam under construction
  - Detector (SuperK) exists
- NOνA
  - Approved by PAC
  - Not yet funded (~$200M+?)
  - Beam exists
  - 50 kt liquid scintillator detector design
  - Begin construction in one year?
  - Fully operational July 2011?



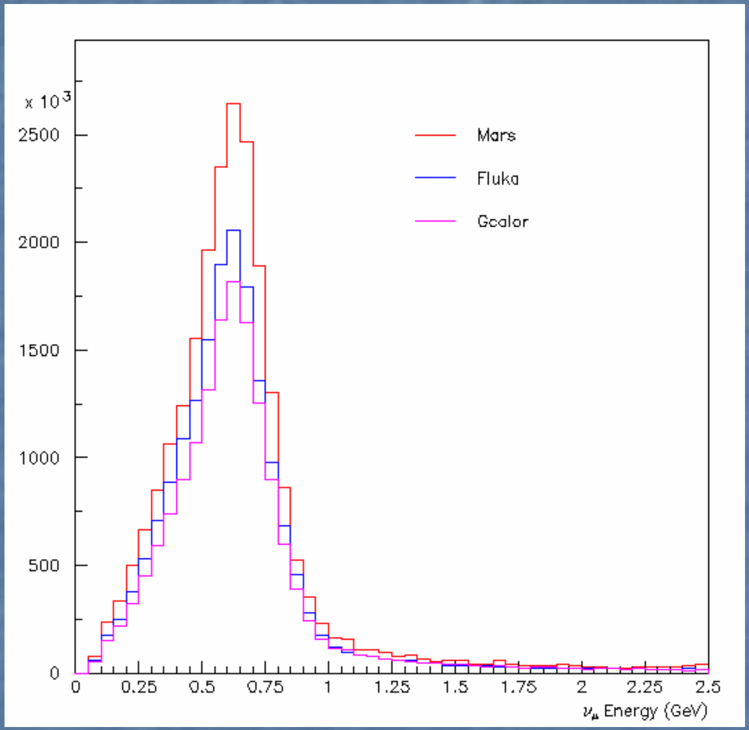


Systematics

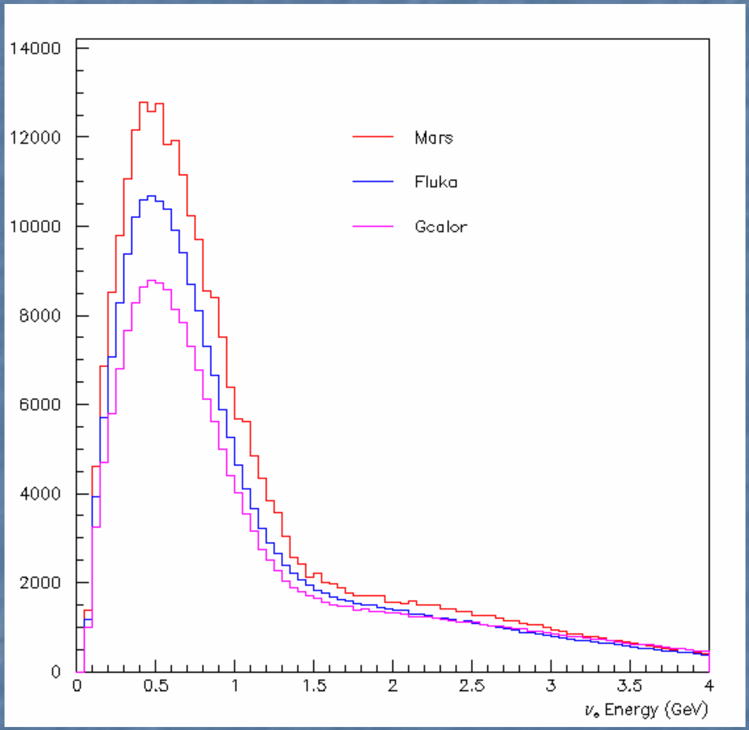
- 1% measurements require careful control of systematics
  - Must compare neutrinos and anti-neutrinos (different cross-sections)
  - Beams are hard to model
  - CC interactions and backgrounds are different in near and far detectors, due to oscillation
  - Near detector cannot easily measure cross-sections for an appearance signal
- Observation:
  - Most sensitivity estimates on the market tend to treat systematics crudely, if at all
    - Example: "Super-NOvA" proposal
  - Realistic estimates should simulate both near and far detector data, and fit them together

Superbeam Flux Uncertainties

- Three flux models
  - GCALOR, FLUKA, MARS



ν_μ Energy (GeV)

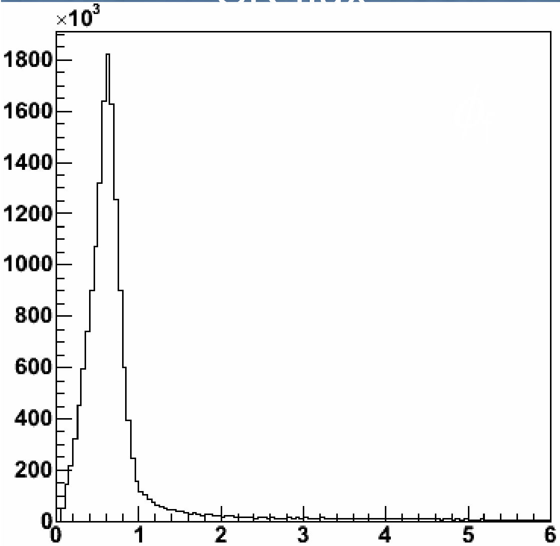


ν_e Energy (GeV)

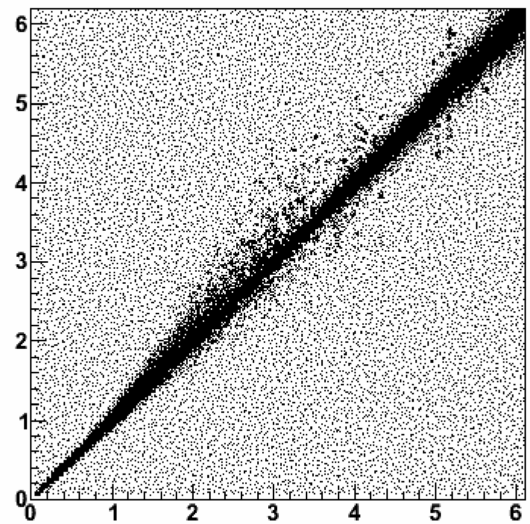
(Work in progress; J. Dunmore, DC, C. Simon)

