Neutrino Factories: Physics Reach & Open Questions

1. What is known / not known
2. Beam properties
3. $\nu_e \rightarrow \nu_\mu$ and wrong-sign muons
4. The challenge: correlations & ambiguities
5. $\sin^2 2\theta_{13}$ sensitivity
6. CP Violation & the pattern of neutrino masses
7. What if LSND is confirmed ?
8. Non-Oscillation physics
9. Brief summary

Introduction

There is now compelling evidence that neutrinos have mass, & neutrinos of one flavor can transform themselves into neutrinos of a different flavor → neutrino oscillations. We already *think* we know the approximate values of the parameters that describe the oscillations:

1. There are at least three flavors participating in neutrino oscillations.
2. $\sin^2 2\theta_{23} \sim 1$ (≥ 0.9 at 90% CL)
3. $|\Delta m_{32}^2| \sim 2 \times 10^{-3}$ eV^2
4. $\Delta m_{21}^2 \sim 5 \times 10^{-5}$ eV^2 (if LMA confirmed)
5. $\sin^2 2\theta_{12} \sim 0.87$ (if LMA confirmed)
6. $\sin^2 2\theta_{13} < O(0.1)$

… 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 Δm_{32}^2 (pattern of neutrino masses) ?

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

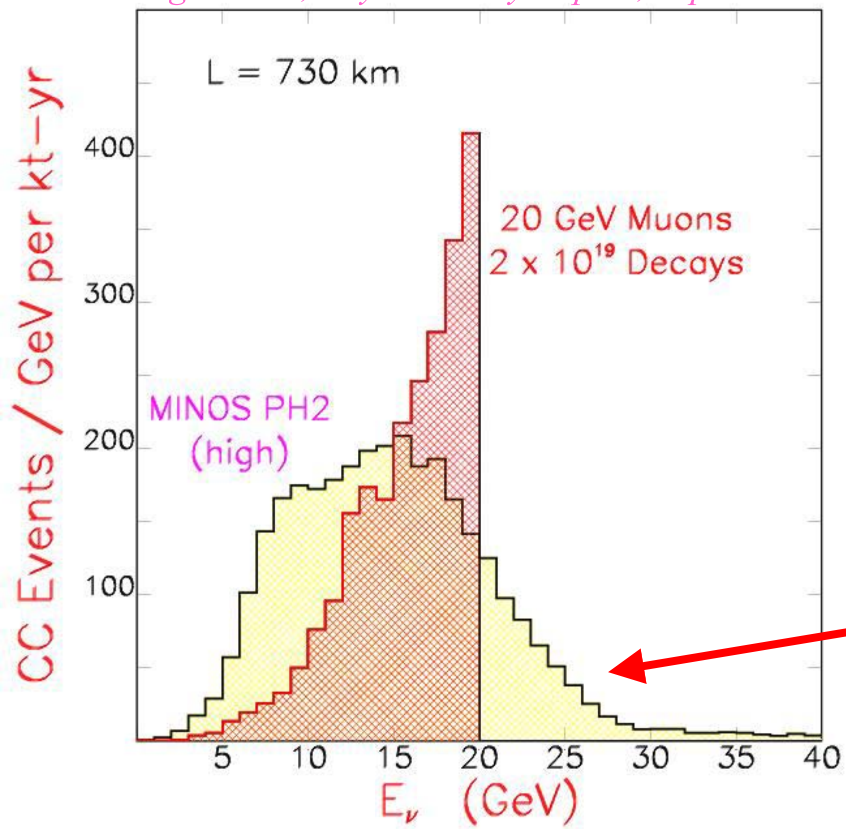
The answers to these questions may lead us towards an understanding of the origin of flavor … but getting the answers will require the right tools.

Beam Properties at a Neutrino Factory

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

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

C. Albright et al., Physics Study Report, hep-ex/0008064



Decay kinematics well known → minimal systematic uncertainties in spectrum, flux, & comparison of neutrino with antineutrino results.

ν_μ flux at 20 GeV NuFact with 2×10^{20} useful decays/yr is comparable to a Superbeam with 10 × the NuMI flux. At higher energies NuFact event rates ~E^3.

The neutrino spectrum has NO HIGH ENERGY TAIL. Note: neutral current back-grounds to $\nu_e \rightarrow \nu_\mu$ oscillations come from this tail which limits the sensitivity of Superbeams.

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.

$$\mu^+ \rightarrow e^+ \, \nu_e \, \bar{\nu}_\mu \quad \overset{CC}{\Rightarrow} \quad \mu^+$$

$$\nu_e \downarrow \nu_\mu \quad \underset{CC}{\Rightarrow} \quad \mu^-$$

$\nu_e \rightarrow \nu_\mu$ 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 $\Rightarrow$ $\nu_e \rightarrow \nu_\mu$ oscillations with amplitudes as small as $O(10^{-4})$ can be measured !

Signal Rates & Signal/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*

JHF-SK: Beam = 0.75 MW, M_{fid} = 22.5 kt, T = 5 yrs
JHF-HK: Beam = 4 MW, M_{fid} = 1000 kt, T = 8 yrs
Entry-Level NUFACT: Beam = 1×10^{19} decays/yr, M_{fid} = 100 kt, T = 5 yrs
High-Performance NUFACT: Beam = 2.6×10^{20} decays/yr, M_{fid} = 100 kt, T = 8 yrs

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

	Superbeams		Neutrino Factories	
	JHF-SK	JHF-HK	Entry Level	High Performance
Signal	140	13000	1500	65000
Background	23	2200	4.2	180
S/B	6		360	

Correlations & Ambiguities

Extracting precise & unambiguous values for all of the three-flavor oscillation parameters ($\Delta m_{32}{}^2$, $\Delta m_{21}{}^2$, $\sin^2 2\theta_{23}$, $\sin^2 2\theta_{13}$, $\sin^2 2\theta_{12}$, $\delta = 0$) will be challenging :

Look at expansion in powers of $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$ **and** $\sin\theta_{13}$; $\Delta = \Delta m^2_{31} L/4E$; $V = 0$

$$\begin{aligned} P(\nu_e \to \nu_\mu) \approx\ & \sin^2 2\theta_{13} \sin^2\theta_{23} \sin^2(\Delta) \\ & \pm \sin\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \sin^3(\Delta) \\ & + \cos\delta_{CP}\, \alpha \sin 2\theta_{12} \cos\theta_{13} \sin 2\theta_{13} \sin 2\theta_{23} \cos(\Delta) \sin^2(\Delta) \\ & + \alpha^2 \sin^2 2\theta_{12} \cos^2\theta_{23} \sin^2(\Delta) \end{aligned}$$

Correlations / Ambiguities → multiple solutions from fits to the data corresponding to :

1. $\theta_{23} \rightarrow \pi/2 - \theta_{23}$
2. $(\delta, \theta_{13}) \rightarrow (\delta', \theta'_{13})$
3. $\Delta m_{32}{}^2 \rightarrow - \Delta m_{32}{}^2$ (once matter effects are introduced)

Each of these introduces a two-fold degeneracy → we need redundancy and precision !

