Neutrino Factory Physics Update

Stephen Parke - Fermilab

MUTAC 4/25-26/2005

The ν Standard Model

- 3 light (m_i <1 eV) Majorana Neutrinos: $\Rightarrow$ only 2 δm^2

  $|\delta m^2_{atm}| \sim 2.5 \times 10^{-3}$ eV^2 and $\delta m^2_{solar} \sim 8.0 \times 10^{-5}$ eV^2

- Only Active flavors (no steriles):
  $e, \ \mu, \ \tau$

- Unitary Mixing Matrix:
  3 angles ($\theta_{12}, \ \theta_{23}, \ \theta_{13}$), 1 Dirac phase ($\delta$), 2 Majorana phases ($\alpha_2, \alpha_3$)

  $|\nu_\alpha\rangle_{flavor} = U_{\alpha i}|\nu_i\rangle_{mass}.$

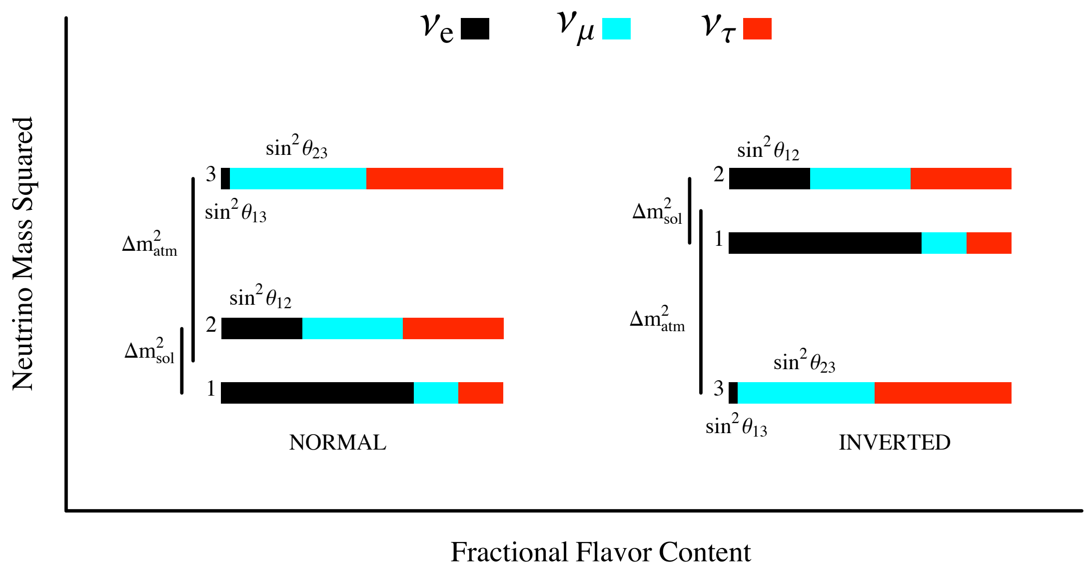
Atmos. L/E $\mu \to \tau$ Atmos. L/E $\mu \leftrightarrow e$ Solar L/E $e \to \mu, \tau$ $\beta\beta 0\nu$ decay

500 km/GeV   15 km/MeV

$$\begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha} & \\ & & e^{i\beta} \end{pmatrix}$$

In oscillation phenomena,

the phases $\alpha_2, \ \alpha_3$ are unobservable ($U_{\alpha i}U^*_{\beta i}$)
and also the value of m_{lite} is irrelevant (δm^2)



