HQ&L 2004

Heavy Quarks and Leptons

University of Puerto Rico - Mayagüez Campus

San Juan, Puerto Rico ▸ June 1 - June 5, 2004

Neutrino Oscillation Phenomenology

HQ&L 2004

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Fermilab
June1, 2004

- Solar (1-2) Sector
- Atmospheric (2-3) Sector
- (1-3) Sector
- CP Violation & Mass Hierarchy
- Conclusions

Mixing Overview:

flavor mass

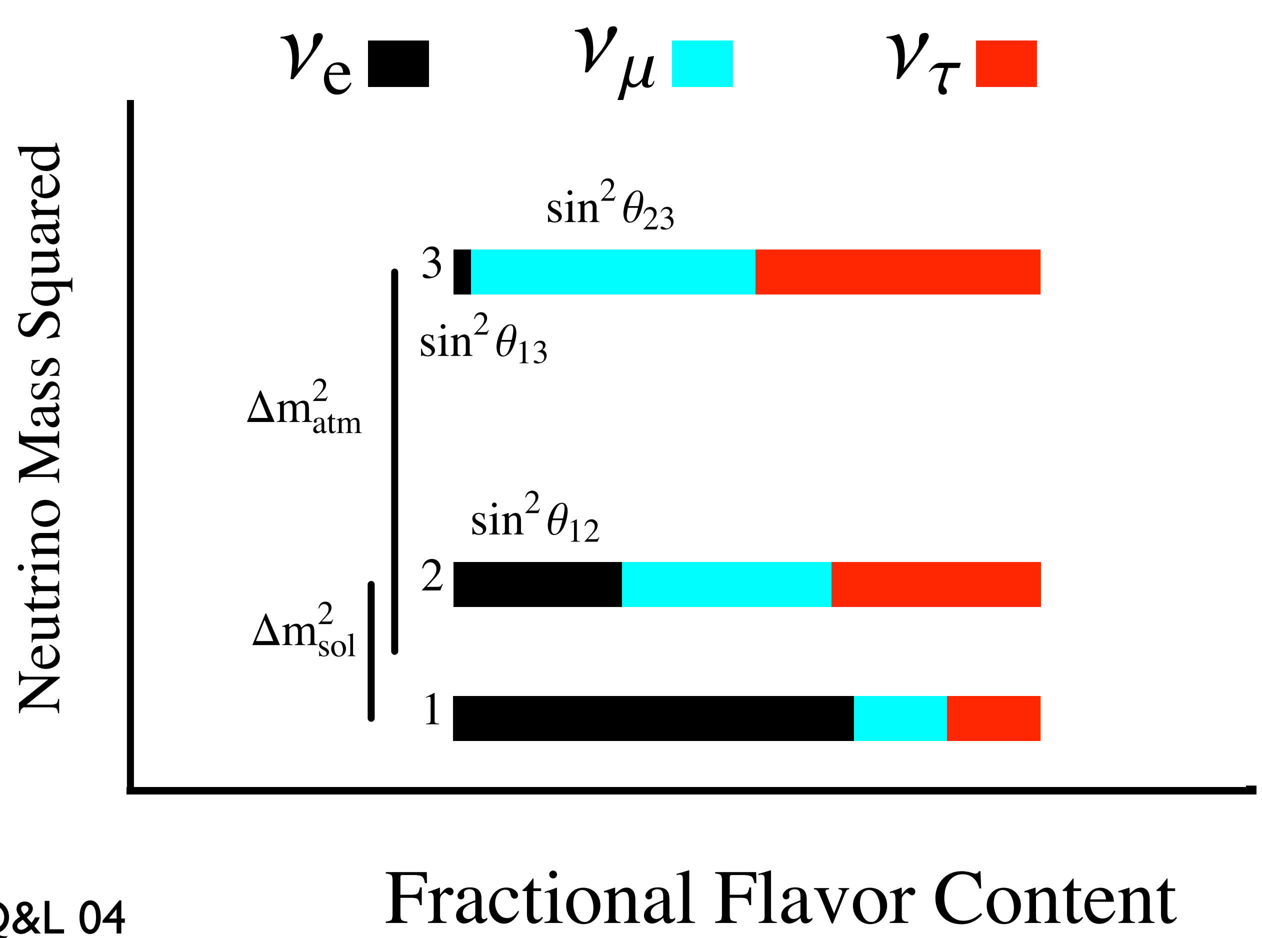
$$|\nu_\alpha\rangle = U_{\alpha i}|\nu_i\rangle.$$

(using $s_{ij} = \sin\theta_{ij}$ and $c_{ij} = \cos\theta_{ij}$)

$$U_{\alpha i} = \begin{pmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\alpha_2} & \\ & & e^{i\alpha_3} \end{pmatrix}$$

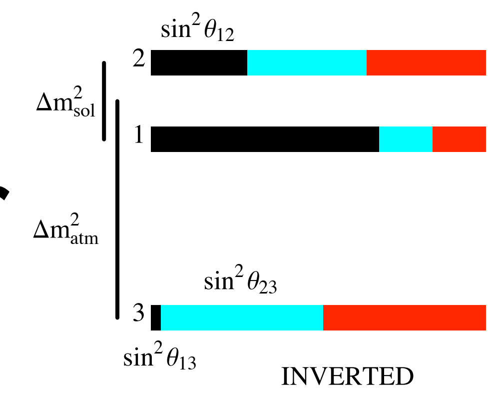
Atmos. L/E $\mu \to \tau$ | Atmos. L/E $\mu \leftrightarrow e$ | Solar L/E $e \to \mu, \tau$ | Majorana

~500 km/GeV | ~18 km/MeV | $0\nu\beta\beta$



central values θ_{12}, θ_{23}
max. for θ_{13}
and $|\sin\delta| = 1$

or



Solar (1-2) Sector:

SNO, KamLAND, SK ...

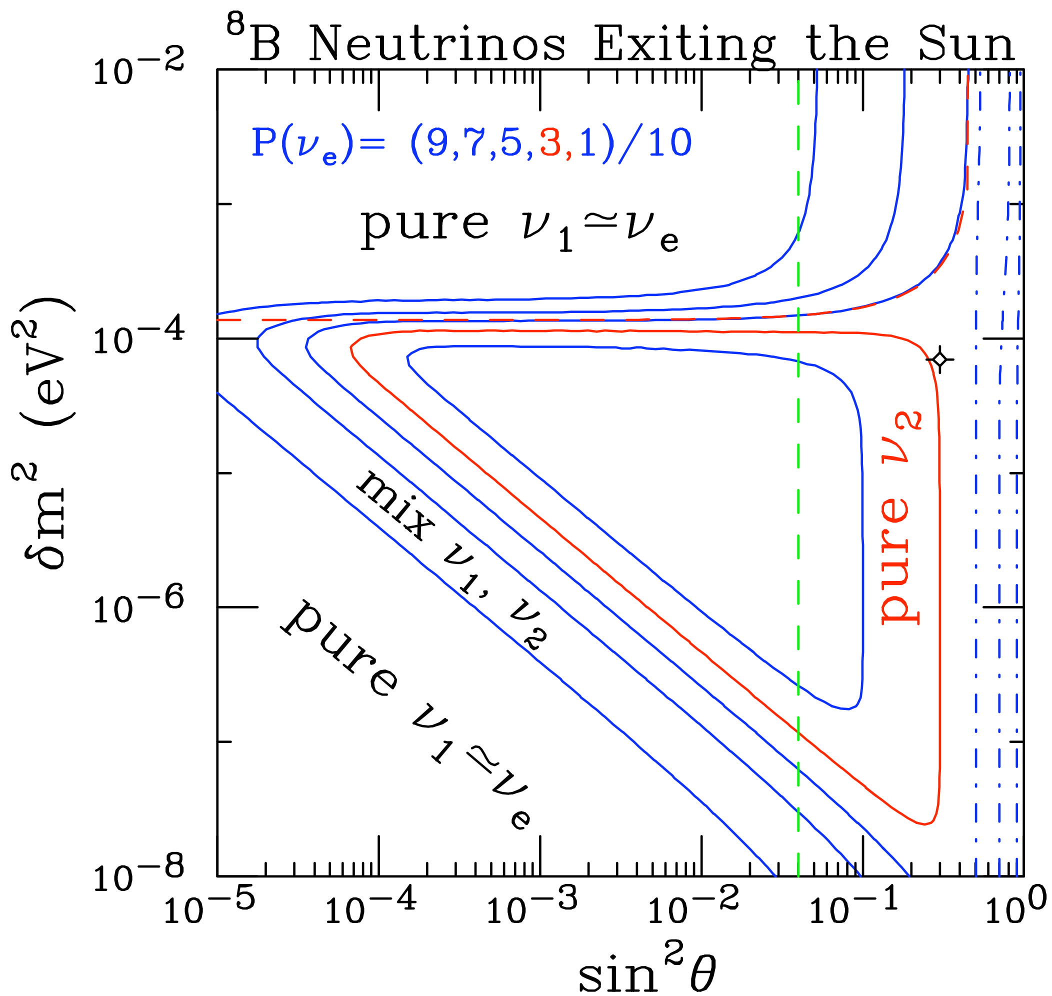
$$\delta m^2_{21} = +7.1 \pm 2.0 \times 10^{-5} eV^2$$

$$0.23 < \sin^2\theta_{12} < 0.35$$

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

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

Due to matter effects
the ^{8}B solar neutrinos exit the sun
primarily as ν_2



$\nu_1 = c_\theta \nu_e + s_\theta \nu_x$ $\quad$ $\nu_2 = -s_\theta \nu_e + c_\theta \nu_x$

$$P_{\nu_e} = \frac{1}{2} + \left(\frac{1}{2} - P_x\right) \cos 2\theta_0 \cos 2\theta_N$$