Oscillation Measurements at a Neutrino Factory

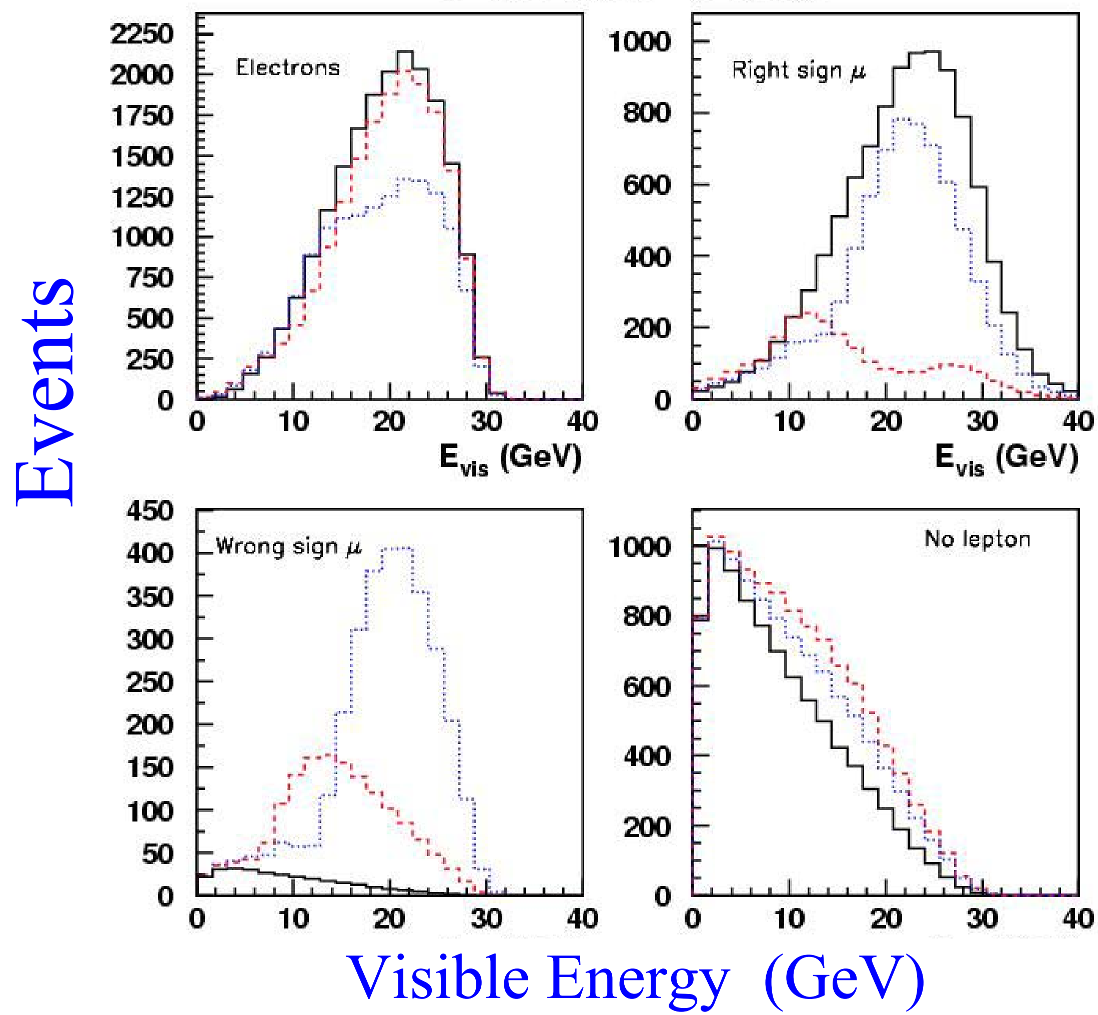
There is a wealth of information that can be used at a neutrino factory. Oscillation parameters can be extracted using events tagged by:

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)

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.



$\sin^2 2\theta_{13}$ Reach - 1

In a long baseline experiment the $\nu_e \leftrightarrow \nu_\mu$ oscillation probability is approximately proportional to the amplitude parameter $\sin^2 2\theta_{13}$:

$$P(\nu_e \leftrightarrow \nu_\mu) \approx \underbrace{\sin^2\theta_{23}}_{\sim 0.5} \sin^2 2\theta_{13} \; \sin^2(1.267\, \Delta m_{32}^2\, L / E)$$