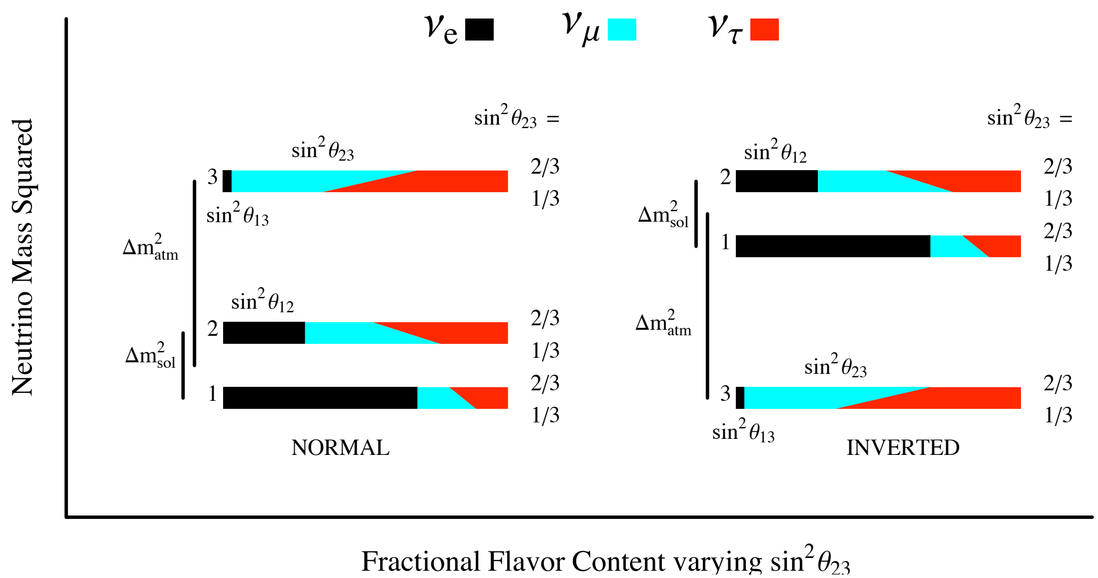
(12) Parameters: SNO, KamLAND, SK

$$\delta m^2_{21} = +8.0 \pm 0.8 \times 10^{-5}\ eV^2$$

$$0.25 < \sin^2\theta_{12} < 0.37$$

$\sin^2\theta_{12} \geq \frac{1}{2}$ excluded at $> 5\ \sigma$!

sign of δm^2_{21} determined at this C.L.



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Mena + SP hep-ph/0312131

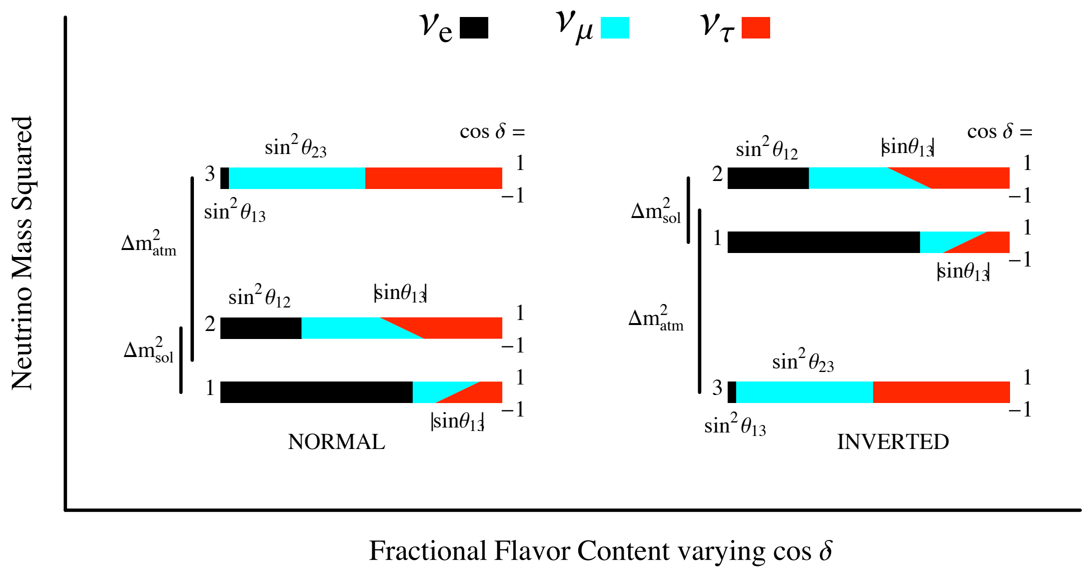
(23) Parameters: SK, K2K

$$|\delta m^2_{32}| = 1.5 - 3.4 \times 10^{-3}\ eV^2$$

$$0.36 < \sin^2\theta_{23} < 0.64$$

(obtained from $\sin^2 2\theta_{23} > 0.91$)

Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ not as well known!
Sign of δm^2_{32} Unknown !!!



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(13) Parameters: Chooz, SK, K2K

$$\sin^2\theta_{13} < 0.03 - 0.05$$

limit $|\delta m^2_{32}|$ dependent

$$0 \leq \delta_{CP} < 2\pi$$

Unknown!

Beyond the ν Standard Model

- Sterile Neutrinos, (LSND/miniBOONE) e.g. 3+n models
- Dirac Neutrinos
- CP and/or T violation requiring more than one phase
- CPT violation
- Exotic interactions:
  magnetic moments, addition matter interactions, . . .
- $\cdots$

The UNEXPECTED is the REAL reason !!!