Near-to-Far Correlation Matrix

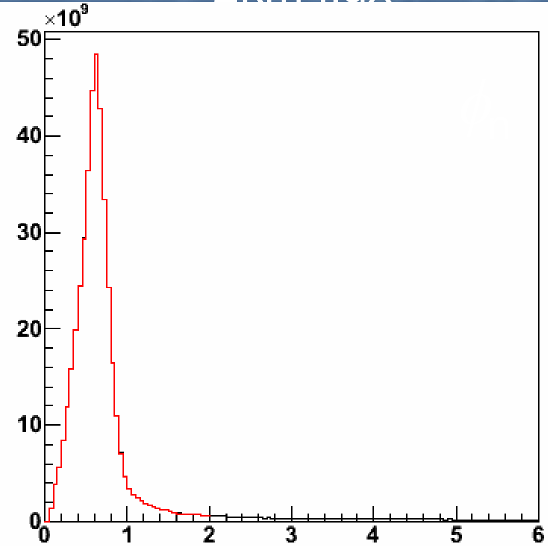
SK flux



Transfer Matrix



2km flux



ν_μ Energy (GeV)

ν_μ Energy (GeV)

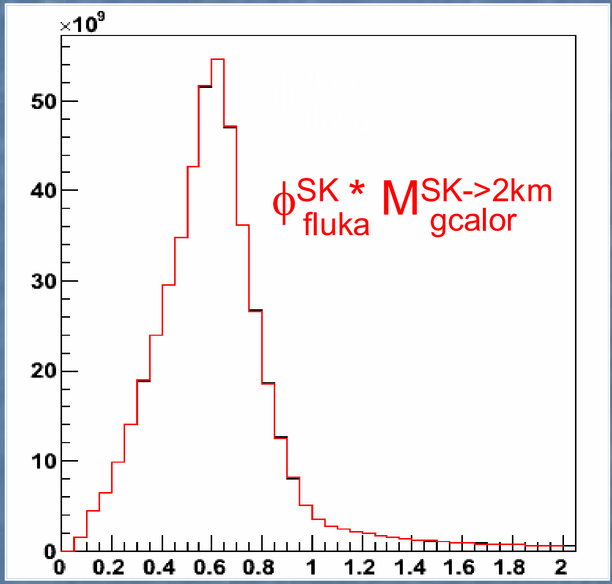
$$\varphi_f = \sum_n M_{fn}\phi_n$$

$$M_{fn} \equiv \frac{\sum_h \left(\frac{\varphi_f^h \phi_n^h}{\sum_n \phi_n^h} \right)}{\sum_h \phi_n^h} = \frac{\sum_h \left(\frac{\varphi_f^h \phi_n^h}{\sum_n \phi_n^h} \right)}{\phi_n}$$

- Improvement over "far/near" ratio technique (see Para and Szleper).
- Robust (few-percent) flux extrapolation between detectors, even if hadronic model is incorrect, beam elements slightly misaligned, etc

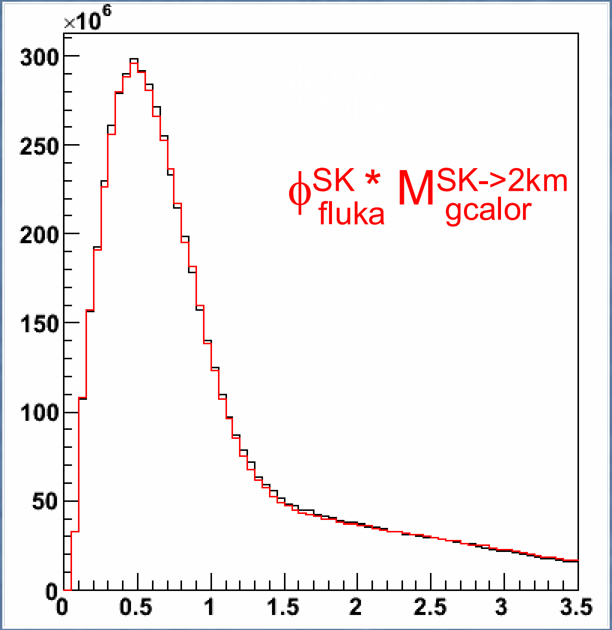
Correlation Matrix Performance

2km ν_μ Flux



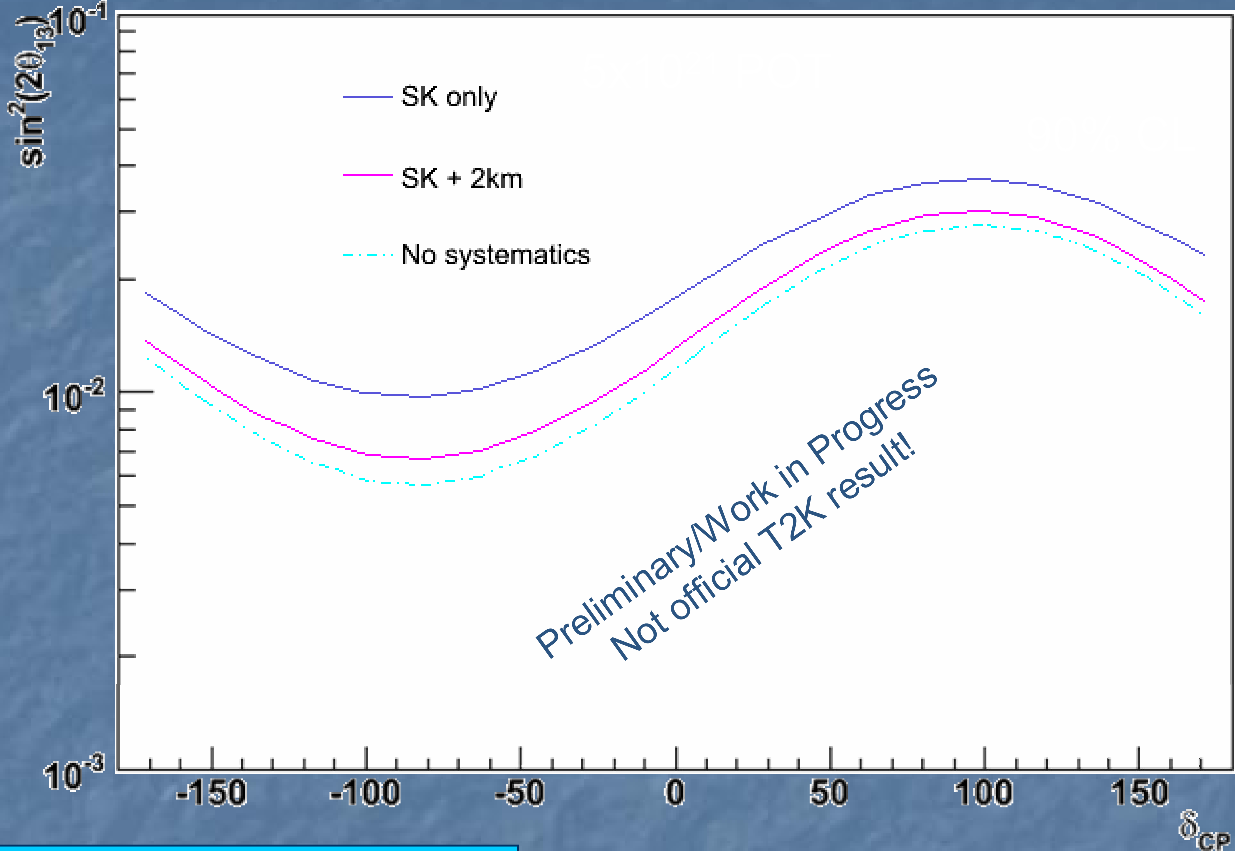
ν_μ Energy (GeV)