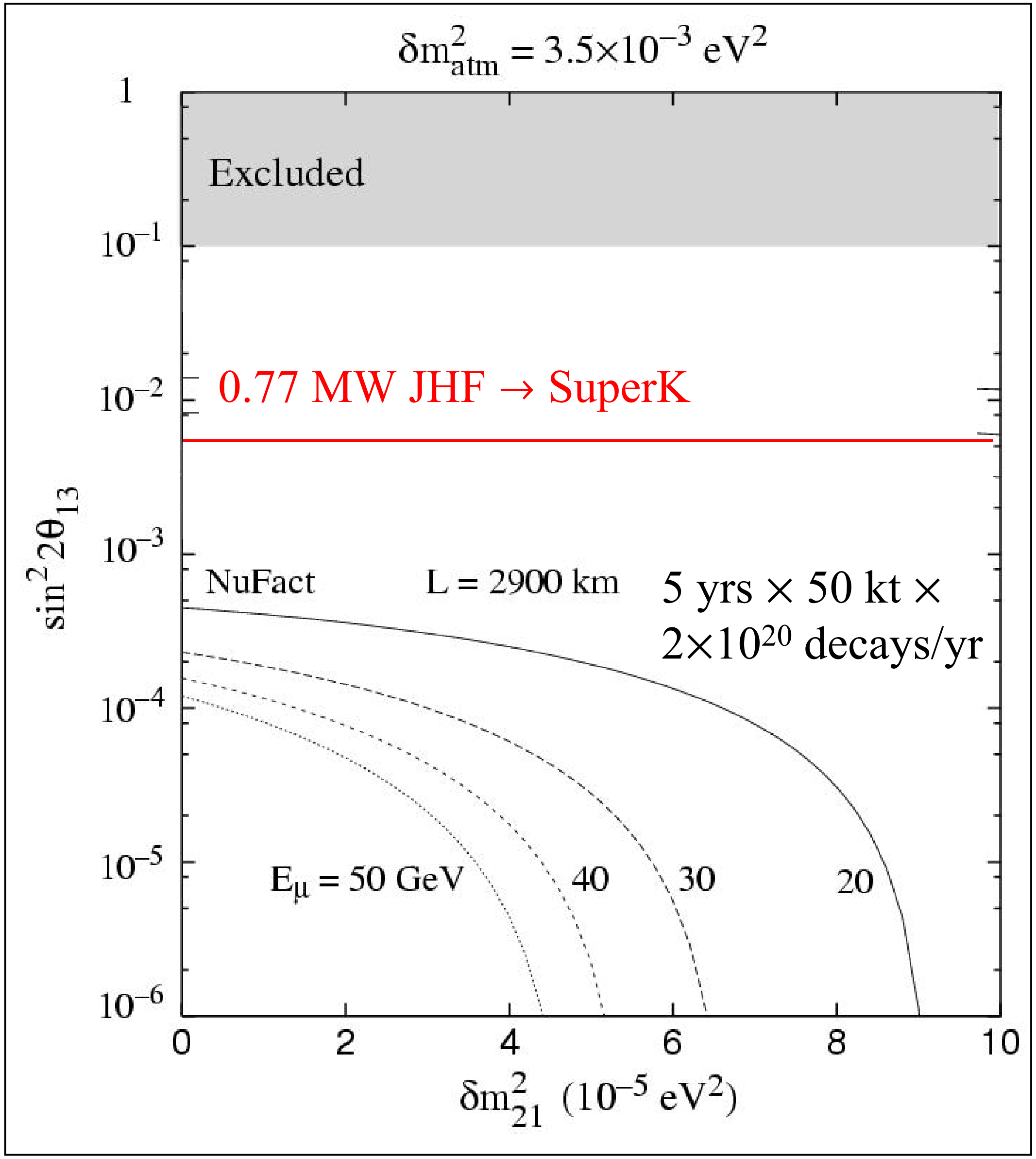
It is useful to define the $\sin^2 2\theta_{13}$ reach for a given experiment as the value of $\sin^2 2\theta_{13}$ for which a $\nu_e \leftrightarrow \nu_\mu$ signal would be observed 3σ above background. If the expected background is less than one event, we define the reach as the value of $\sin^2 2\theta_{13}$ that yields 10 signal events.

From the CHOOZ reactor ν_e disappearance search we know that at 90% CL: $\sin^2 2\theta_{13} < O(0.1)$

In the next 10 years Superbeam experiments are expected to achieve a $\sin^2 2\theta_{13}$ reach $\sim O(0.01)$

$Sin^2 2\theta_{13}$ Reach - 2

K. Whisnant (based on BGRW PRD 62, 073002)

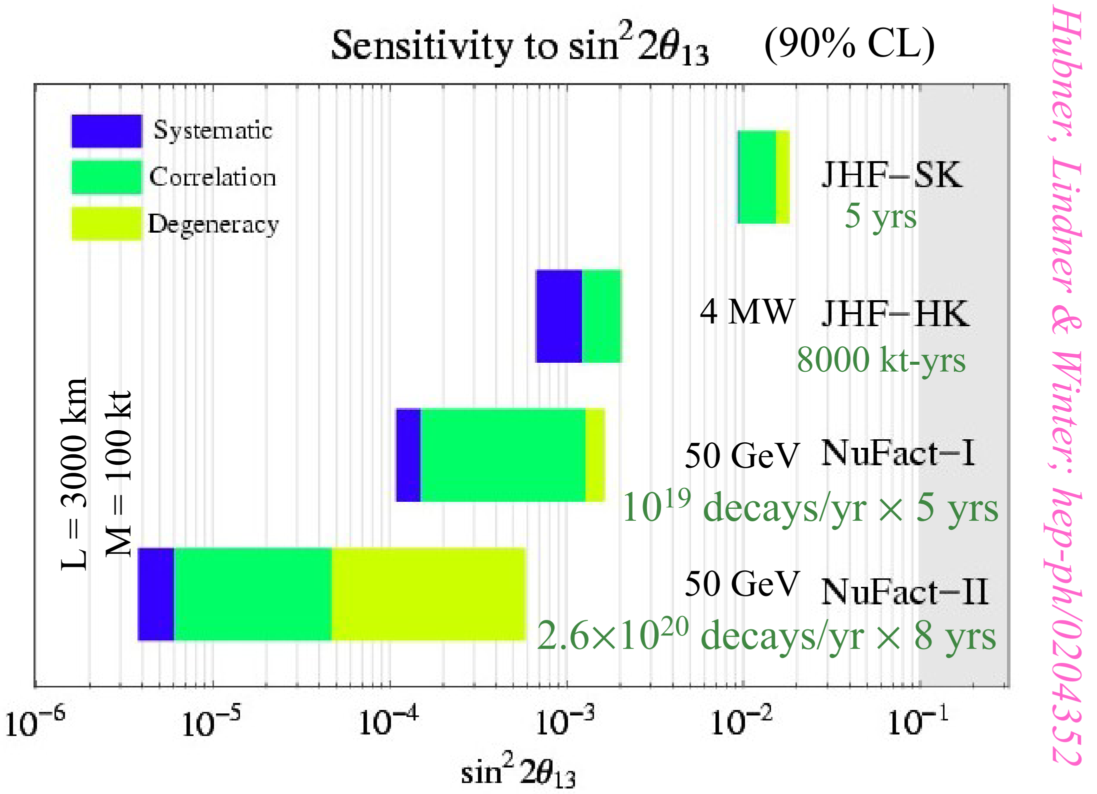


Neutrino Factory experiments are so sensitive that the signal rates depend upon the sub-leading $|\Delta m_{21}{}^2|$ scale.

At large $|\Delta m_{21}{}^2|$ and very small $\sin^2 2\theta_{13}$ the sub-leading scale begins to dominate !