(remember $\star$NDKE)

Within ν Standard Model

The Big Questions that can be Addressed in Oscillation Phenomena

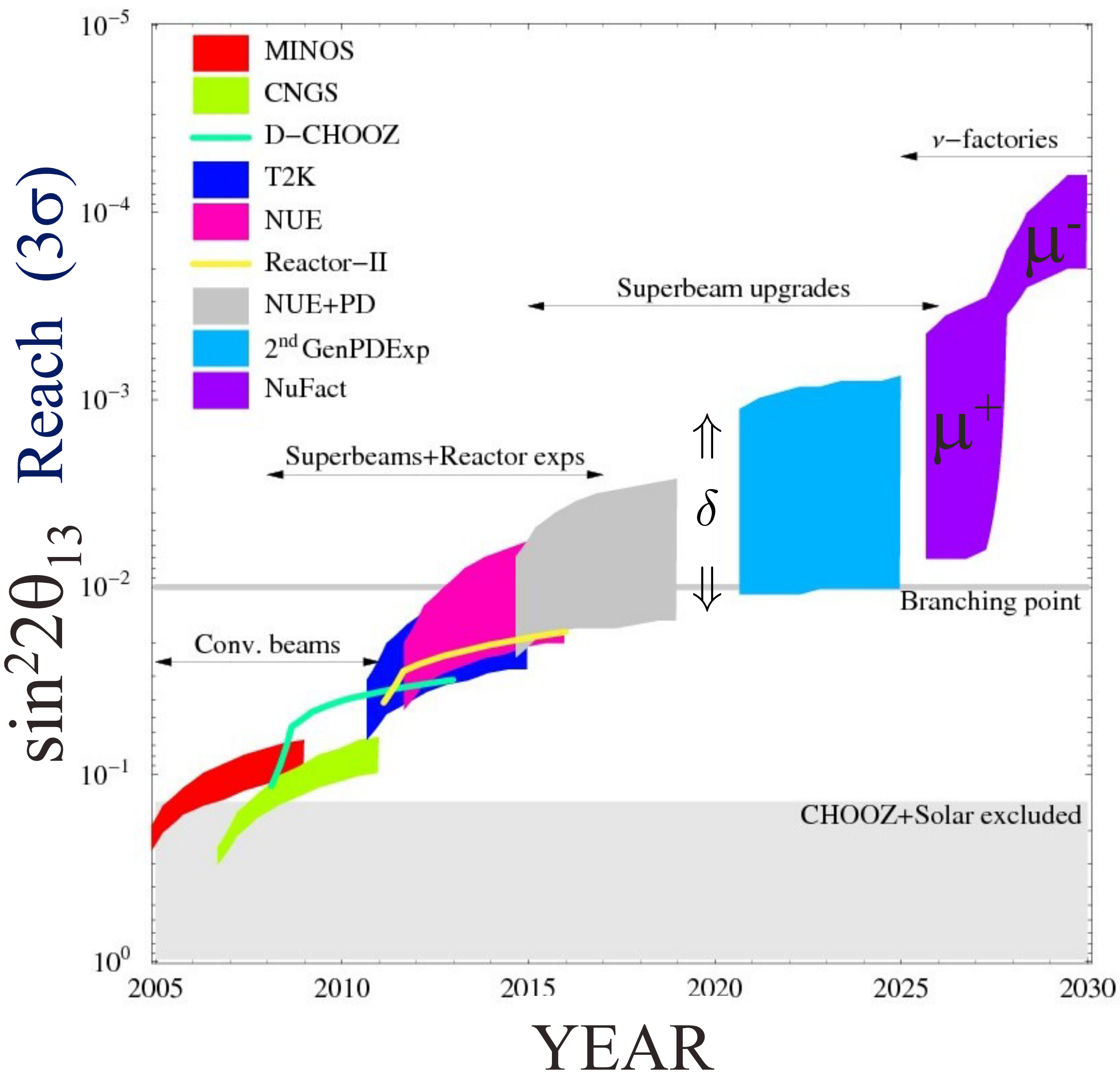
- ν_e fraction of ν_3: – size of $\sin^2\theta_{13}$
- mass hierarchy: – sign of δm^2_{31}
- CP violation: – $\sin\delta \neq 0$

Other Questions

- $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$
- sign of $\cos\delta = \pm\sqrt{1-\sin^2\delta}$

ν_e fraction of ν_3: – size of $\sin^2\theta_{13}$

- Reactor $\bar{\nu}_e$ Disappearance at few kilometers ($< 10\%$)
  Chooz, Pale Verde, Double-Chooz, ...
- Long Baseline $\nu_\mu \rightarrow \nu_e$ Appearance
  using conventional neutrino beams
  K2K, MINOS, T2K, NOνA, ...
- (Very) Long Baseline $\nu_e \rightarrow \nu_\mu$ Appearance
  using Neutrino Factory beams.