2km ν_e Flux



ν_e Energy (GeV)

Effect of a Near Detector



$\Delta\chi^2$=4.61 (2 dof)

- This figure now includes
  - μ-like, e-like, and π^0-like samples
  - Statistical fluctuations
  - Poisson χ^2 (with pulls)
  - Uncertainty due to sign(Δm^2)
  - 3ν oscillation model
- Disappearance parameters assumed known

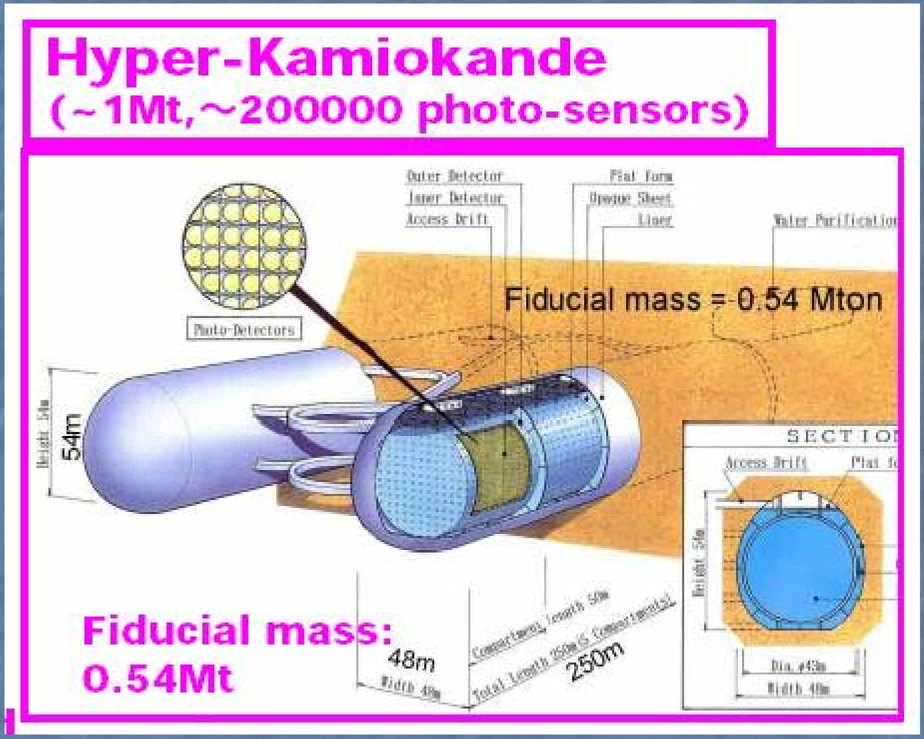
- Included systematic effects
  - ν_μ and ν_e flux
  - Cross-sections
  - Fiducial volume of each detector
  - Energy scale for each detector
  - Detection efficiency for each event type in each detector (uncorrelated)

CP Violation in Neutrino Oscillation

- CP violation is manifest in differences between neutrino and anti-neutrino appearance probabilities
  - Unfortunately matter effects are also CP violating
  - Matter effects in turn depend on the mass hierarchy
  - Knowledge of other parameters is important too
  - CP violation does not affect disappearance channels
- These differences are typically a few percent
  - i.e. 1% or 3% appearance probability vs. 2% with no CP violation
  - Show and Tell, part II…