Impact of correlations & ambiguities on the $\sin^2 2\theta_{13}$ sensitivity

The impact of ambiguities & correlations between the fitted parameter values can dramatically reduce the sensitivity of the most sensitive (NUFACT) experiments:



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

The ($\theta_{23} \rightarrow \pi/2 - \theta_{23}$) dominated degeneracy uncertainty can be lifted for the NUFACTs using 2 baselines

For a high performance NuFACT this improves the sensitivity by × 10 $\rightarrow$ $\sin^2 2\theta_{13} \sim 5\times 10^{-5}$ (90% CL)

Correlation uncertainties can be fought with multiple measurements & possibly combining Superbeam & NUFACT results ?

$\sin^2 2\theta_{13}$ "Predictions"

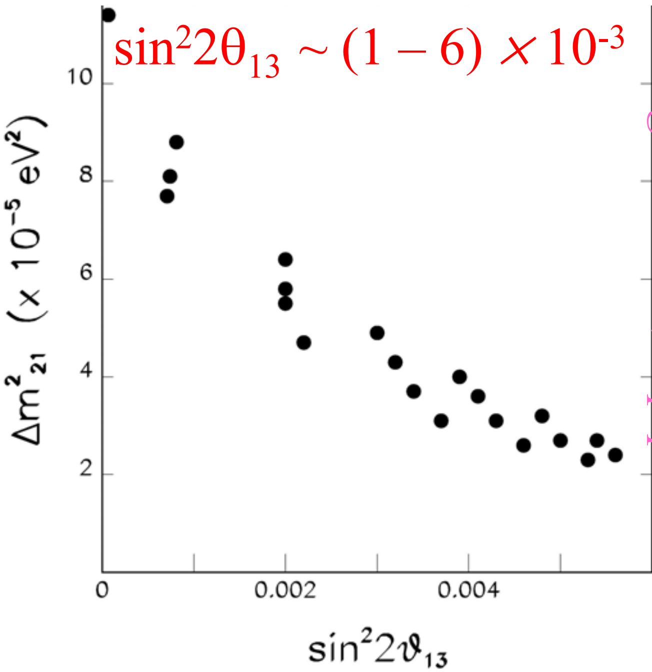
Lots of GUT models, but very few explicit predictions for parameter values that are consistent with the LMA solar neutrino solution

Prediction 1 : *Naturalness*

$\sin^2 2\theta_{13} > m_2 / m_3 \sim 0.01$ (will this suffer the same fate as small mixing angles ?)

Prediction 2: *SO(10) with $U(1) \times Z_2 \times Z_2$ flavor symmetry*

$\sin^2 2\theta_{13} \sim (1 - 6) \times 10^{-3}$



Albright & Geer, hep-ph/0108070

Prediction 3 : *Phenomenological Model for charged lepton mass matrix; Bi & Dai, hep-ph/0204317*

$\sin^2 2\theta_{13} \sim 10^{-4}$

Prediction 4 : *L_e-L_μ-L_τ symmetry broken by Planck-scale effects; Babu & Mohapatra, hep-ph/0201176*

$\sin^2 2\theta_{13} \sim 10^{-3}$

Conclude that predictions are all over the map → measurements/constraints can reject models ! Maybe if Superbeam experiments tell us that $\sin^2 2\theta_{13} < 10^{-2} - 10^{-3}$ we should keep on searching ?!

CP-Violation & the pattern on neutrino masses

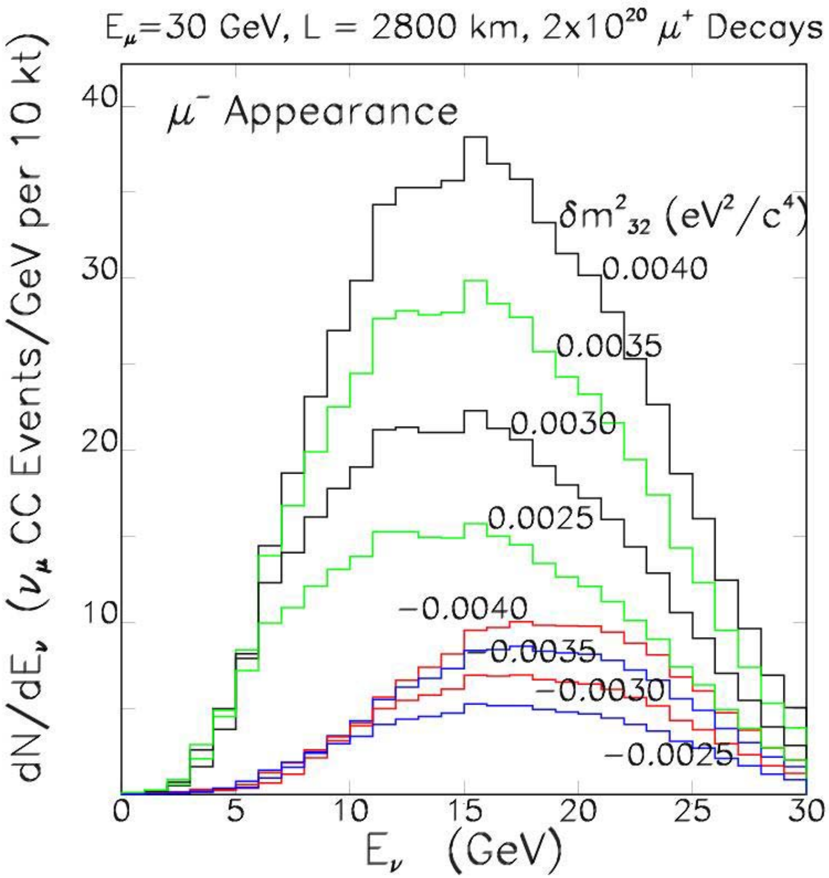
CP Violation requires contributions from both leading & sub-leading Δm^2 scales.