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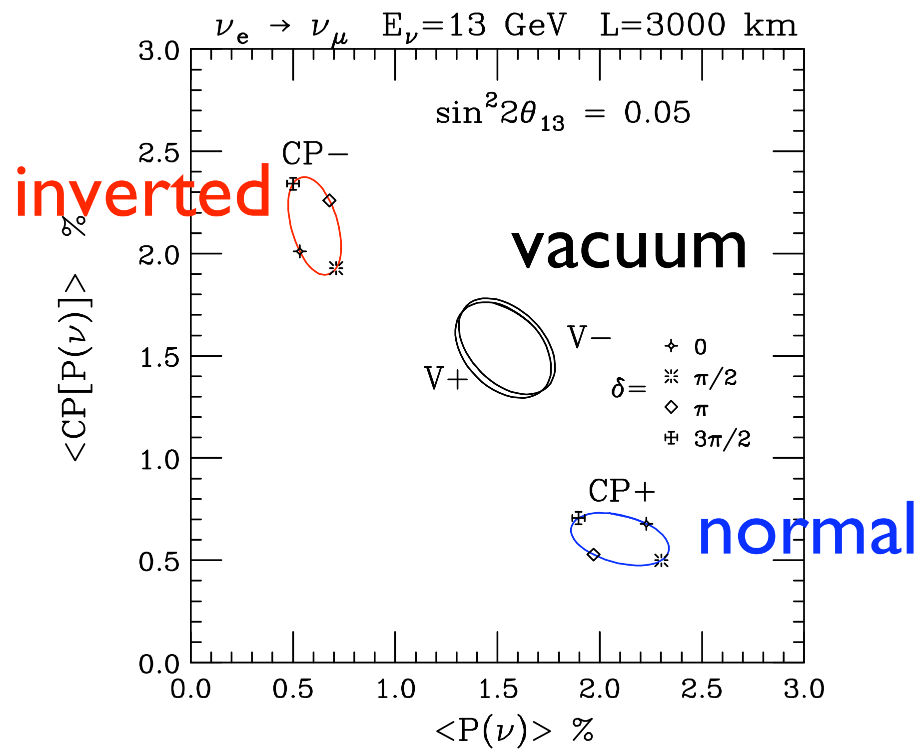
Mass Hierarchy: – sign of δm^2_{31}

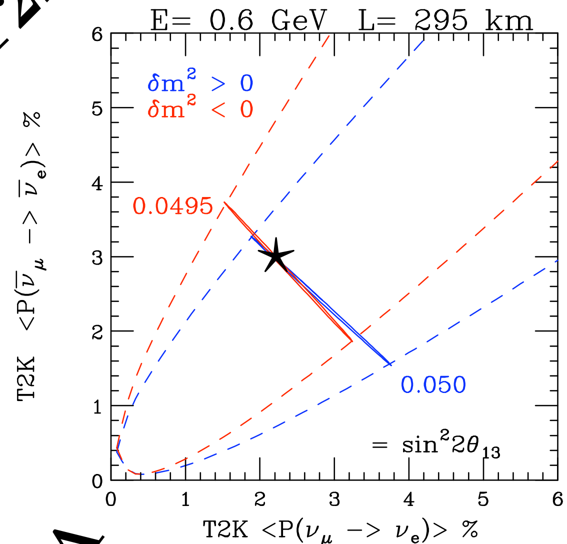
Matter Effects

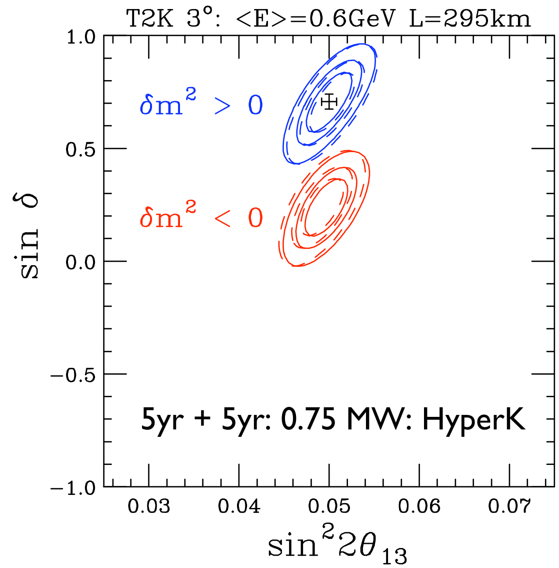
$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$