Detector Challenges

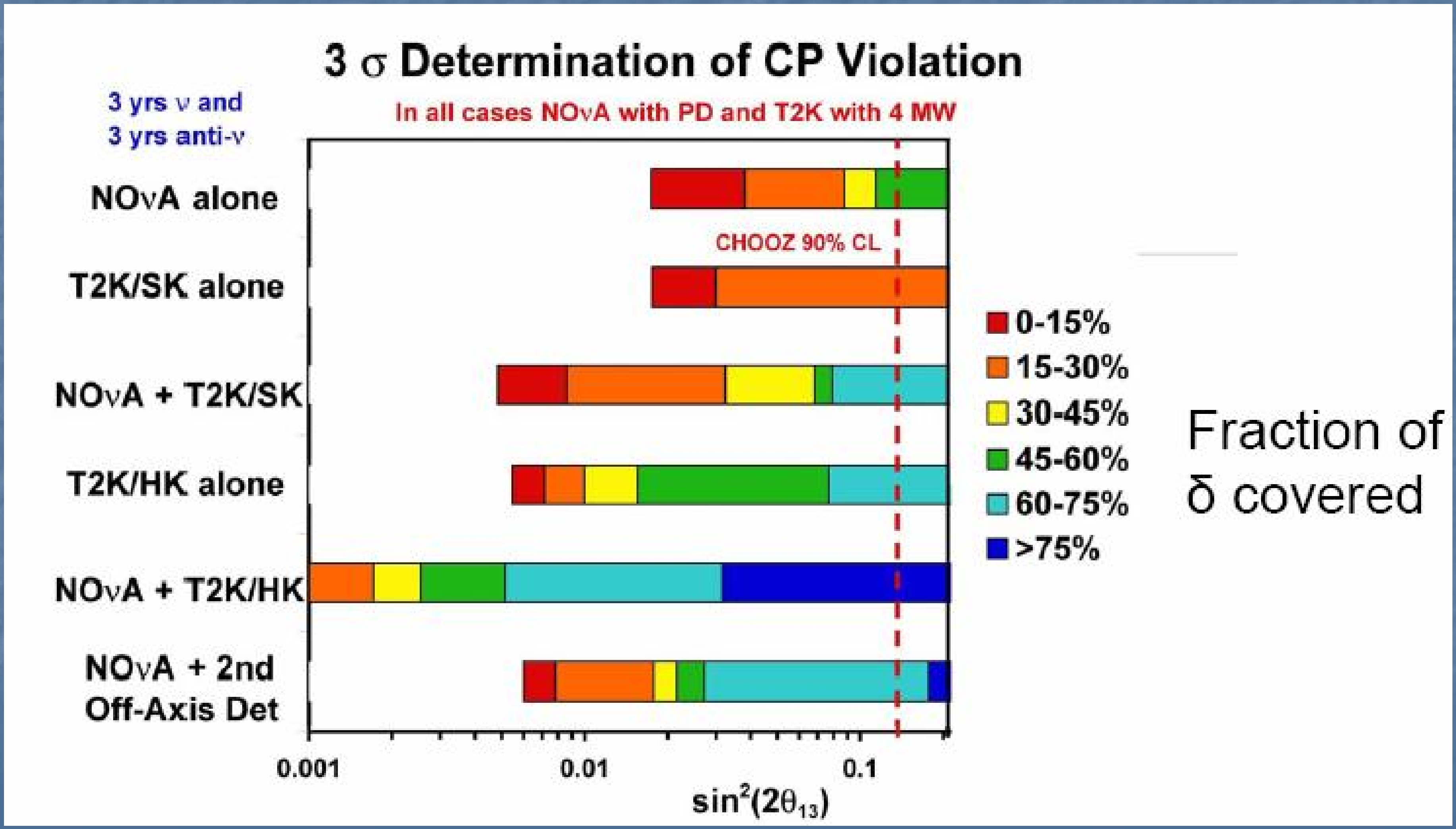
- Since CP violation causes small changes in probability, large data samples are required to measure them
  - Big detectors…
  - Expensive detectors…



Matter Effects and Degeneracies

- Observable oscillation probabilities may not uniquely determine the physical parameters
- Parameter degeneracies
  - θ_{13} - δ
  - $\mathrm{sgn}(\Delta m_{23}^2)$
  - octant of θ_{23}

Superbeams?



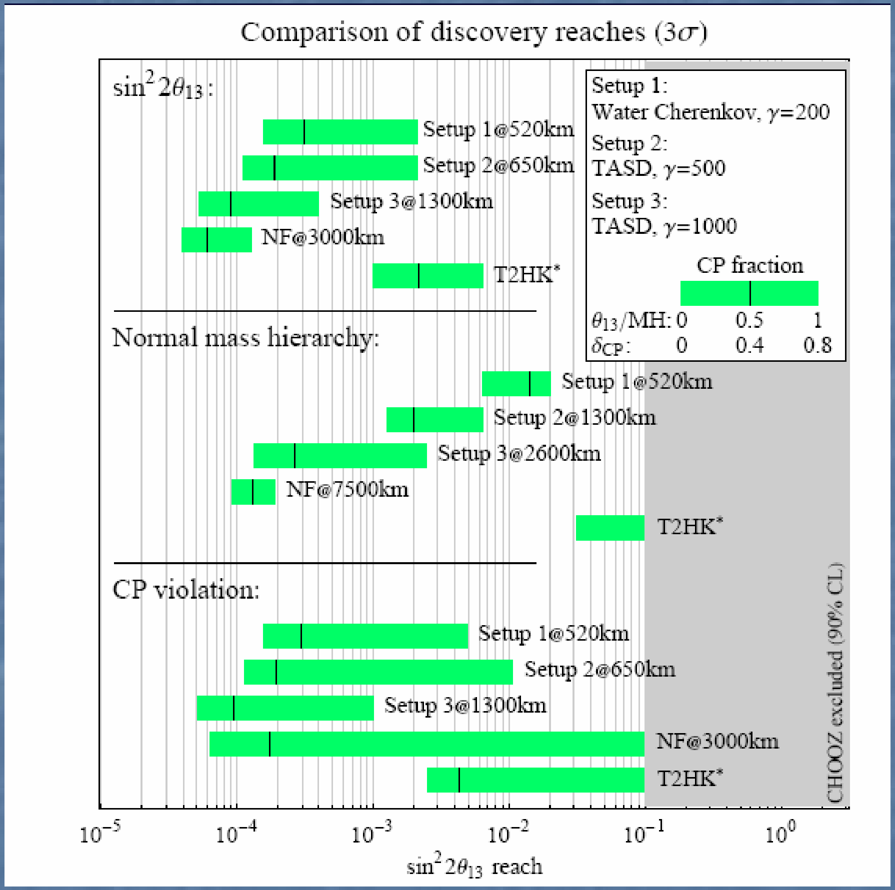
Nelson, NUFACT 2005

Limitations of Conventional Beams

- Uncertain flux and spectrum
  - Relies to some extent on modeling hadron production
  - Experiment relies on comparing neutrino and anti-neutrino beams
- Uncertain cross-sections
  - Again, comparing neutrino and anti-neutrino will be tough
- Flavor contamination
  - No way to eliminate ν_e from K and μ decay
- Wrong-sign contamination
  - Big problem for anti-neutrino beam
    - Higher neutrino cross-section
    - Leading charge effects

A Neutrino Factory?