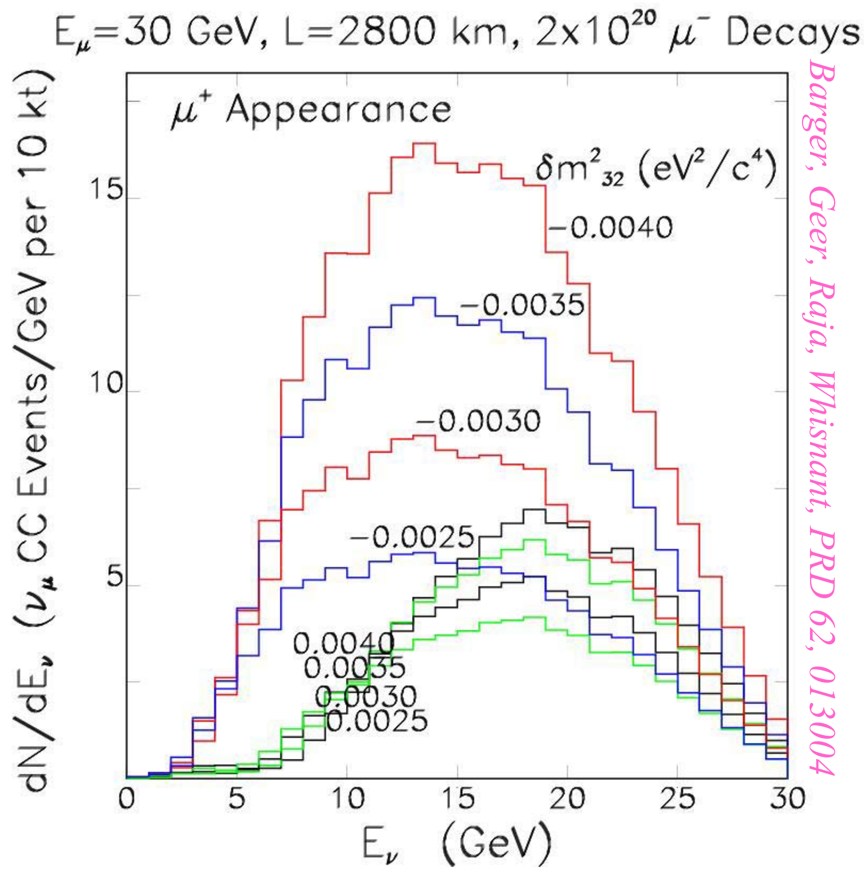
If the sub-leading scale ($\Delta m_{21}{}^2$) & the associated oscillation amplitude are large enough ($\rightarrow$ LMA) then CP violation might be observable in long-baseline experiments !

The signature for CP violation would be an inequality between $P(\nu_e \leftrightarrow \nu_\mu)$ and $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu)$ $\rightarrow$ 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 $P(\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu)$ and $P(\nu_e \leftrightarrow \nu_\mu)$ which depends upon the sign of $\Delta m_{32}{}^2$ $\rightarrow$ the pattern of neutrino masses.

The pattern on neutrino masses





Barger, Geer, Raja, Whisnant, PRD 62, 013004

μ^- Appearance

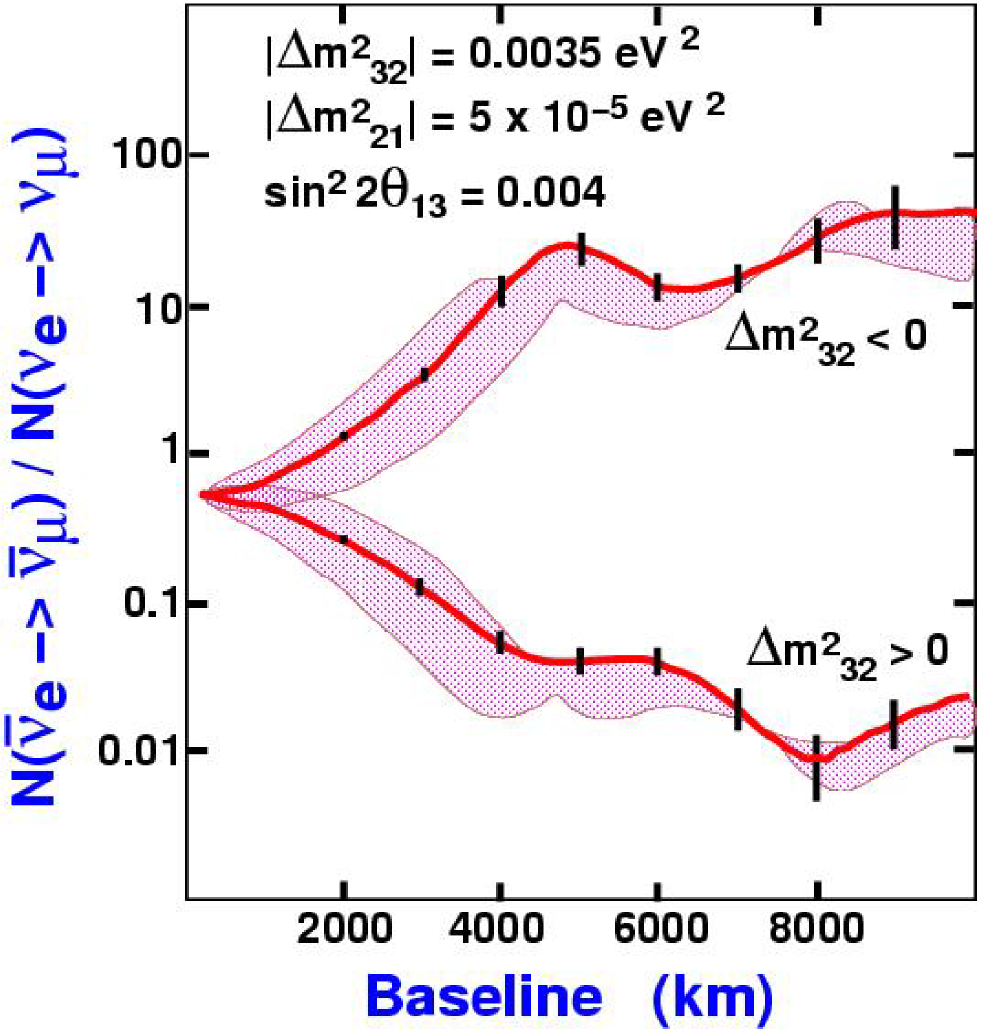
+tve Δm_{32}^2 gives larger rate & softer spectrum than –tve Δm_{32}^2