SP. PRL 57,1275(1986)

$$r = N_1/(N_1 + N_2)$$

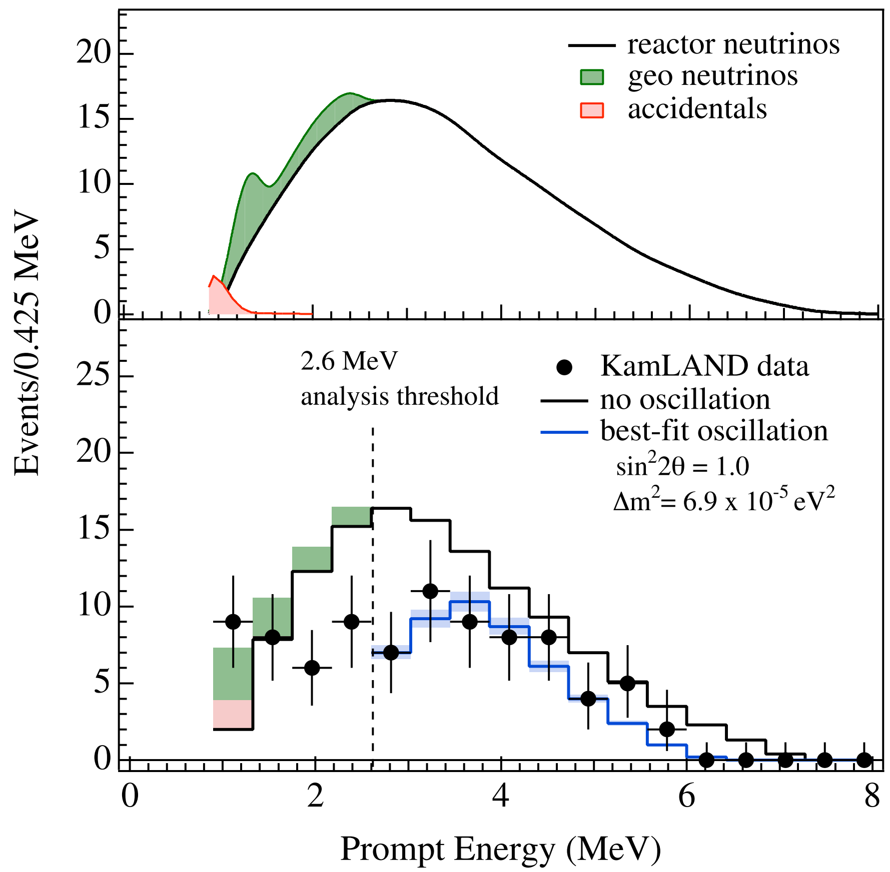
$$\begin{aligned} \frac{CC}{NC} &= r\cos^2\theta_{12} + (1-r)\sin^2\theta_{12} \\ &= \sin^2\theta_{12} + r\cos 2\theta_{12} \\ &\approx \sin^2\theta_{12} \end{aligned}$$

$$0.31 \pm 0.03 \approx 0.29 \pm 0.03 \quad \Rightarrow \quad r \approx 5\%$$

Thus SNO's $\frac{CC}{NC}$ is a direct measure of $\sin^2\theta_{12}$.

(Up to small corrections.)

KamLAND Result:



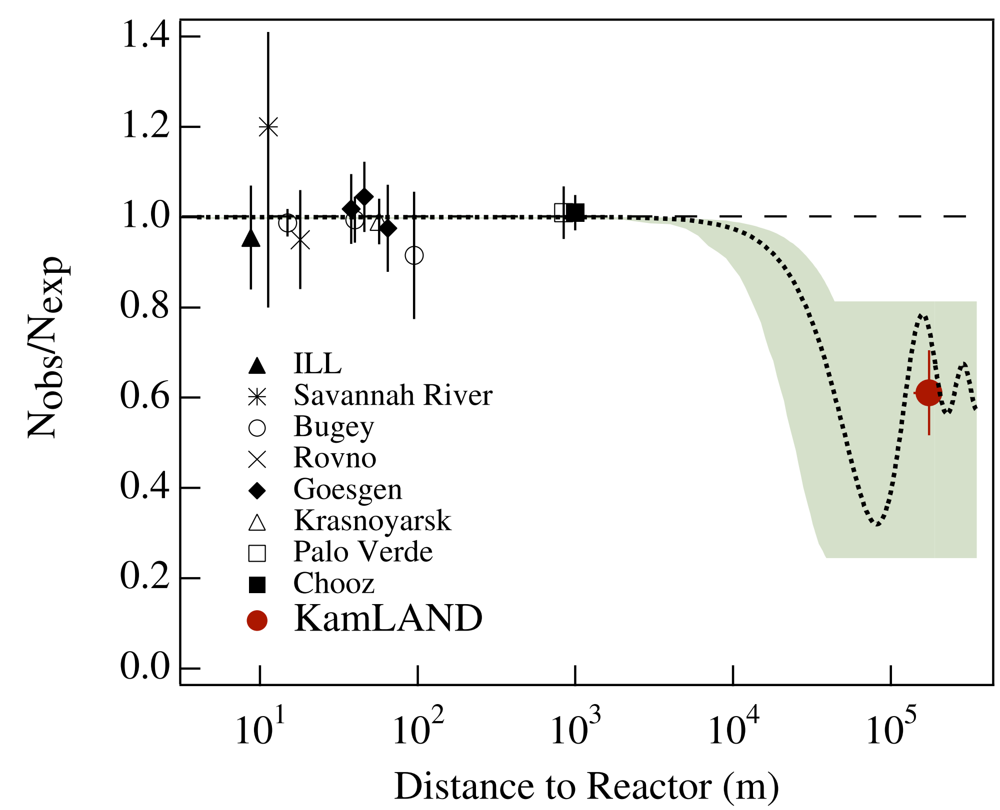
No spectral distortion seen:

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2}\sin^2 2\theta_{12}$$

Use SNO's $\sin^2\theta_{12}$

$$= 1 - 2(0.3)(0.7) \approx 0.6$$

$$\frac{N_{obs} - N_{BG}}{N_{expected}} = 0.611 \pm 0.085(\text{stat}) \pm 0.041(\text{syst}).$$



Atmospheric (2-3) Sector:

(23)-Sector: SK, K2K

$$|\delta m^2_{32}| = 1.9 - 3.0 \times 10^{-3}\ eV^2$$

$$0.35 < \sin^2\theta_{23} < 0.65$$

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

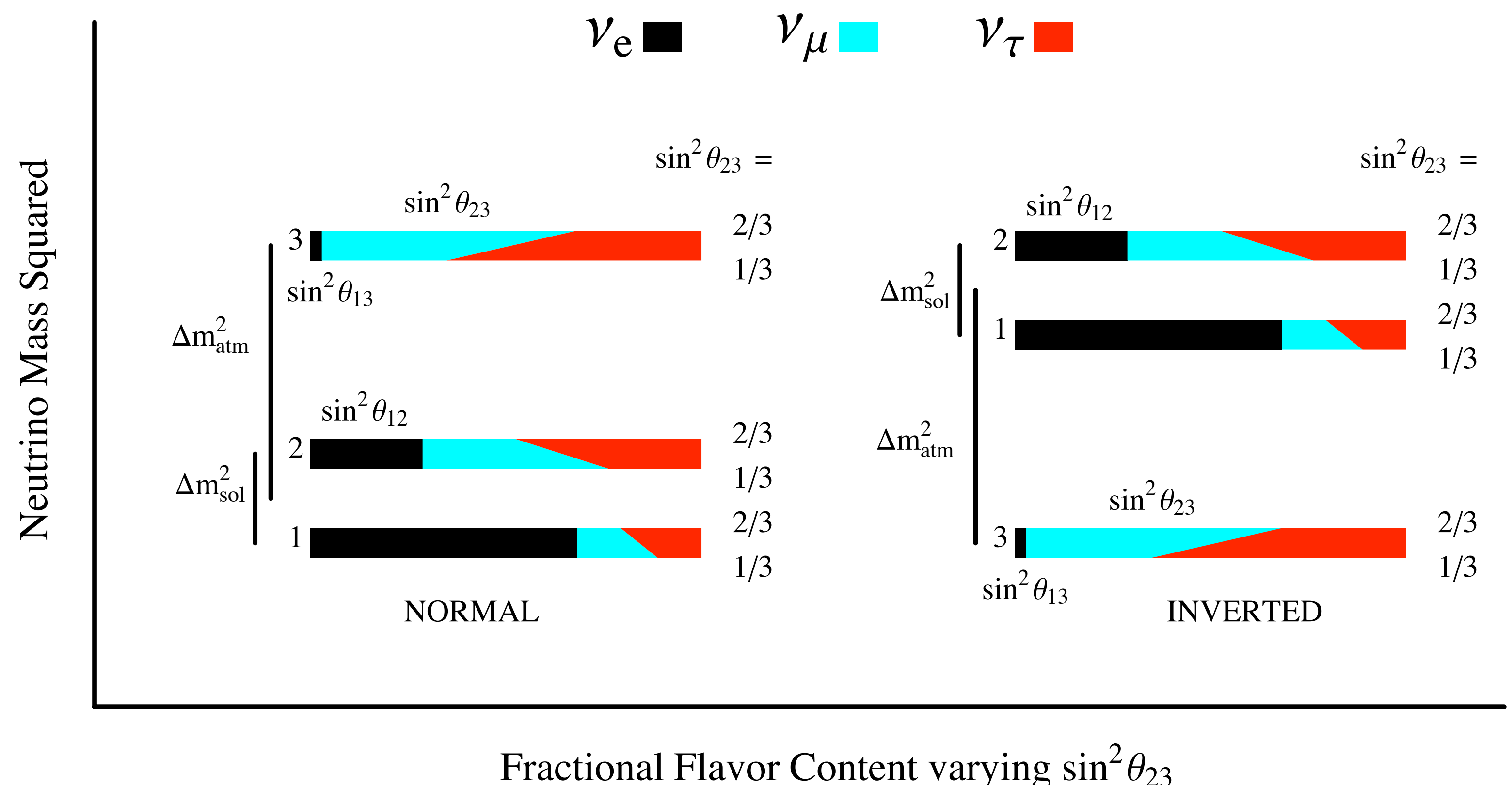
$$\nu_\mu \longrightarrow \nu_\mu$$

$$\sin^2 2\theta_{23} > 0.91$$

Magnitude of δm^2_{32} and $\sin^2\theta_{23}$ both poorly known!

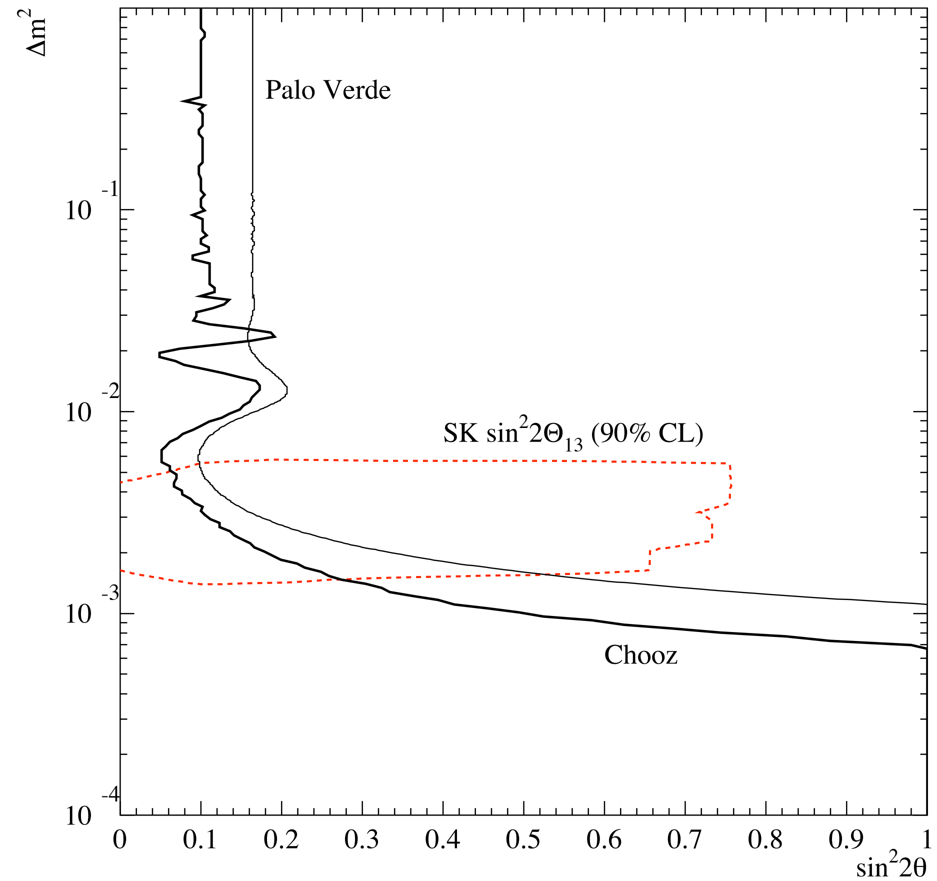
Sign of δm^2_{32} Unknown !!!