- A neutrino factory (20-50 GeV muon storage ring) is the ultimate tool for studying neutrino oscillation
- Important step toward muon collider
  - Relevant to non-neutrino community
- Serious technical and cost challenges
- Important R&D ramping up
  - MICE
  - MUCOOL
  - nTOF11
  - …
- Realistically, not within a 10-15 year horizon



P. Huber, NUFACT 2005

Neutrino Factory Advantages

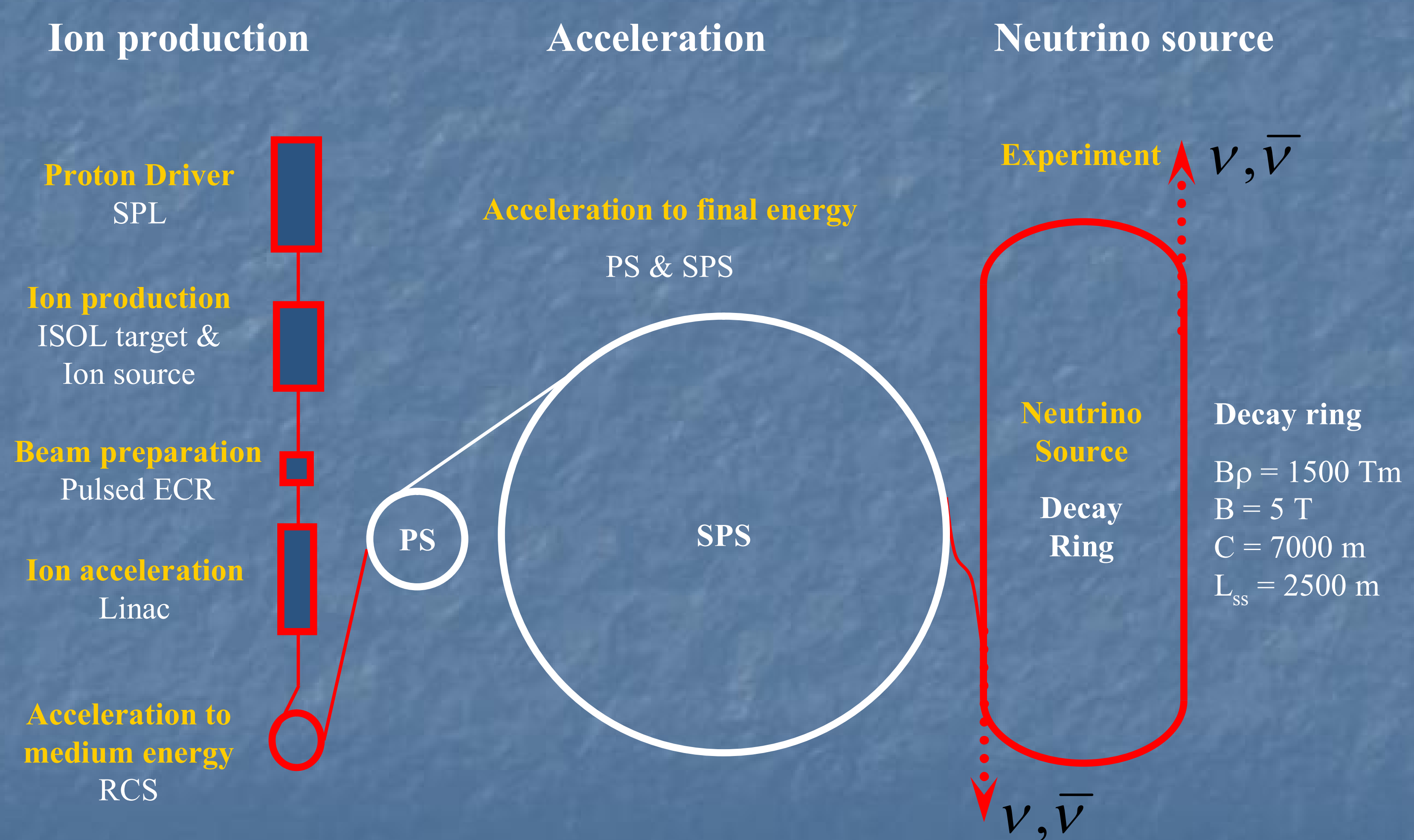
- Known spectrum
- Known (enormous) flux
- Run neutrinos and anti-neutrinos simultaneously
- Exploit different baselines to resolve degeneracies
- "Golden channel"
  - Wrong-sign muon appearance in magnetic spectrometer
- "Silver channel"
  - Wrong-sign tau appearance ($\nu_e \rightarrow \nu_\tau$) leading to wrong-sign muon from tau decay
    - Tagged in OPERA-style emulsion detector

A Betabeam?

- The idea: accelerate and store β-unstable ions to create a pure *electron-flavor* beam
  - β^-: ^{6}He
  - β^+: ^{18}Ne
- Shares many advantages of neutrino factory:
  - Spectrum is ~perfectly known
  - Flux is ~perfectly known
  - Muon appearance allows easier background rejection
  - Can in principle run neutrinos and anti-neutrinos simultaneously
  - Near and far spectra nearly identical
- No secondary beam cooling/reacceleration challenges
  - Technically, a much simpler problem
  - Promising new ideas in high-intensity ion production
    - C. Rubbia, et al., hep-ph/0602032 – table-top source of 10^{14} ions/s?