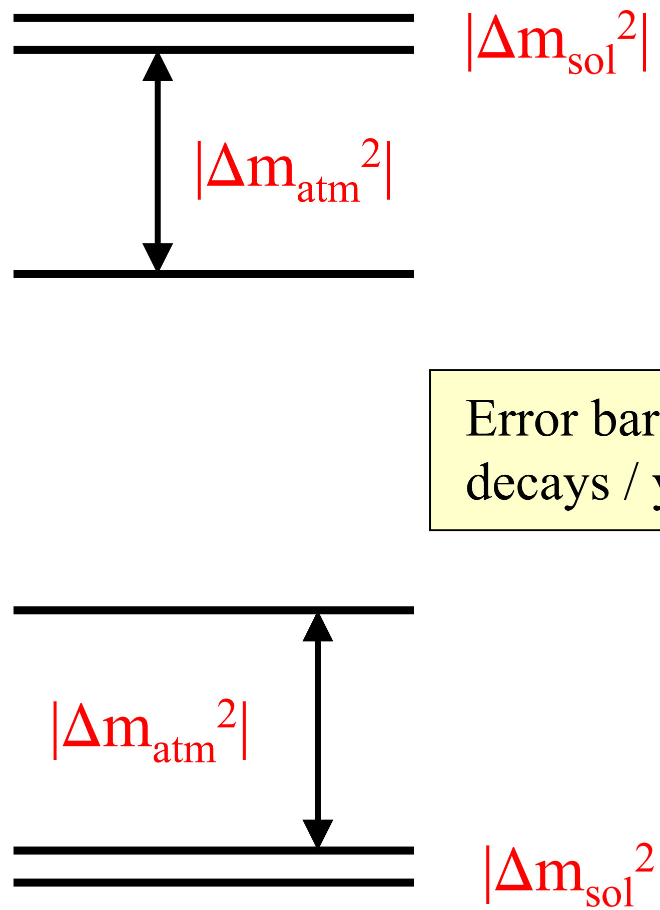
μ^+ Appearance

+tve Δm_{32}^2 gives smaller rate & harder spectrum than –tve Δm_{32}^2

CP-Violation & the pattern on neutrino masses

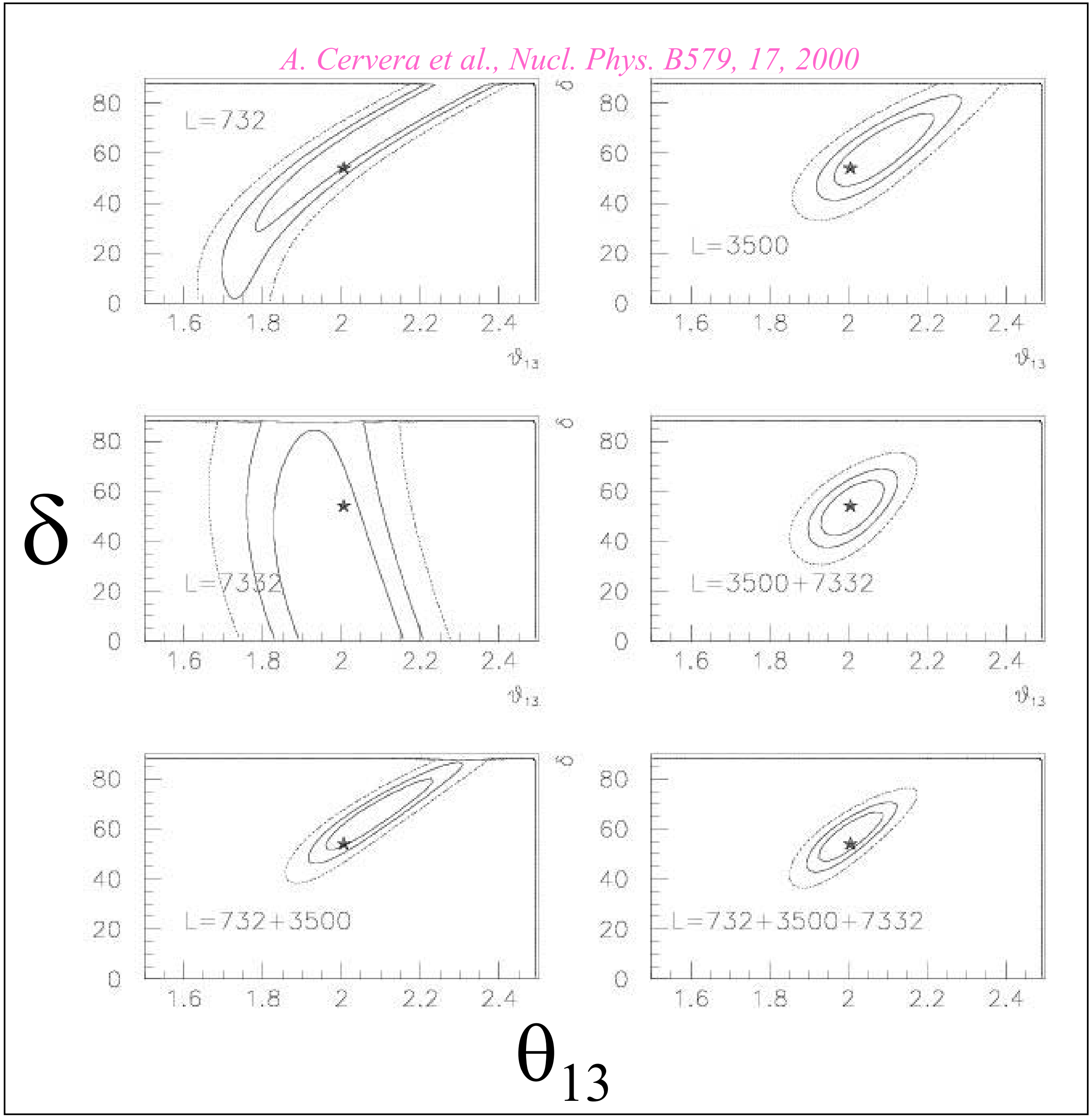
Barger, Geer, Raja, Whisnant, PRD 62, 073002
S. Geer, hep-ph/0008155