$\nu_e \leftrightarrow \nu_\mu$

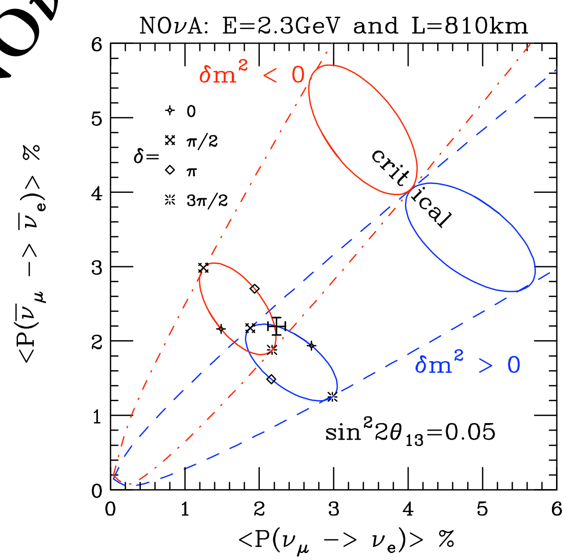
T2K

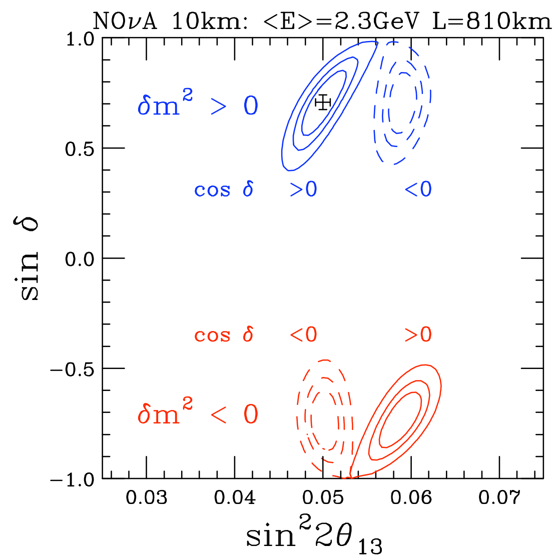




$$\langle \sin\delta\rangle_+ - \langle \sin\delta\rangle_- \;=\; \mathbf{0.47}\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

NOνA

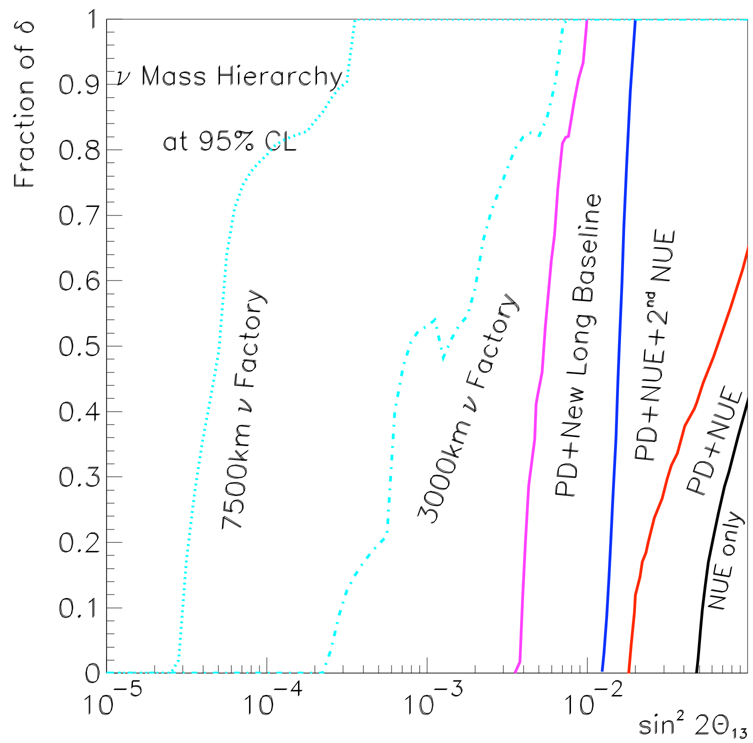




$$\langle \sin\delta\rangle_+ - \langle \sin\delta\rangle_- \;=\; \mathbf{1.41}\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

5yr+5yr: 2 MW: 50kton hi-eff.

MASS HIERARCHY



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Leptonic CP and T Violation in Neutrino Oscillations

CP

$\nu_\mu \leftrightarrow \nu_e \quad \Longleftrightarrow \quad \bar{\nu}_\mu \leftrightarrow \bar{\nu}_e$ Super-Beams

T $\Updownarrow$ $\Updownarrow$ T

$\nu_e \leftrightarrow \nu_\mu \quad \Longleftrightarrow \quad \bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$ Nu-Factory