P. Zucchelli, Phys.Lett.B 532, 166-172 (2002)

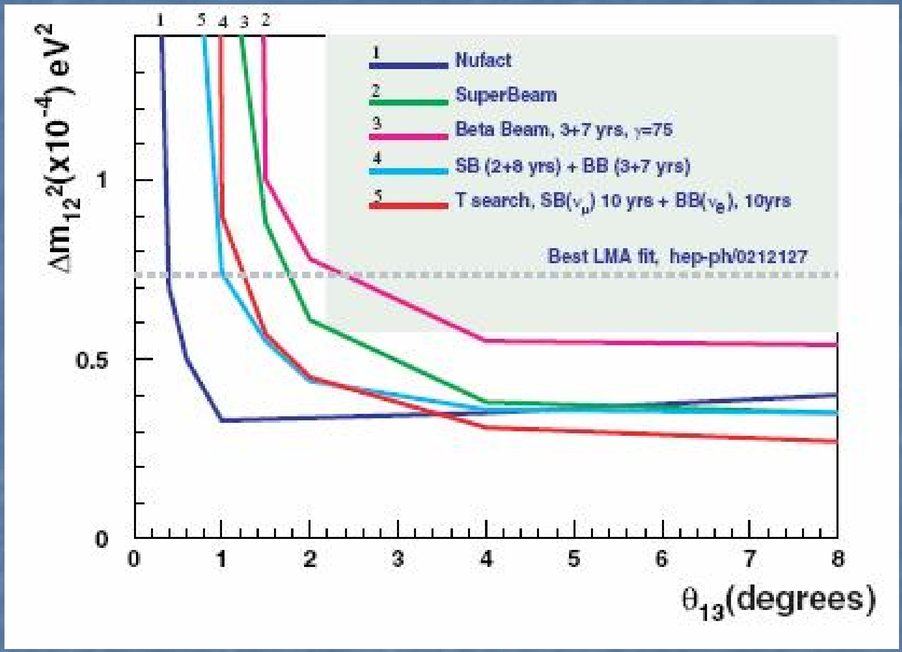
CERN Betabeam Concept



M. Lindroos, NUFACT 2005

Low-Energy Betabeam

- Initial studies focused on low-γ scenario at 150 km baseline
  - Reduce backgrounds by sitting near π threshold
  - No energy dependence available
    - Counting experiment
  - Low boost reduces focusing and flux

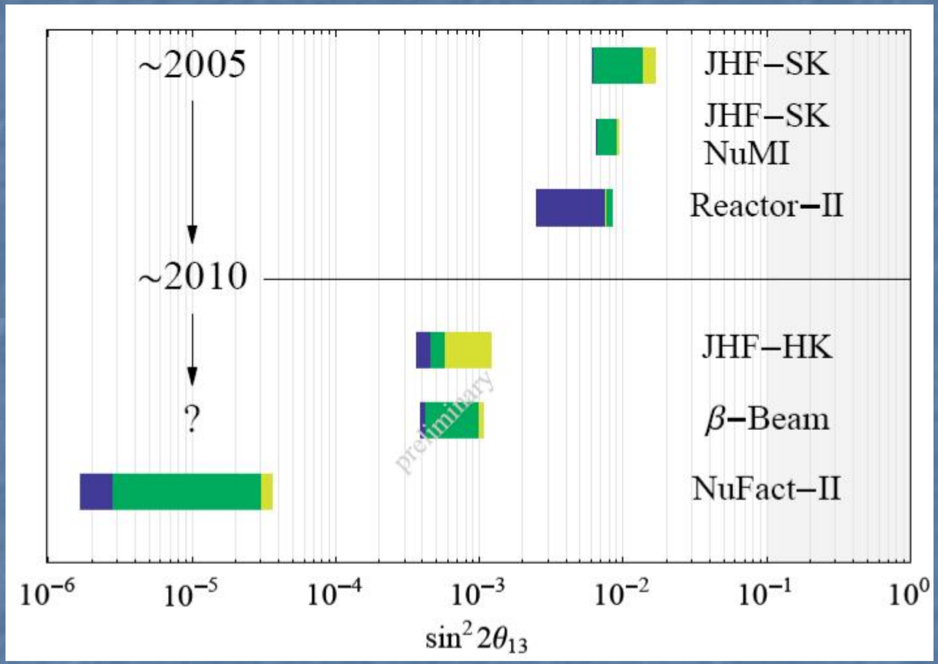


Sensitivity to distinguish δ=0° from δ=90° at 99% CL: betabeam and betabeam plus superbeam, compared to NUFACT and and T2K

M. Mezzetto, J.Phys.G 29, 1771-1776 (2003) [hep-ex/0302007]

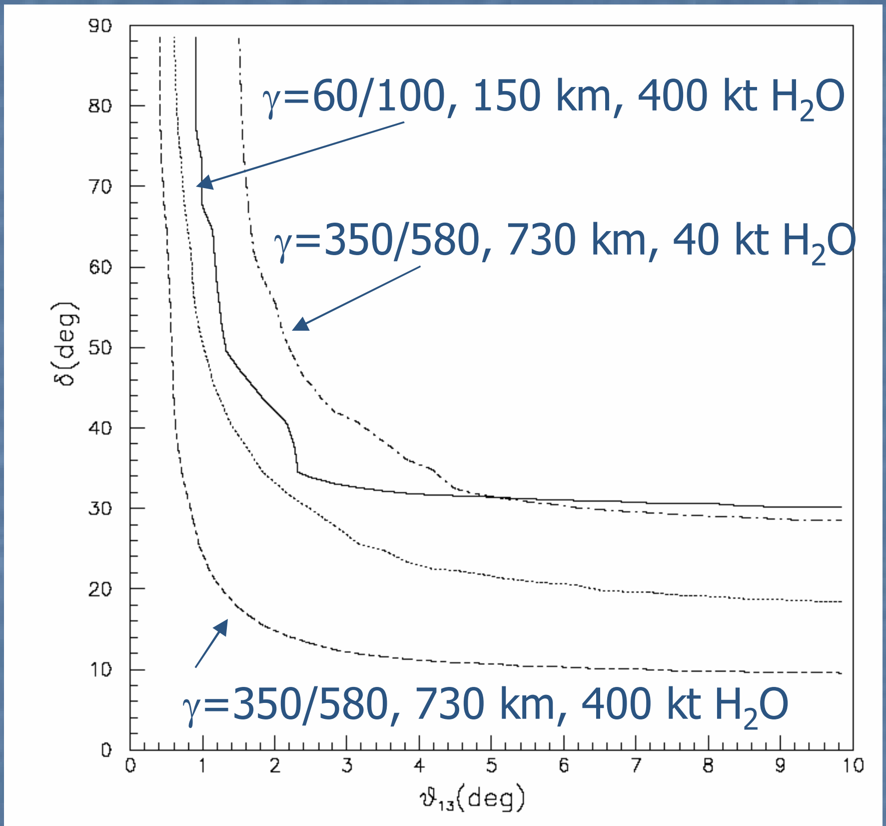
Betabeam Sensitivity in APS Study

- The recent APS study compared the low-energy betabeam to other facilities
- Although new work on higher energies was cited, it was not included in this figure…



A Higher-Energy Betabeam

- New approach: higher energy, longer baseline
  - $$\left.\frac{dN}{d\Omega dE}\right|_{\theta=0} \propto \frac{\gamma^2}{L^2}$$
  - $\sigma \sim \gamma$
  - Exploit energy dependence
  - Increase flux with more focusing
  - More cross-section at higher energy
  - NC backgrounds still manageable