Error bars → 2×10^{20} decays / yr for 5 years

CP-Violation – Detailed Fitting

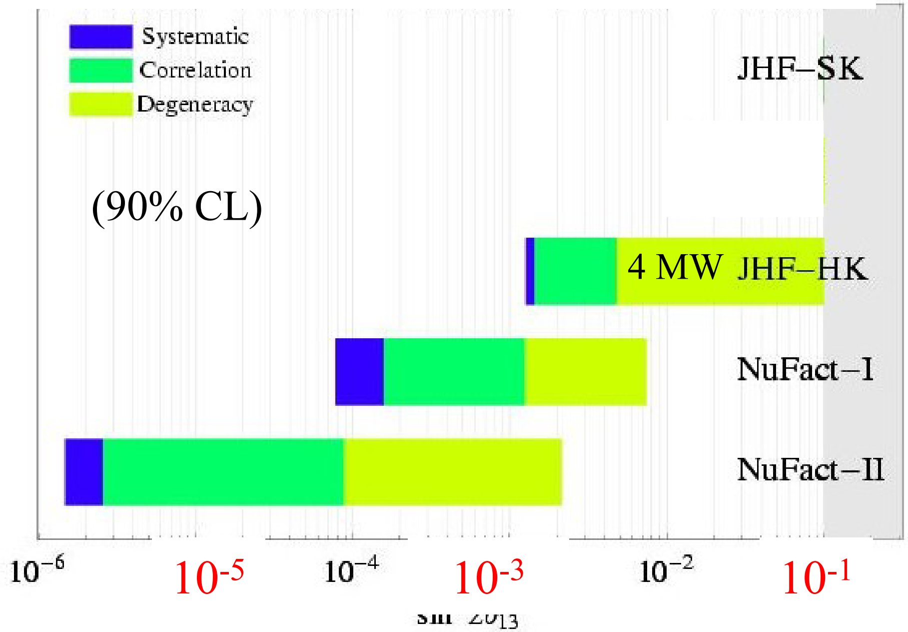


For a single baseline we expect a strong correlation between the extracted values of $\sin^2 2\theta_{13}$ and δ.

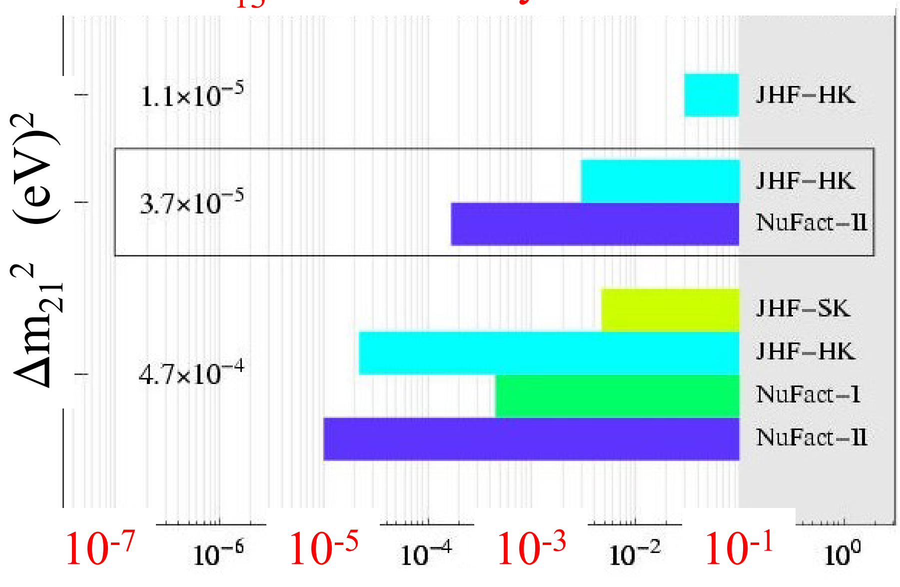
However, the correlation can reduced with two (or more) baselines → motivation for more than two straight sections.

Hubner, Lindner & Winter; hep-ph/0204352

Min. $\sin^2 2\theta_{13}$ for sensitivity to sign Δm_{32}^2



Min. $\sin^2 2\theta_{13}$ for sensitivity to maximal CPV



Sign of Δm_{32}^2

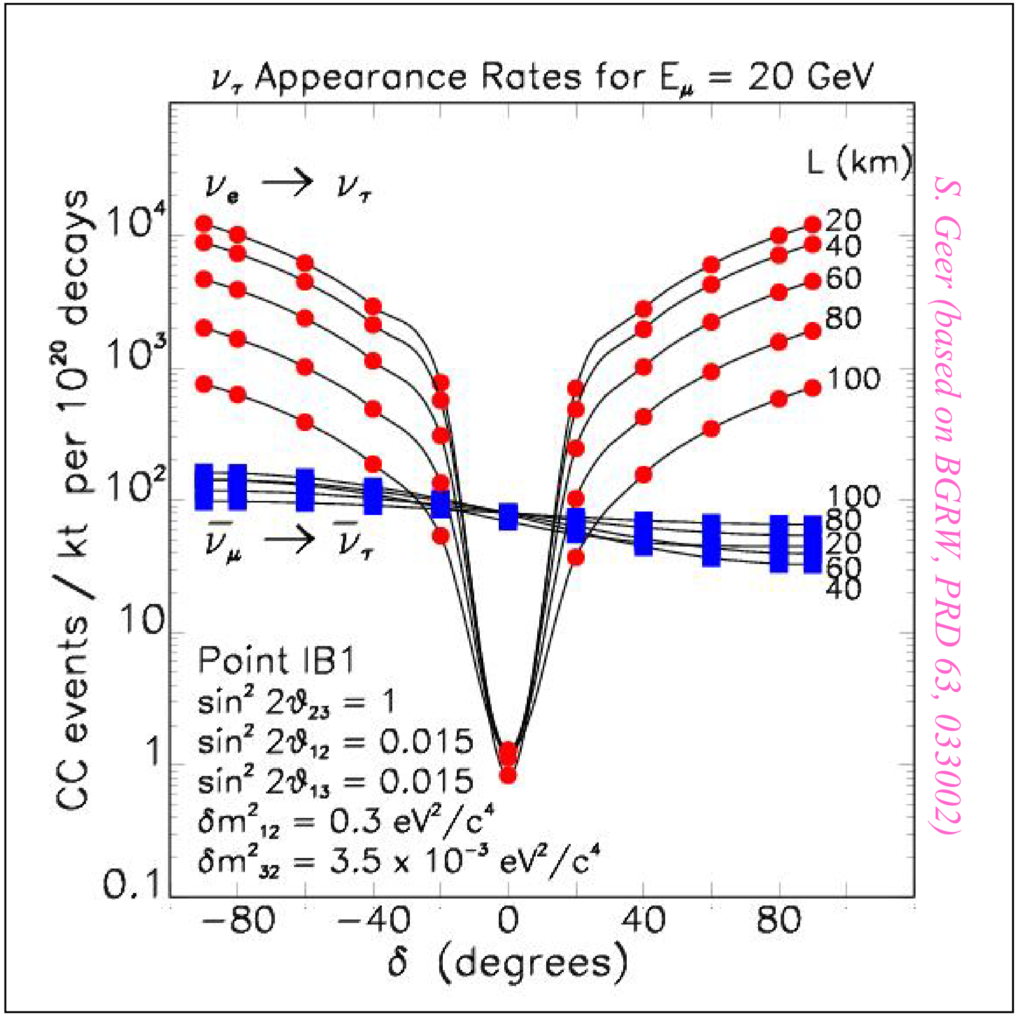
It is claimed that the degeneracies in (δ, sign of Δm_{32}^2)-space may completely destroy the capability of Superbeams to determine the sign of Δm_{32}^2. The degeneracy can be lifted at NuFacts (Superbeams ?) using 2 baselines … one long enough formatter effects to dominate (10-20 GeV neutrinos sitting at the oscillation max).