MINOS improves on $|\delta m^2_{32}|$



O. Mena and SP hep-ph/0312312

(1-3) Sector:



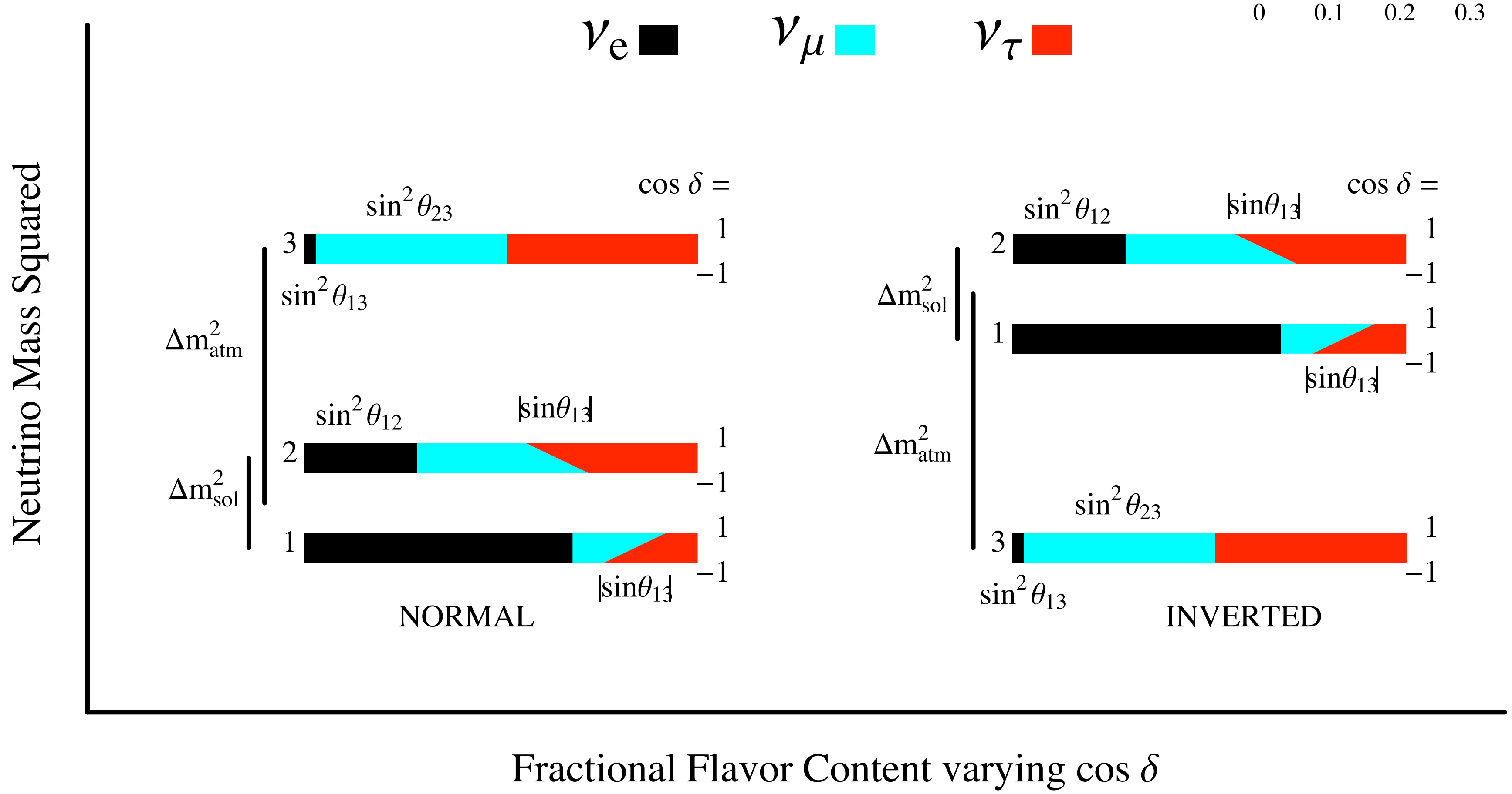
Chooz, SK and K2K

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

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

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

Unknown!



Only insensitive to sign of $\sin\delta$

For $\mu \Leftrightarrow \tau$ symmetry
$\theta_{23} = \pi/4$ and
$\delta = \pi/2$ or $3\pi/2$
unless $\theta_{13} \equiv 0$

Super-Chooz:

interest in Japan, Europe, Russia, USA (CA and IL), China ....

$$1 - P_{\nu_e \to \nu_e} = \sin^2 2\theta_{13} \left[\sin^2 \Delta_{atm} + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)\right] + \mathcal{O}\left(\frac{\Delta_{solar}}{\Delta_{atm}}\right)^2$$

>1% 1 <3% <0.1%

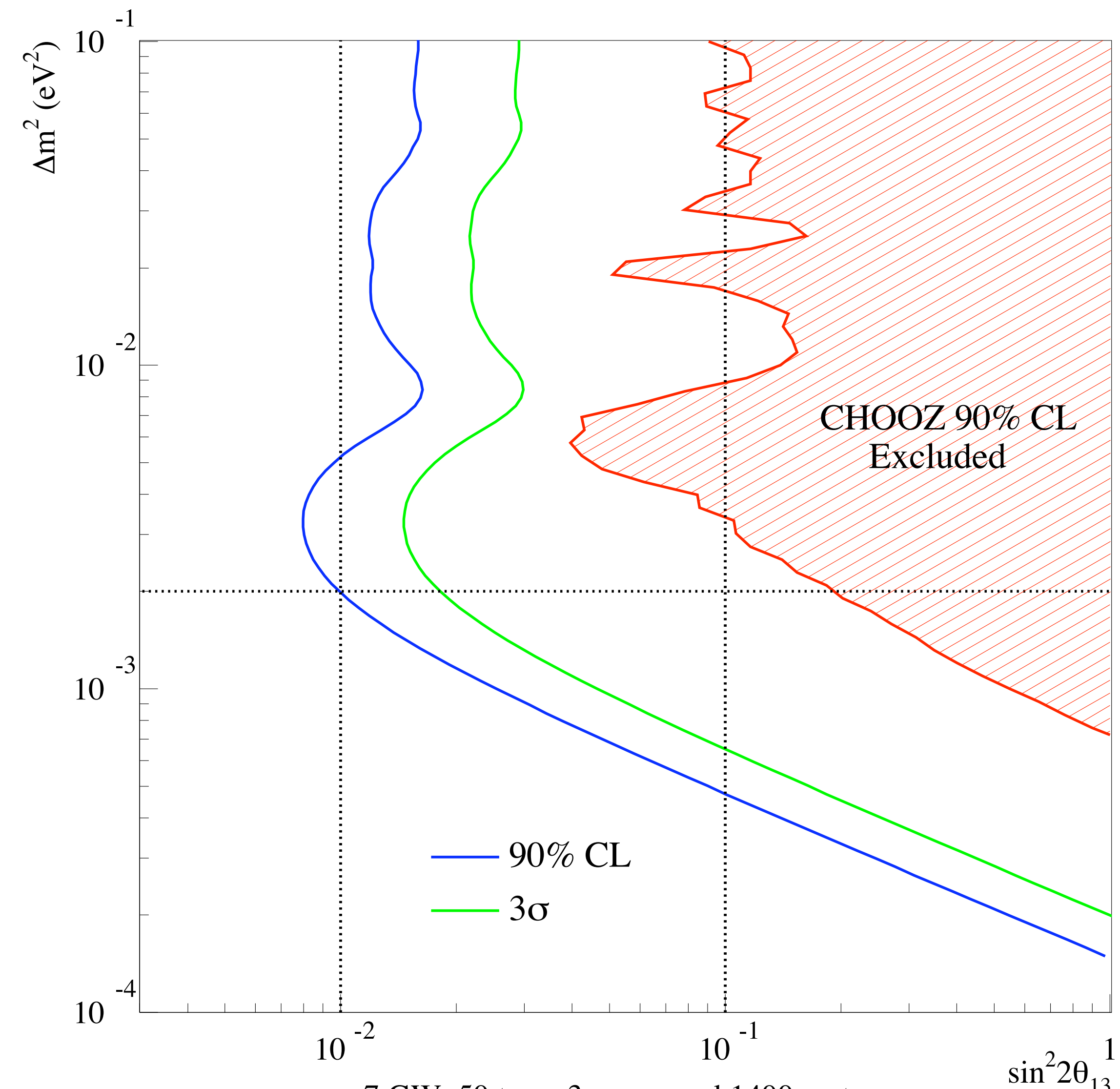
kinematical phase $\Delta_{atm} = \frac{\delta m^2_{atm} L}{4E} = 1.27 \frac{\delta m^2_{atm} L}{E}$

Clean measurement of

$\sin^2 2\theta_{13}$ down to 0.01

Systematics limit experiment:

Could be "quick" and "cheap" but ...