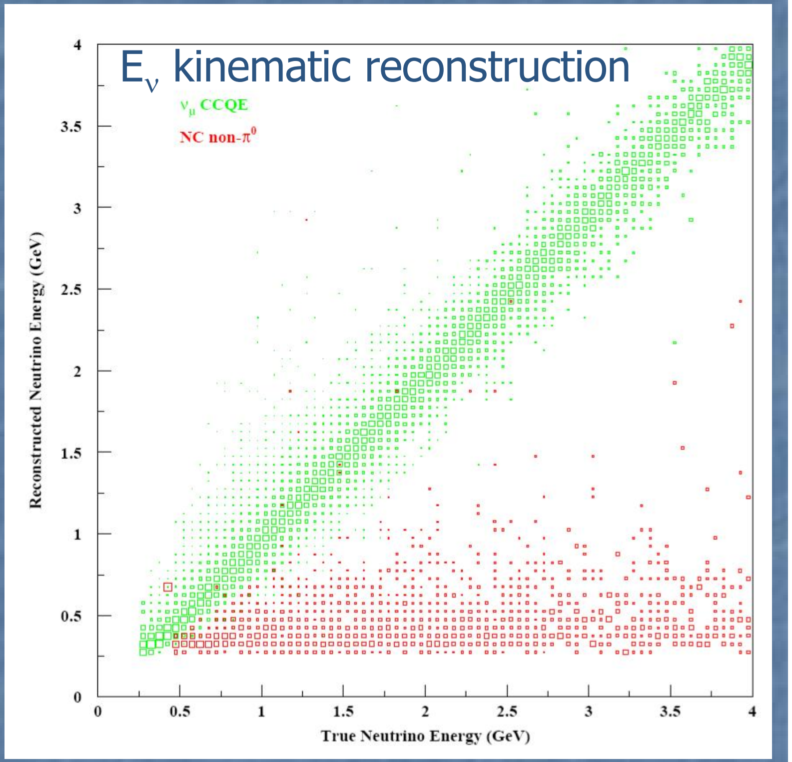


Region where δ can be distinguished from δ=0 and δ=90 at 99% CL

J.Burguet-Castell, D. Casper, J.J. Gomez-Cadenas, P.Hernandez, F. Sanchez, Nucl.Phys.B 695, 217-240 (2004) [hep-ph/0312068]

Backgrounds

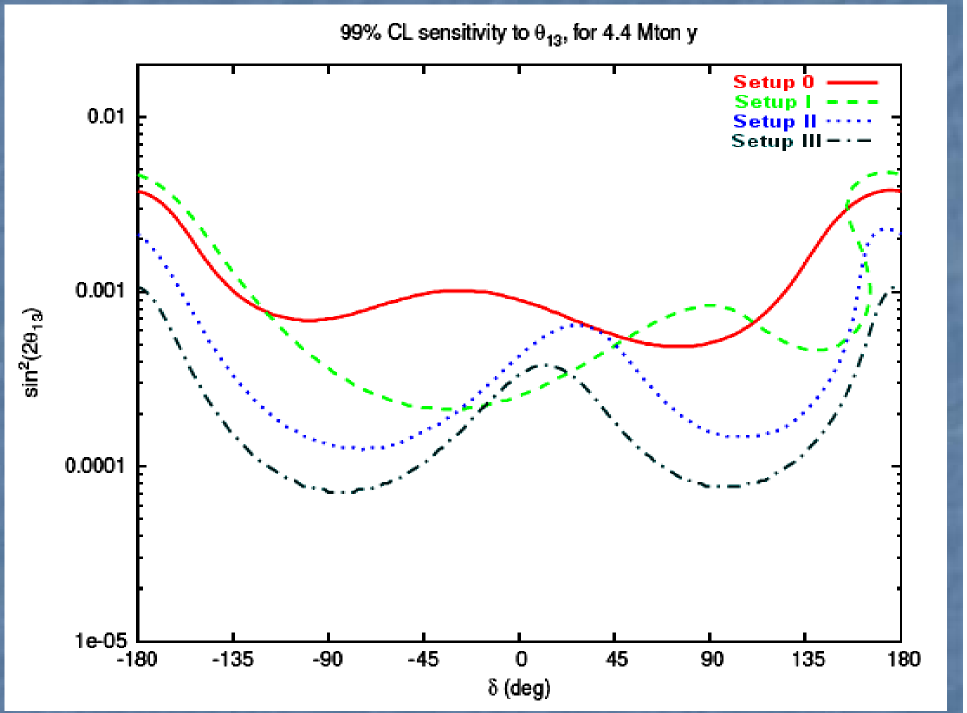
- The analogous background to NC π^0 production (in a superbeam) is NC $\pi^\pm$ production
  - Even at higher beam energies, this background appears manageable in a water detector
  - Higher beam energies allow a spectral analysis instead of counting



(Plots based on full detector simulation and reconstruction)

Optimizing the Betabeam

- Relax baseline and boost constraints to maximize θ_{13} and δ sensitivity
- Setup 0:
  - Original Frejus, low-γ
- Setup 1:
  - Optimal Frejus (γ=120)
- Setup 2:
  - Optimal SPS (L=350 km, γ=150)
- Setup 3:
  - Optimal betabeam (L=730 km, γ=350)