CP-Violation

For the central LMA values, NuFACT does an order of magnitude better than JHF-HK … but the result is very sensitive to Δm_{21}^2. Reducing the uncertainty on the matter density traversed (multiple baselines, other measurements ?) would improve further the NuFACT sensitivity.

If Oscillations at the LSND Scale are Confirmed

We must be prepared to respond to surprises. If the LSND result is confirmed, then perhaps CPT is violated, or perhaps there are light sterile neutrinos:



Searching for $\nu_e \rightarrow \nu_\tau$ becomes important $\rightarrow$ Neutrino Factory

CP Violation might be observed with a low intensity Neutrino Factory … perhaps as low as 10^{18} decays / year !

In the LSND-confirmed scenario it might even be possible to motivate a learning Neutrino Factory with a limited physics program delivering only 10^{17} decays / year ???

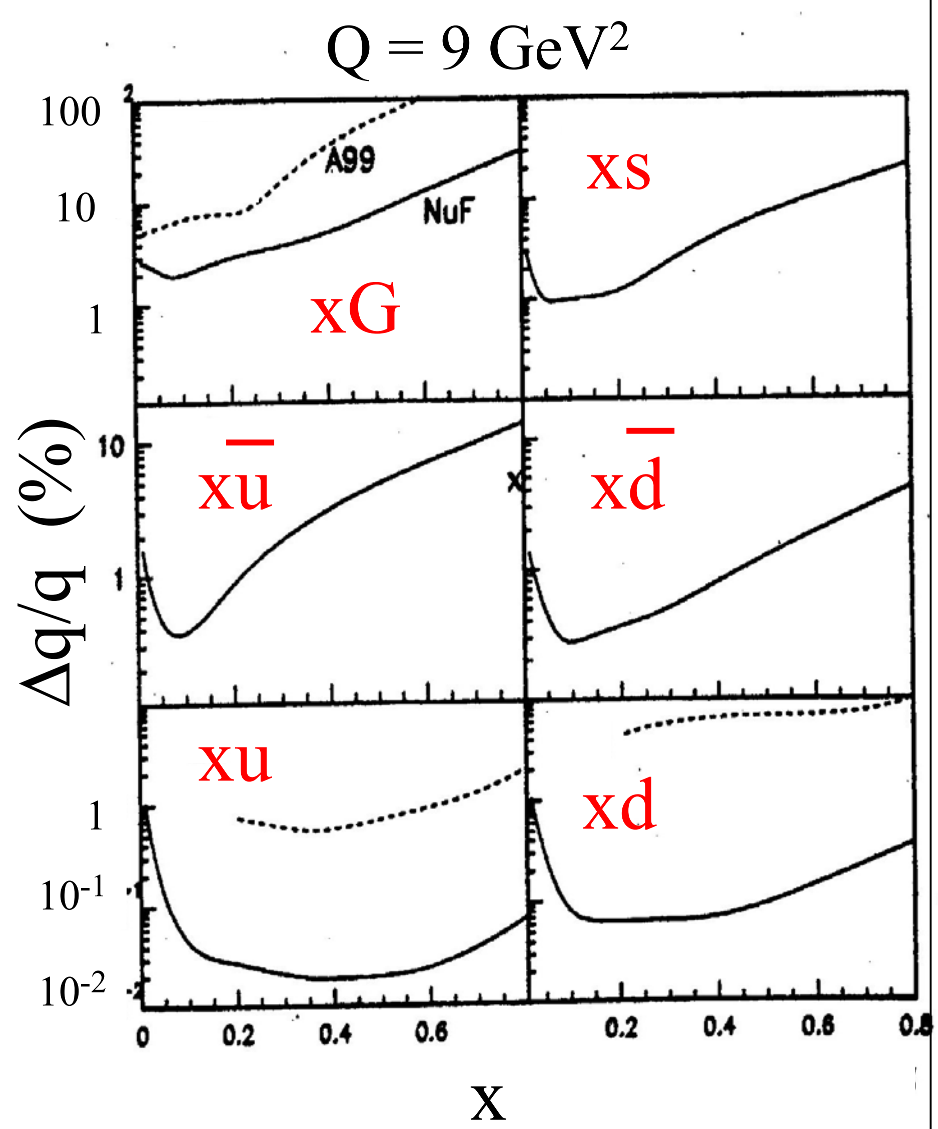
Non-Oscillation Physics Program

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

Broad program – many experiments

1. Precise σ(ν) measurements
2. Structure Fus (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. shaddowing) 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-$\bar{D}^0$ 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

One Example



Summary - 1

1. Neutrino oscillations are exciting. There is potential for unexpected discoveries. We might gain insight that helps us understand the physics of flavor. Furthermore, nature might have arranged things so that we have a fighting chance to observe CP violation in the lepton sector !

2. Unambiguously determining all the oscillation parameters will be a challenge. We must chose the right set of experiments that together will enable us to overcome parameter correlations & degenerate solutions extracted from our global fits.

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

Summary - 2

5. Neutrino Factories offer unprecedented sensitivity. Recent studies suggest that, provided there are experiments at two well chosen baselines, Neutrino Factories may be able to probe $\sin^2 2\theta_{13}$ down to $O(10^{-5})$ and be sensitive to maximal CP violation for $\sin^2 2\theta_{13} > O(10^{-4})$. These estimates are sensitive to Δm_{21}^2, and should be revisited once we have results from KamLAND.

6. We should be prepared for surprises. If MiniBooNE confirms LSND there might be a case for a first Neutrino Factory delivering only 10^{18} decays / year (?) In fact any big surprise might motivate a low intensity Neutrino Factory .

7. Finally, we should not forget all the great non-oscillation experiments that could exploit the fantastic beam fluxes at the near site.