CP

Leptogenesis

CP Violation and Leptogenesis

- For most Neutrino Mass Models there is a relationship between the Dirac CP phase δ and Majorana CP phases $\alpha_2,\ \alpha_3$.
- At a minimum they are all zero or all non-zero.
- $\alpha_2,\ \alpha_3$ are responsible for Leptogenesis in the early universe by allowing for different decay rates of Neutral Heavy Leptons:

$$N \rightarrow l^+\phi^- \text{ and } N \rightarrow l^-\phi^+$$

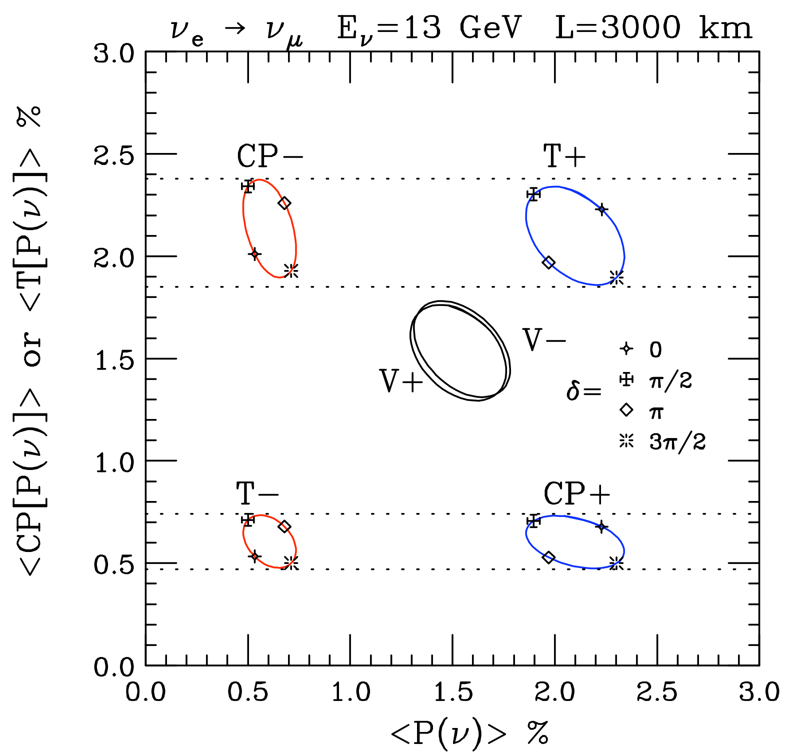
- $B = \frac{1}{2}(B-L) + \frac{1}{2}(B+L)$, however $(B+L)$ violated.
- Hence the Dirac CP violating phase, δ, is a handle on Leptogenesis and hence Baryogenesis.

Fukugita and Yanagida, Phys. Lett. B174, 45 (1986)
Frampton, Glashow and Yanagida – hep-ph/0208157
Endoh, Kaneko, Kang, Morozumi – hep-ph/0209098