7 GW, 50 tons, 3 years, and 1400 meters

J. Link, Columbia

Leptonic CP and T Violation in 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

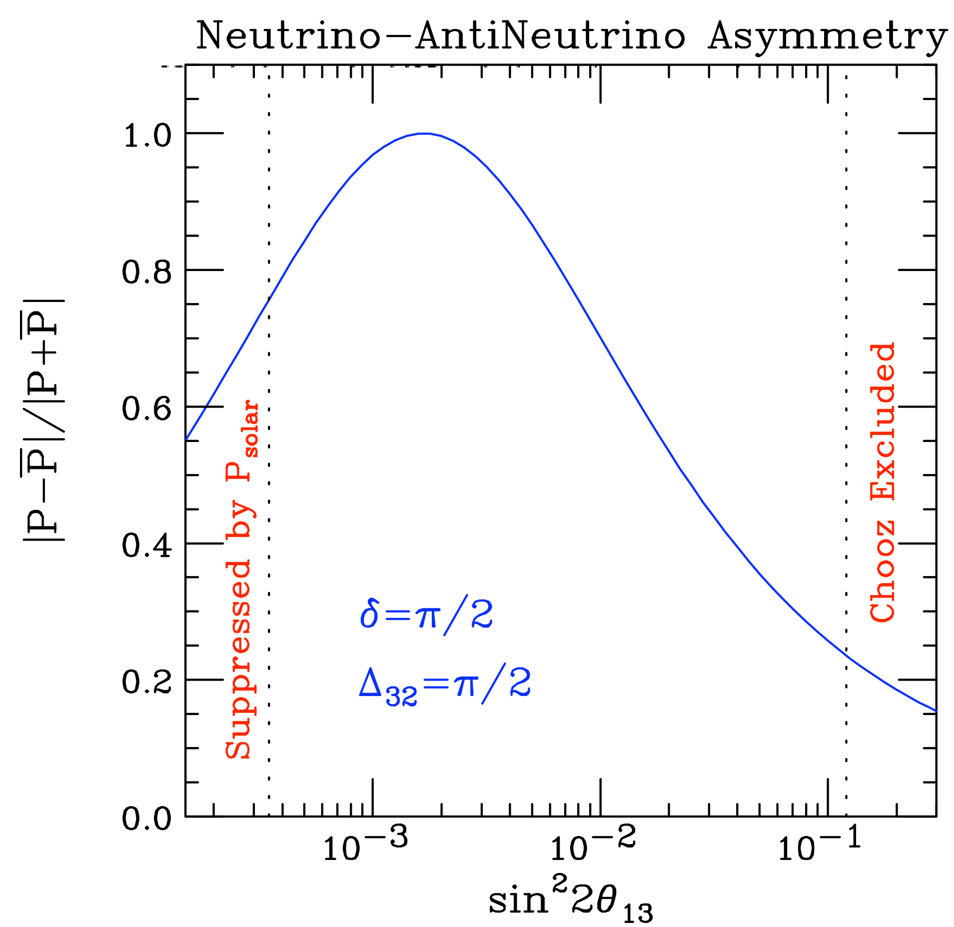
CP

$$P_{\nu_\mu \to \nu_e} = |\ a^{atm}_{\mu\to e} \ + \ a^{sol}_{\mu\to e}\ |^2$$

CP Violation comes from the Difference in the Interference of $a^{atm}_{\mu\to e}$ amd $a^{sol}_{\mu\to e}$ for neutrinos verses anti-neutrinos.

CAN BE LARGE!!!.

Important parameters are θ_{13} and δ.



kinematical phase
$$\Delta_{ij} = \frac{\delta m^2_{ij} L}{4E} = 1.27 \frac{\delta m^2_{ij} L}{E}$$

Leptonic CP and T Violation in Oscillations

Leptogenesis

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

$$P_{\nu_\mu \to \nu_e} = |\ a^{atm}_{\mu\to e} + a^{sol}_{\mu\to e}\ |^2$$

CP Violation comes from the Difference in the Interference of $a^{atm}_{\mu\to e}$ amd $a^{sol}_{\mu\to e}$ for neutrinos verses anti-neutrinos.

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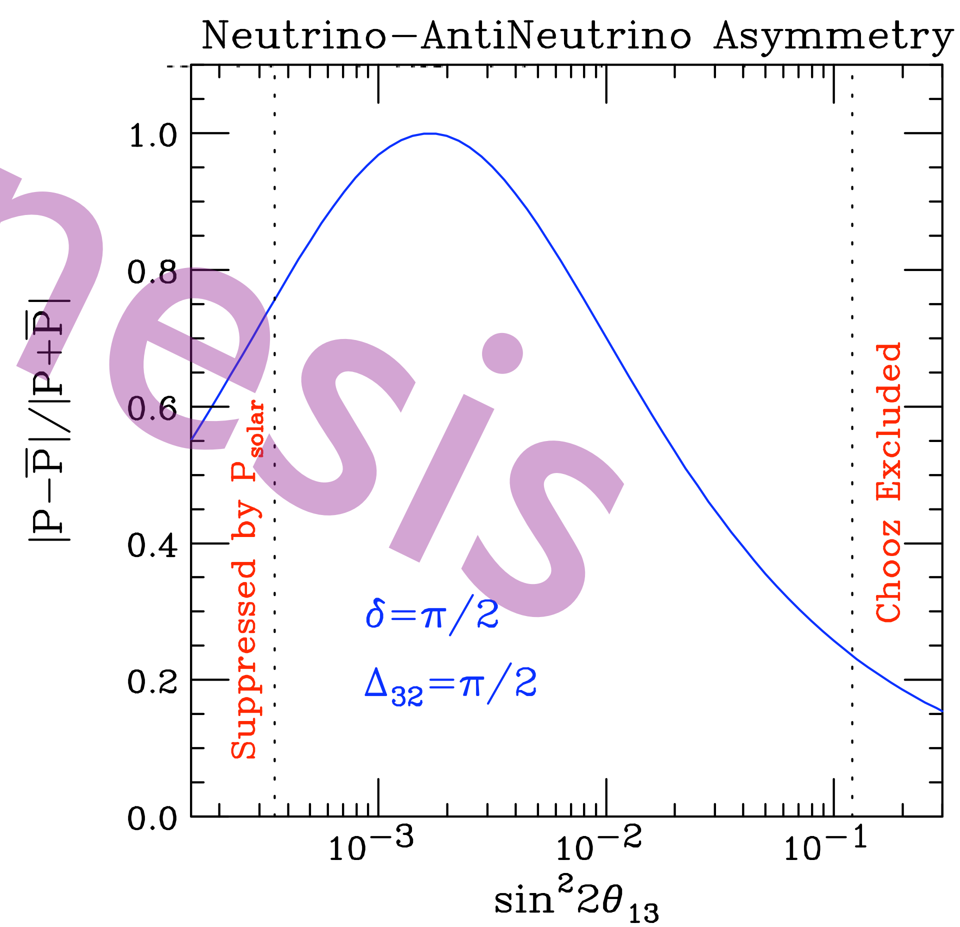


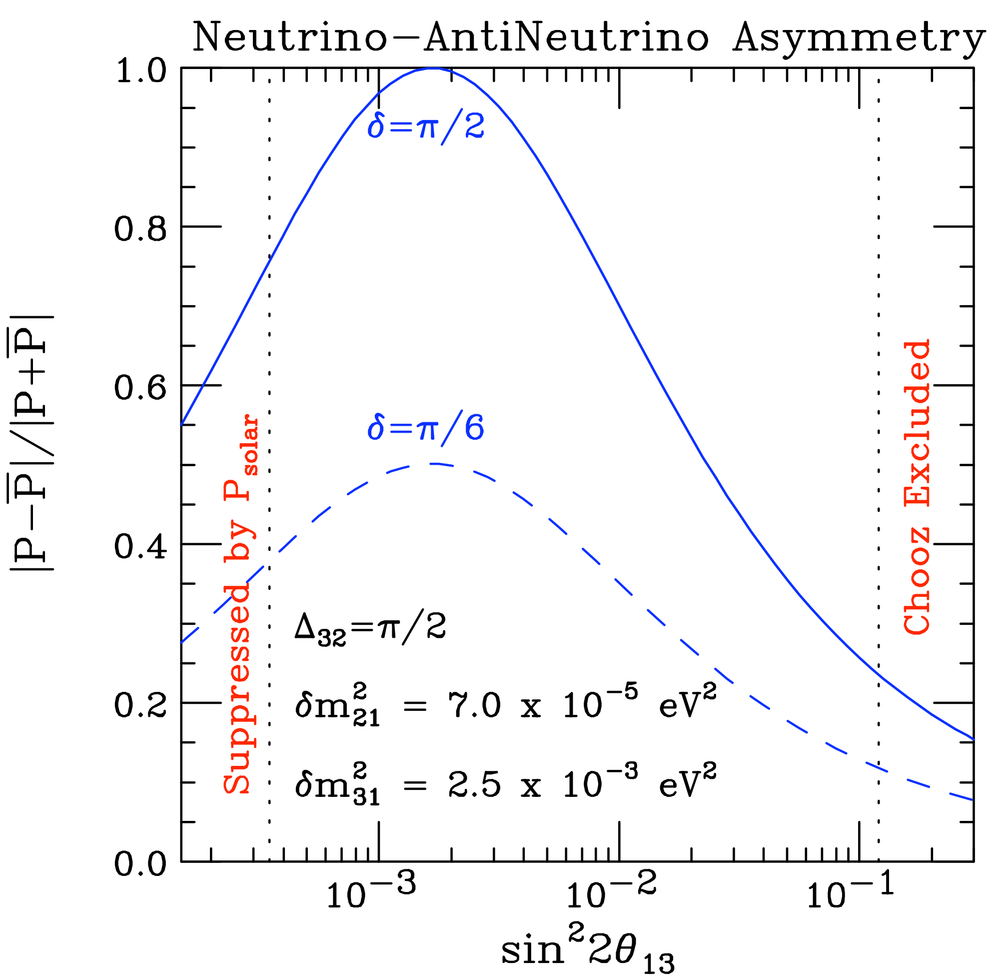
kinematical phase $\Delta_{ij} = \dfrac{\delta m^2_{ij} L}{4E} = 1.27 \dfrac{\delta m^2_{ij} L}{E}$

$$P^{atm}(\nu_\mu \to \nu_e) = |a^{atm}|^2 = \sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta_{31}$$

$$P^{sol}(\nu_\mu \to \nu_e) = |a^{sol}|^2 = \cos^2\theta_{23}\cos^2\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}$$

relative phase is $\Delta_{32} \pm \delta$

$$P(\nu_\mu \to \nu_e) = |a^{atm} + a^{sol}|^2 = P^{atm} + P^{sol} + 2\sqrt{P^{atm}.P^{sol}}\cos(\Delta_{32} \pm \delta)$$