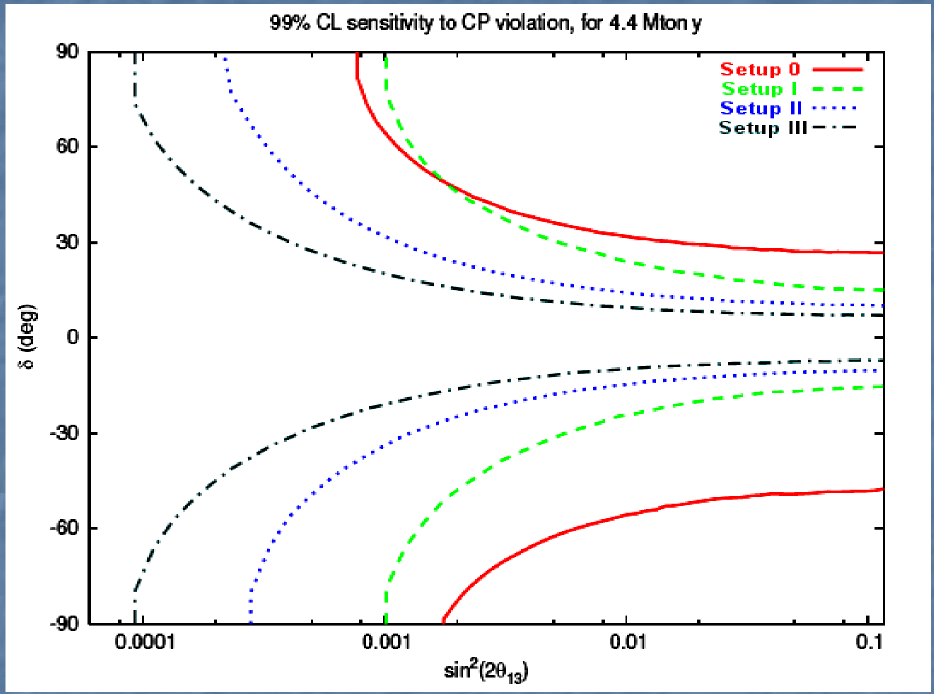


Region of the θ_{13} - δ plane where we can determine at 99% CL that $\theta_{13} \neq 0$

J. Burguet-Castell, D. Casper, E. Couce, J.J. Gomez-Cadenas, P. Hernandez, Nucl.Phys.B 725, 306-326 (2005) [hep-ph/0503021]

Optimized Betabeam CP Sensitivity

- For optimal betabeam
  - δ sensitivity ~ 10°
  - θ_{13} sensitivity ~ 10^{-4}
- Also sensitive to sgn(Δm^2_{23})
- With higher luminosity, sensitivity down to θ_{13} ~ (few) × 10^{-5}
- If T2K sees non-zero θ_{13}, measure δ
- If T2K sees no signal, extend θ_{13} sensitivity by another factor of 10
- Proton decay sensitivity ~10^{35} years ($e^+ \pi^0$)

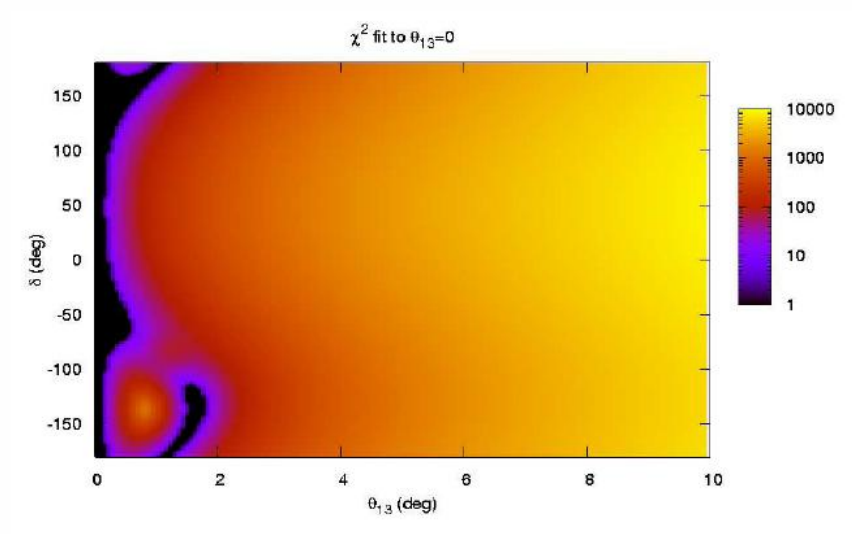


Region of the θ_{13} - δ plane where we can distinguish δ from δ=0 and δ=180 at 99% CL for any best-fit value of θ_{13} (i.e. that there is leptonic CP violation)

For follow-up comparisons (with T2HK) see E. Couce, et al, http://www-kuno.phys.sci.osaka-u.ac.jp/~yoshida/ISS/presentations/24Ple_couce.ppt

A Mono-energetic Beam?

- Extension of beta-beam concept
- Accelerate an ion that decays by electron capture
  - Two-body final state
  - Monoenergetic ν
- A challenge
  - Ions cannot be completely stripped
  - Finite survival time in partially ionized state
  - Must decay rapidly
  - Must have small enough Q value
- ^{150}Dysprosium
  - Short decay time (~7 minutes)
  - 1.4 MeV neutrino in rest frame
  - 0.1% β-decay



3σ θ_{13} reach of EC beam
(5 + 5 years, at two energies)

J. Bernabeu, J. Burguet-Castell, C. Espinoza, M. Lindroos, hep-ph/0505054 and hep-ph/0512278

βTeV?

- Our studies show that increasing the Lorentz boost optimizes the sensitivity of the beta-beam
- Two feasible sites for $\gamma \sim$ few hundred:
  - CERN-SPS (possibly with upgrade)
  - Tevatron
- Need Fermilab feasibility study to estimate realistic costs
  - Similar to neutrino factory study
- An opportunity for the <u>decisive</u> neutrino oscillation experiment!
  - Unfortunately, Fermilab is not interested…

"A very exciting neutrino program"

- The sensitivity of these Beta Beams to small values of θ_{13} appears to be comparable with the ultimate sensitivity of Superbeam experiments. Better performance might be achieved with higher energy Beta Beams, requiring the ions to be accelerated to at least TeV energies. This requires further study. This R&D is currently being pursued in Europe, where the proponents hope that a Beta Beam facility together with a Superbeam at CERN and a very massive water Cerenkov detector in the Frejus tunnel, would yield a very exciting neutrino program.

But…

- We recommend that progress on Beta Beam development be monitored, and that our U.S. colleagues cooperate fully with their EU counterparts in assessing how U.S. facilities might play a role in such a program. We note that there is no significant U.S. R&D effort on Beta Beams due to our limited R&D resources. Insofar as an intermediate energy solution is desirable, however, the Beta Beam idea is potentially of interest to the U.S. physics community.

Conclusion

- Reasonable to expect leptonic CP violation occurs
- The most challenging neutrino physics measurement ever attempted
- A betabeam at Fermilab or CERN could be the decisive, complementary follow-on to T2K

Invitation

- 8th International Workshop on Neutrino Factories, Superbeams and Betabeams (NUFACT06)
  - UC Irvine, August 24-30, 2006
  - First bulletin coming end of this month