CP violation: $-\sin\delta \neq 0$

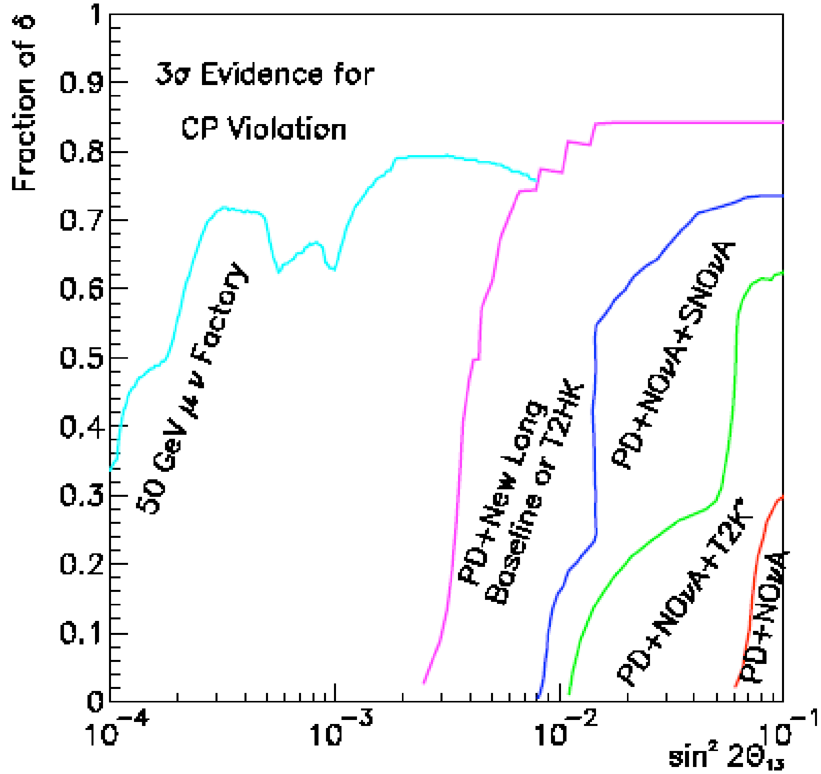
$\nu_\mu \leftrightarrow \nu_e$

$\bar{\nu}_e \leftrightarrow \bar{\nu}_\mu$



$\nu_e \leftrightarrow \nu_\mu$

CP Violation



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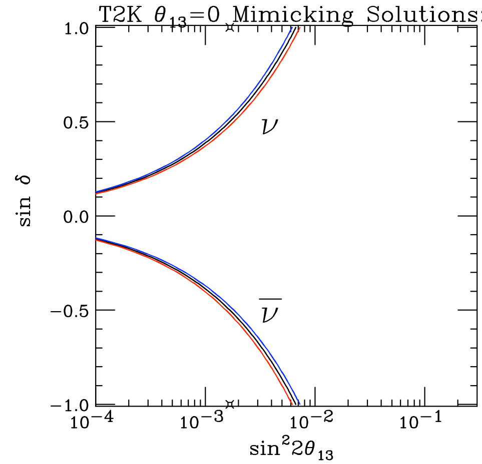
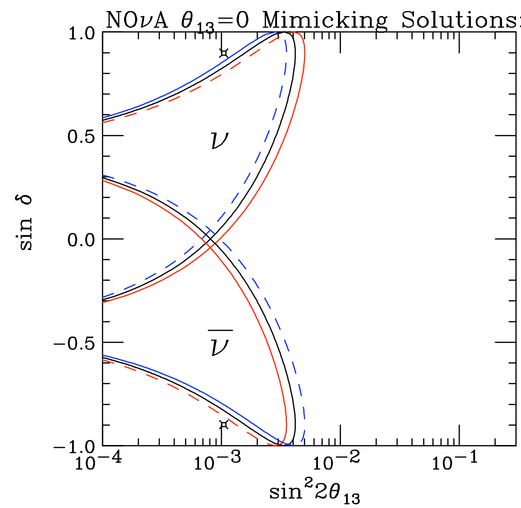
Why is $\nu_\mu \rightarrow \nu_e$ so hard for $\sin^2 2\theta_{13} < 0.01$

Besides event rates
and backgrounds there are
Zero Mimicking Solutions:
(loose info from one channel)





$$P_{\mu\rightarrow e} \approx P_{atm} + 2\sqrt{P_{atm}P_{sol}}\cos(\Delta_{32} \pm \delta) + P_{sol}$$

where $P_{atm} = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$

and $P_{sol} = \cos^2\theta_{13}\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2\Delta_{21}$

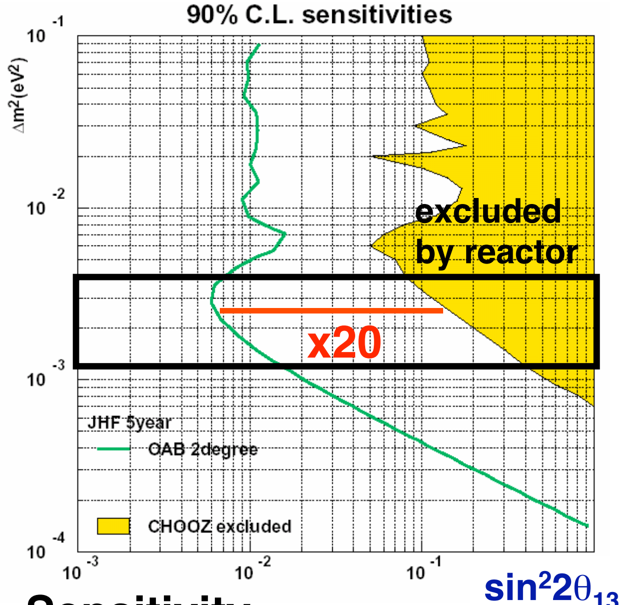
$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E}$$

$$\sqrt{P_{atm}} = -2\sqrt{P_{sol}}\cos(\Delta_{32} \pm \delta)$$

Sensitivity to θ_{13}

T2K:

Search for ν_e appearance



Sensitivity

$\sin^2 2\theta_{13} > 0.006$ (90%)

5 yrs 0.75MW with SK

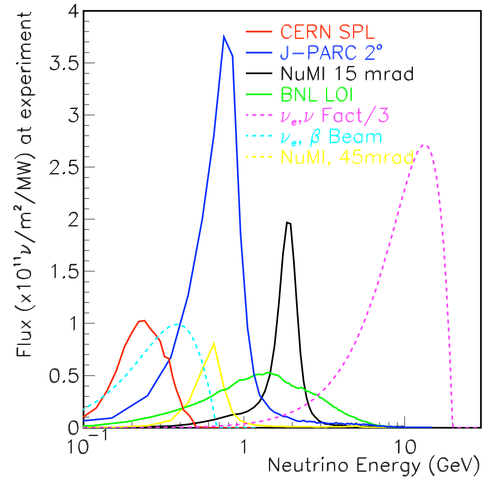
assumes $\delta = 0$

Question: What exposure is required to reach this sensitivity if $\delta = \pm\frac{\pi}{2}$?

Why is $\nu_e \to \nu_\mu$ at a ν Factory Easy?

- Neutrinos/MW proton power *cf* conventional beams $\propto (E_\mu/15)^3$
- No Intrinsic ν_μ in the beam, only $\bar{\nu}_\mu$'s
- Charge of Muon easier to measure than e/π^0 separation
- Detector Technology straightforward (see MINOS)
- Backgrounds at $\leq 10^{-4}$ level, not few $\times 10^{-3}$

Comparison of Fluxes
per MegaWatt
at each experiment:



Note ν Factory flux
divided by 3
to fit on graph!

- Higher E means larger cross section, more events.
- Higher E allows larger L for same E/L, bigger matter effects (amplifies P_{atm}).

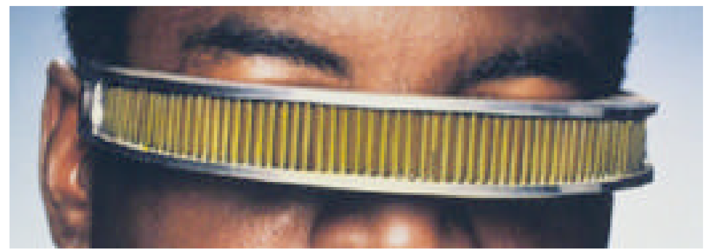
Conclusions

- For $0.04 < \sin^2 2\theta_{13} < 0.1$ (large)
  Neutrino Factory NEEDED to measure δ_{CP},
  the parameter controlling CP violation, with any precision.
- For $0.01 < \sin^2 2\theta_{13} < 0.04$ (medium)
  Neutrino Factory probably NEEDED to determine Hierarchy
  (plus CP violation).
- If $\sin^2 2\theta_{13} < 0.01$ (small)
  Neutrino Factory NEEDED for observation or best limits
  (as well as hierarchy and CP violation)
- but don't forget the UNEXPECTED!!!
  (Neutrino Factory is a big step in event rates.)

only competition .....

Star Trek: The Next Generation

Geordi La Forge: in "The Enemy"

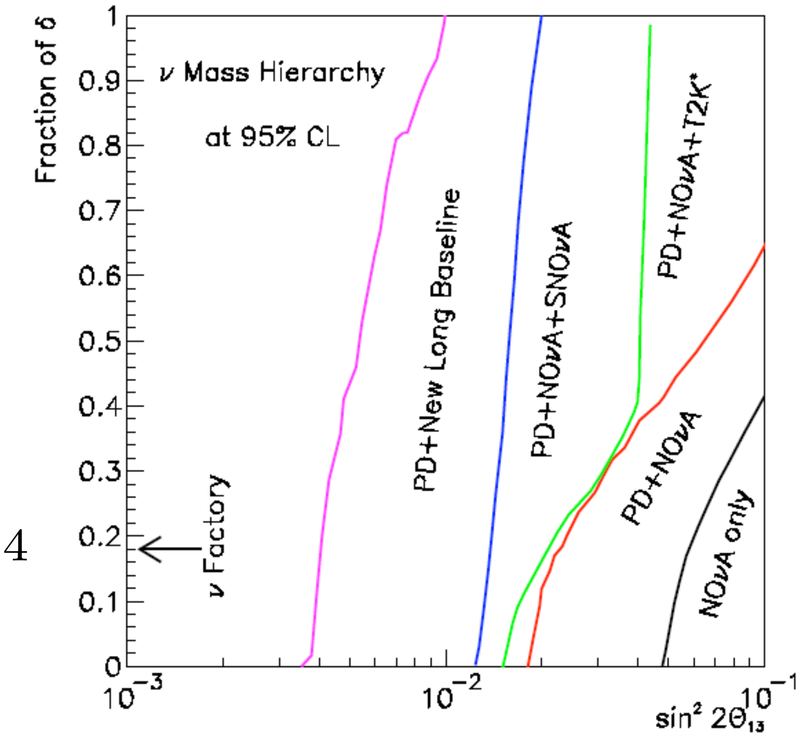


The visor "sees" Neutrinos!!!

... but this requires special New Physics !!!

Mass Hierarchy

10^{-4}



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