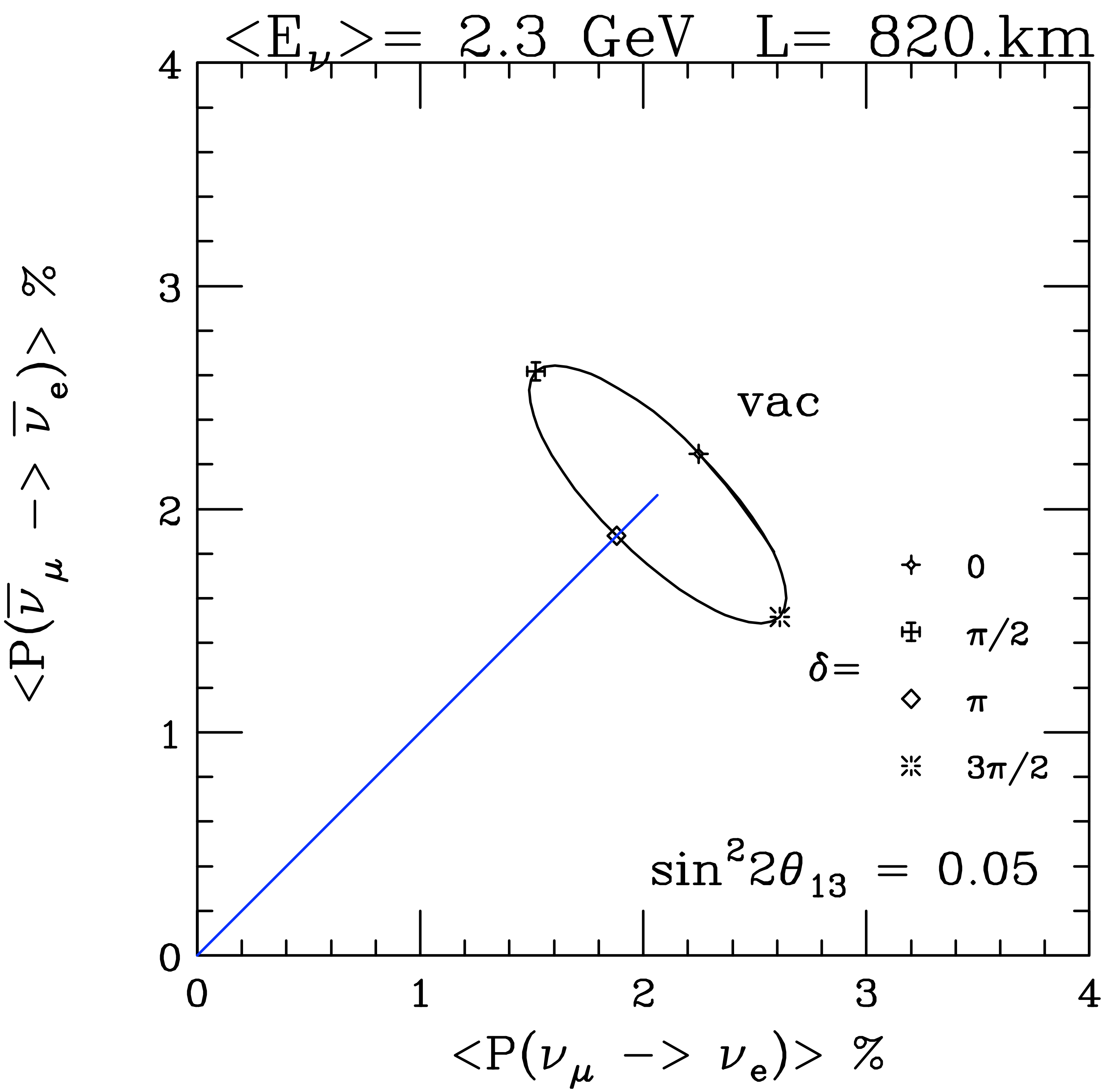


Maximum Asymmetry when

$$|a^{atm}| = |a^{sol}|$$

$$\sin^2 2\theta_{13} \approx \frac{\sin^2 2\theta_{12}}{\tan^2\theta_{23}}\left[\frac{\pi}{2}\ \frac{\delta m^2_{21}}{\delta m^2_{31}}\right]^2$$

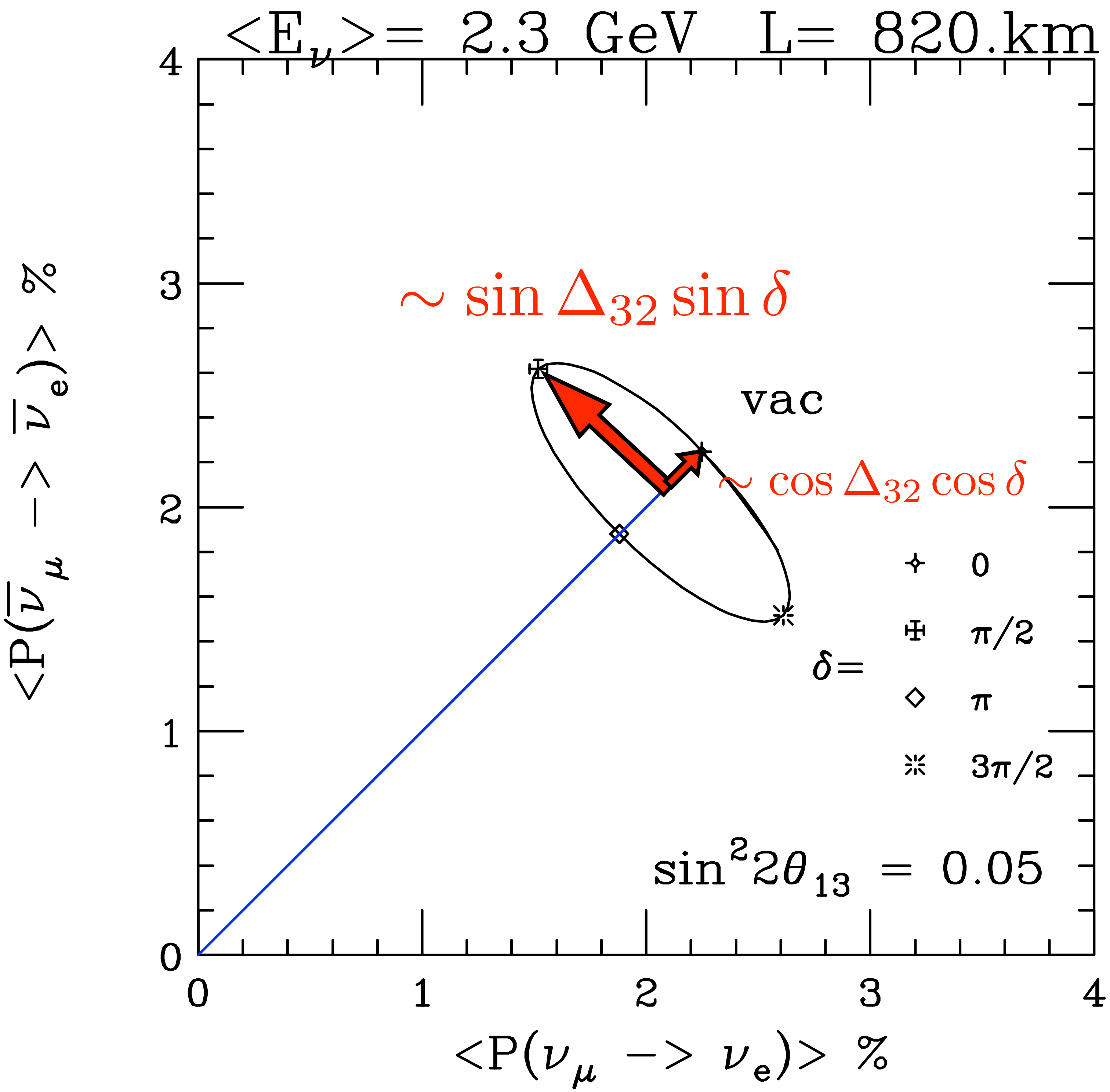
$$\approx 0.002$$



Bi-Probability Plots:

Minakata and Nunokawa

hep-ph/0108085



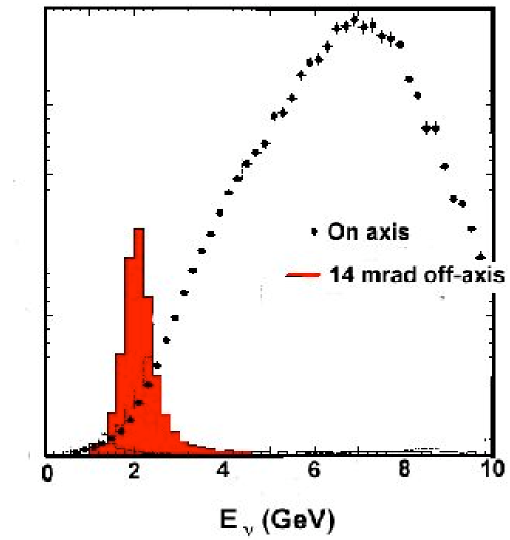
Bi-Probability Plots:

Minakata and Nunokawa

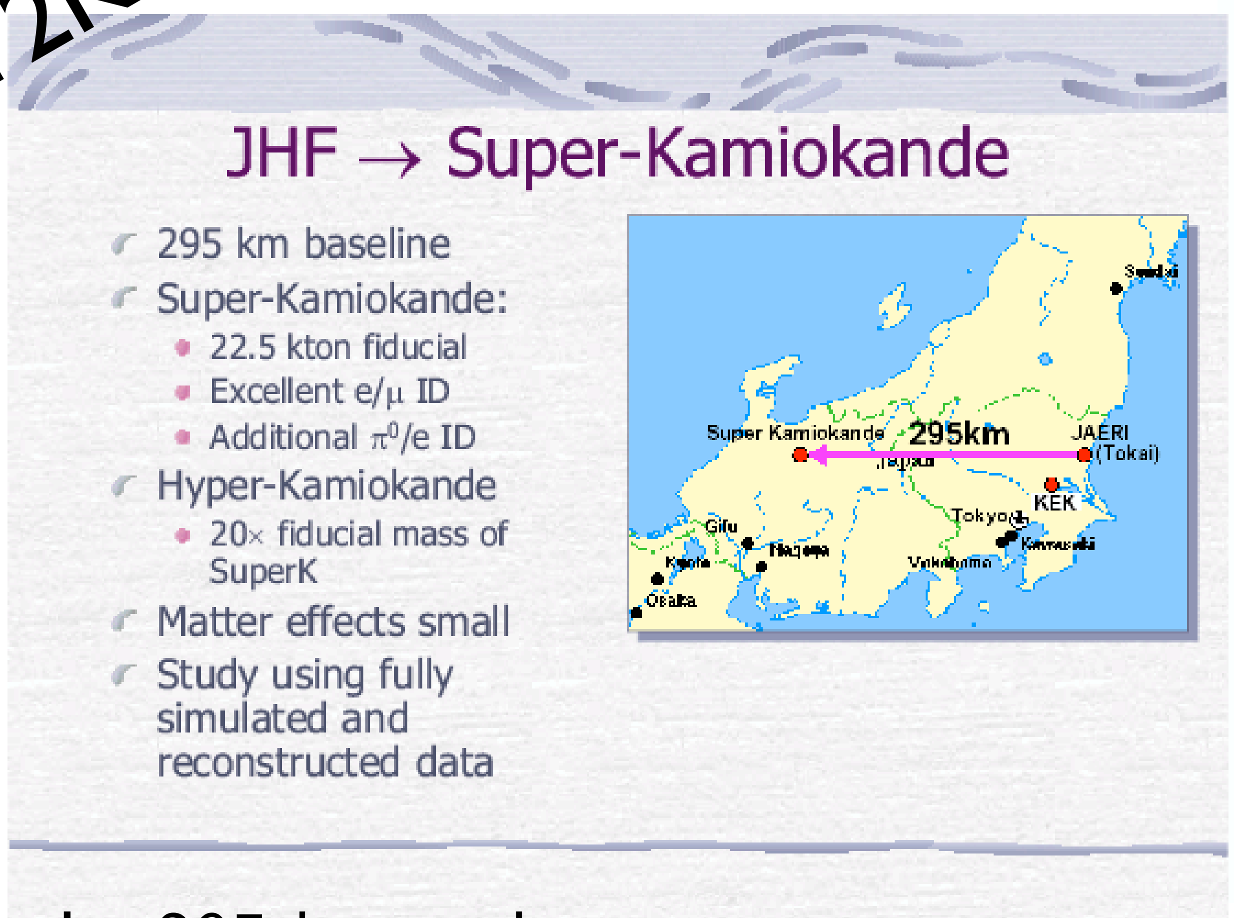
hep-ph/0108085

Off-Axis Beams:

BNL 1994



T2K



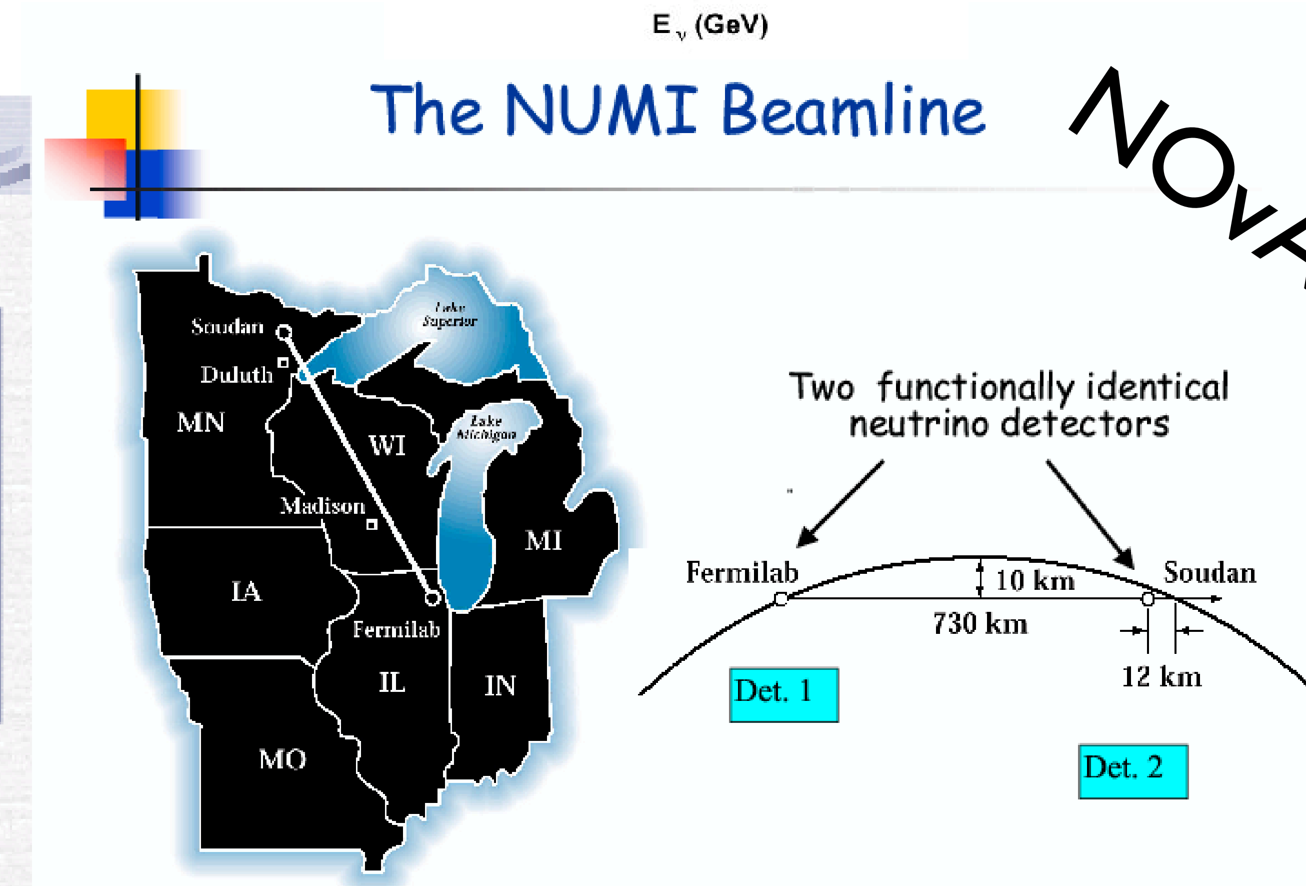
L=295 km and

Energy at Vac. Osc. Max. (vom)

$$E_{vom} = 0.6\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\}$$

0.75 upgrade to 4 MW

NOvA



L=700 - 1000 km and

Energy near 2 GeV

$$E_{vom} = 1.8\ GeV \left\{ \frac{\delta m^2_{32}}{2.5\times10^{-3}\ eV^2} \right\} \times \left\{ \frac{L}{820\ km} \right\}$$

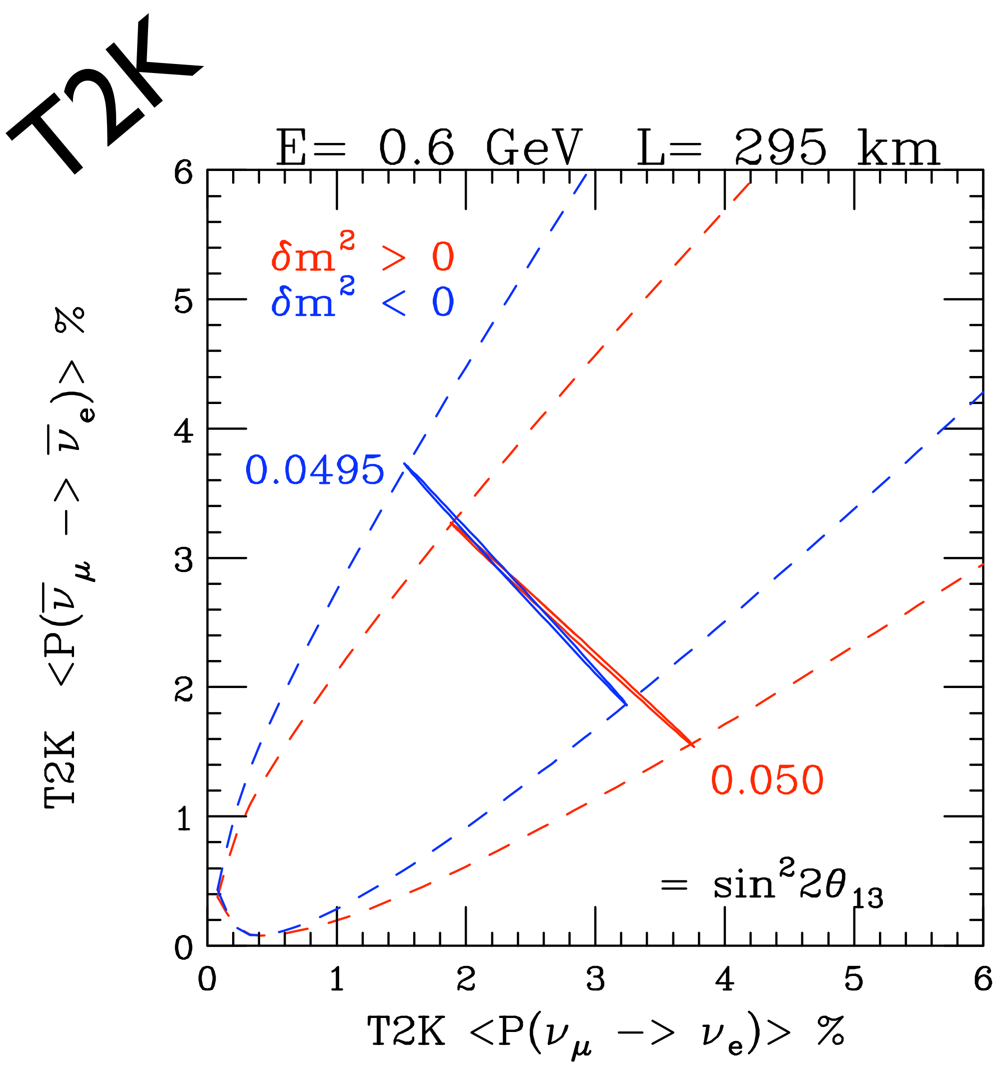
0.4 upgrade to 2 MW

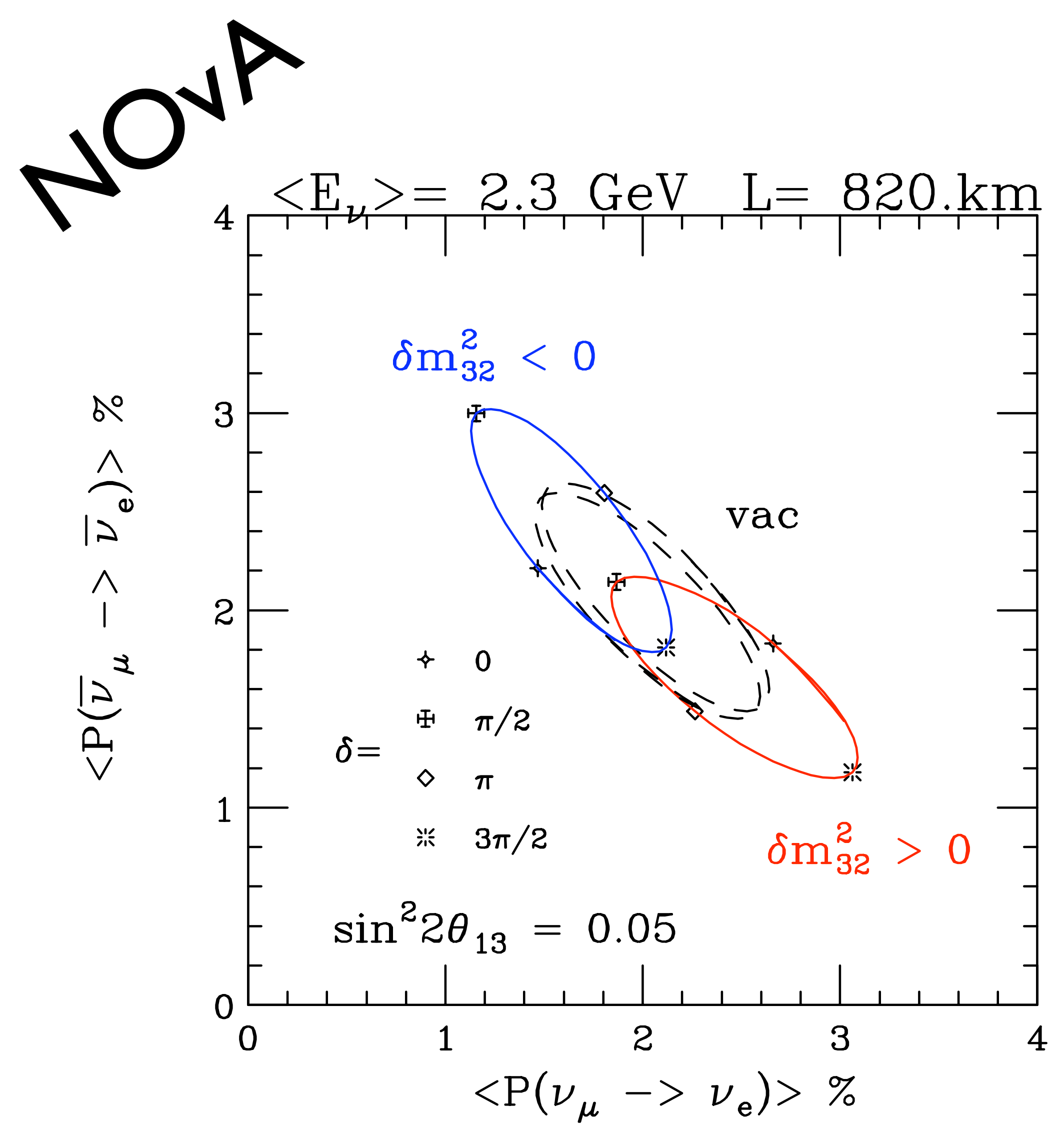
Matter Effects:

$$a = G_F N_e/\sqrt{2} = (4000\ km)^{-1}$$

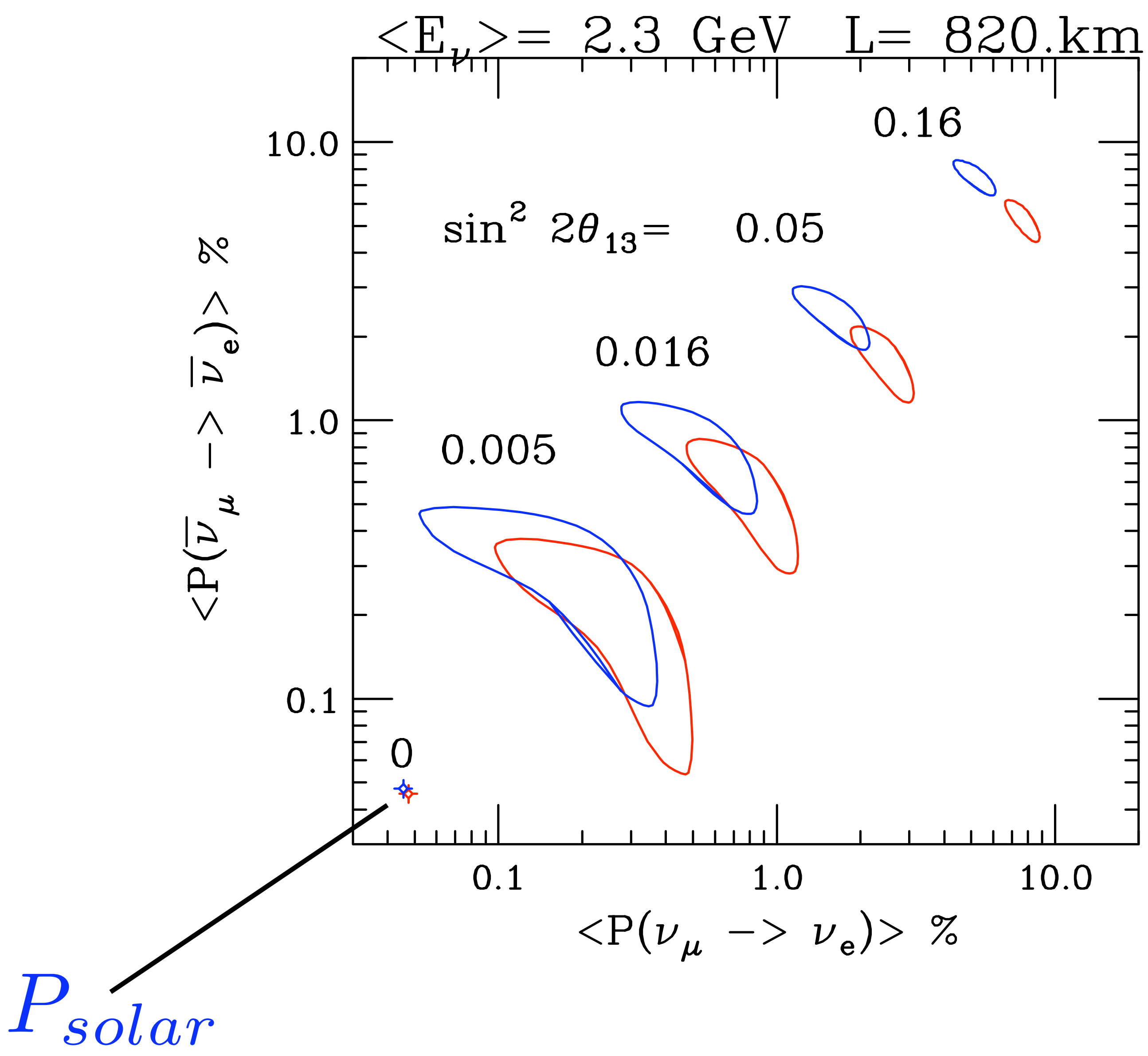
$$\sin \Delta_{31} \quad \Rightarrow \quad \left(\frac{\Delta_{31}}{\Delta_{31} \mp aL}\right) \sin(\Delta_{31} \mp aL)$$

$$\sin \Delta_{21} \quad \Rightarrow \quad \left(\frac{\Delta_{21}}{\Delta_{21} \mp aL}\right) \sin(\Delta_{21} \mp aL) \approx \Delta_{21}$$





Varying $\sin^2 2\theta_{13}$ Log scale:



Two Signs:

$\text{sign of } \delta m^2_{31}$

normal v inverted hierarchy

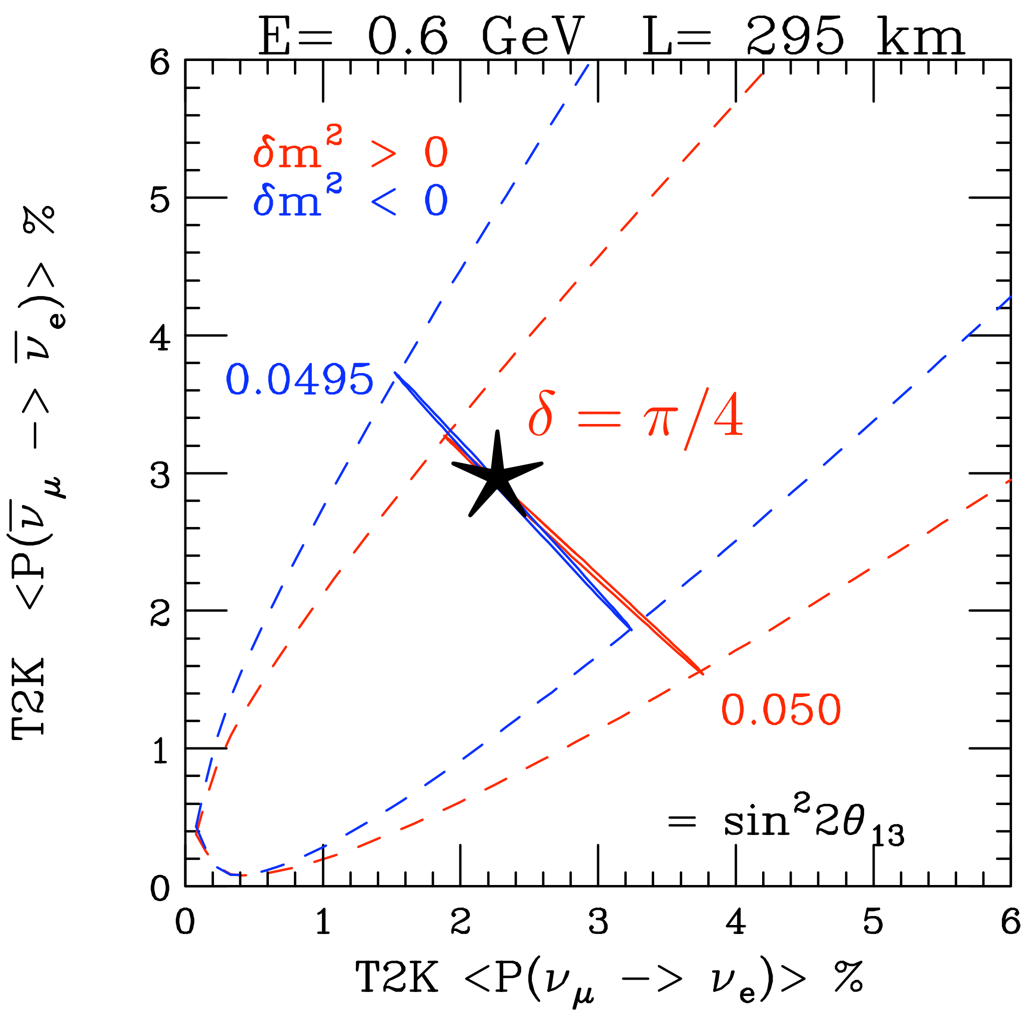
and

Leptonic CP Violation

$\sin\delta$

O. Mena and SP

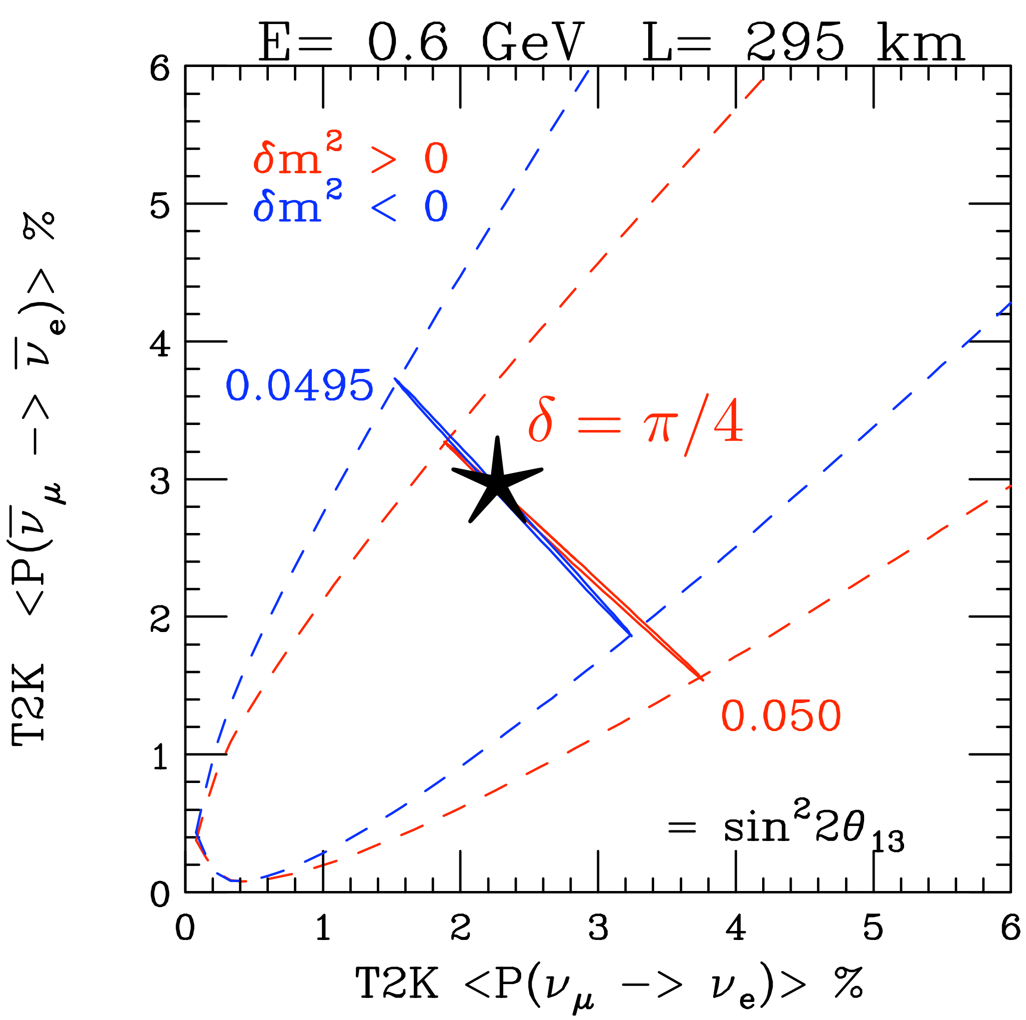
T2K:

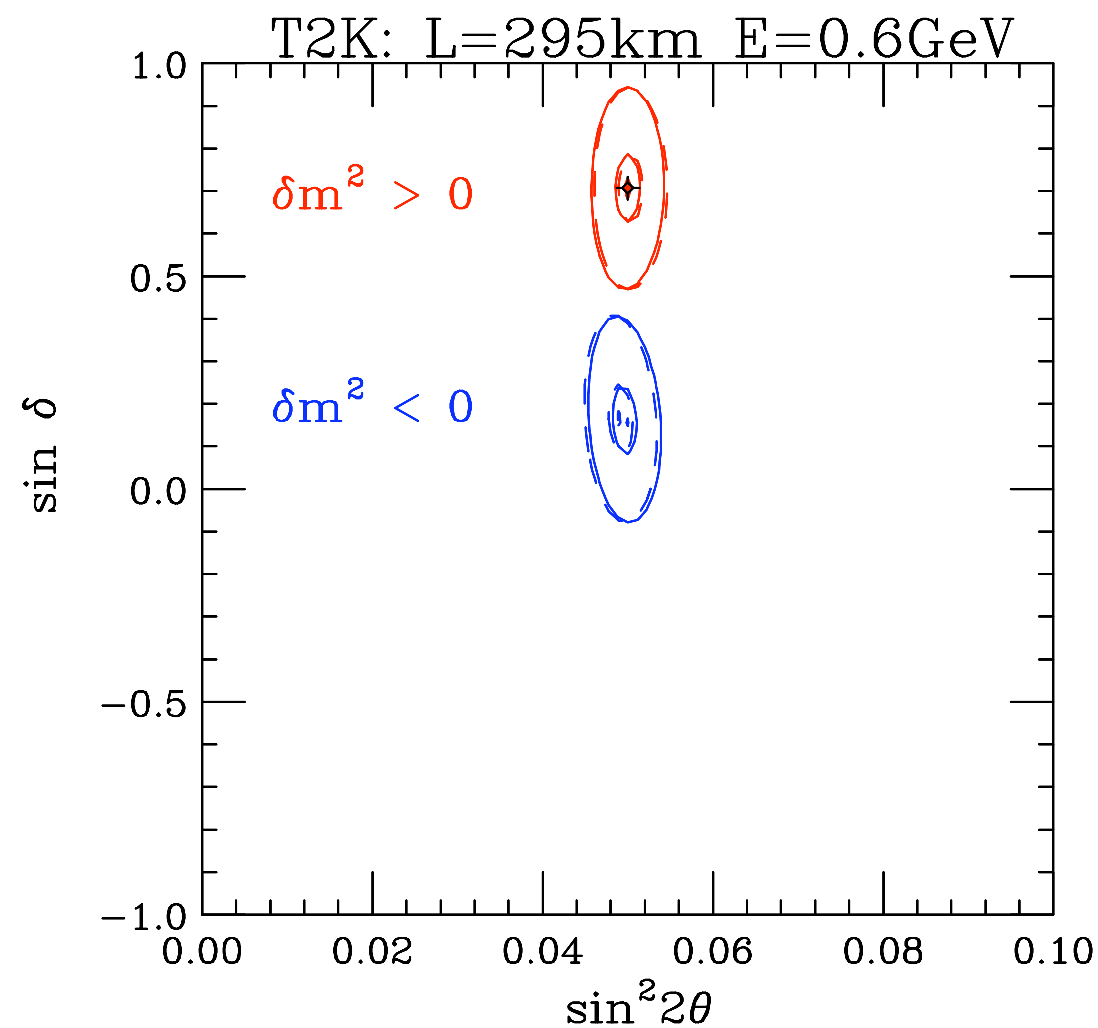


E= 0.6 GeV L= 295 km
δm² > 0
δm² < 0
0.0495
δ = π/4
0.050
= sin²2θ13
T2K <P(ν̄μ -> ν̄e)> %
T2K <P(νμ -> νe)> %
0
1
2
3
4
5
6

T2K:

$$\sin\delta_+ = \sin\delta_- + 0.5\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

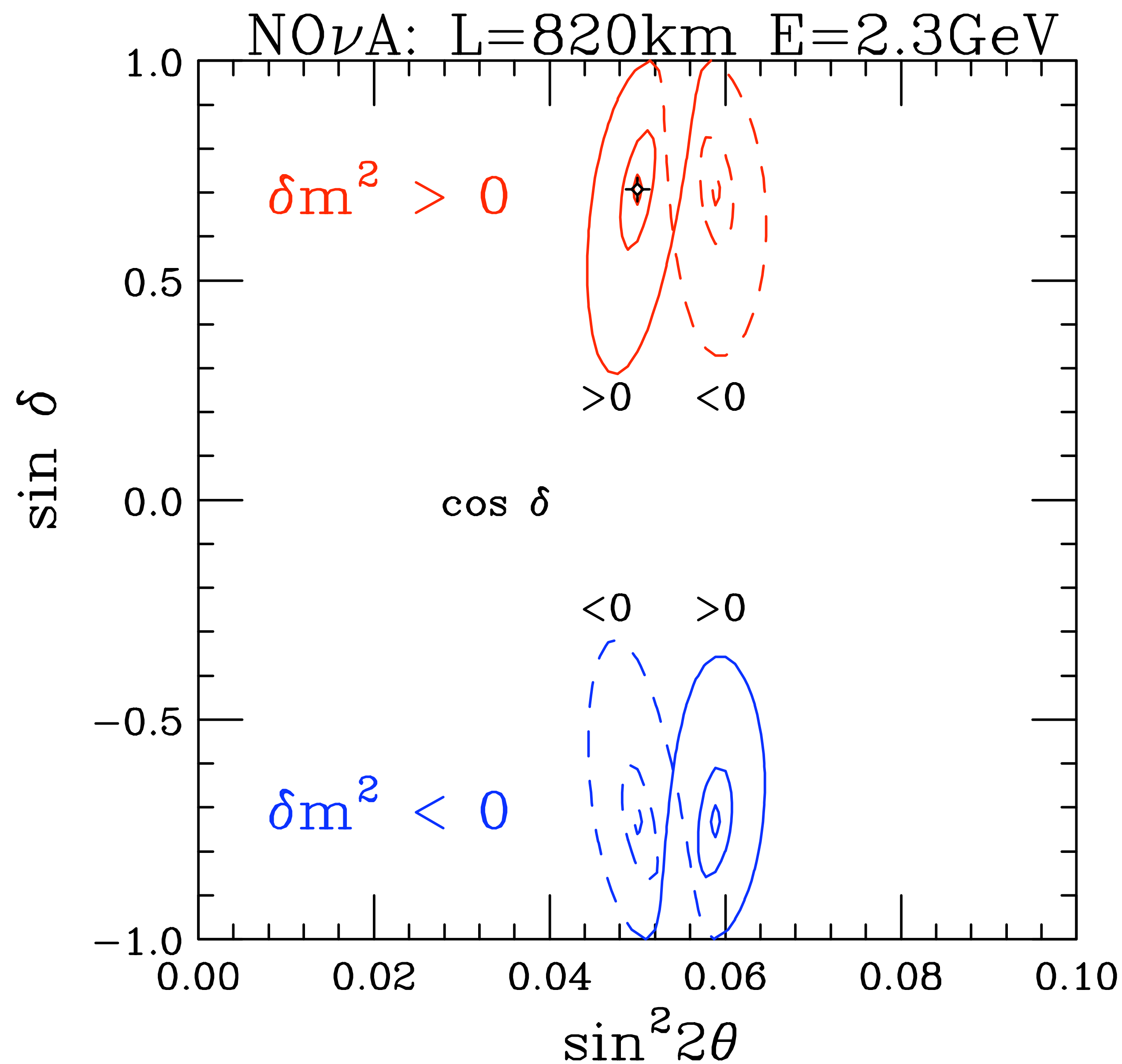


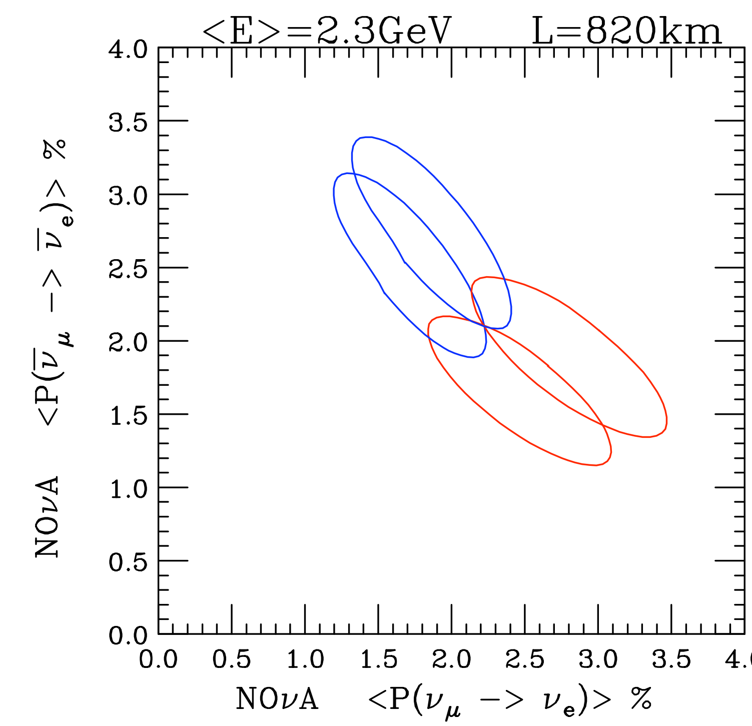


no info on sign of $\cos\delta = \pm\sqrt{1-\sin^2\delta}$

NOvA:

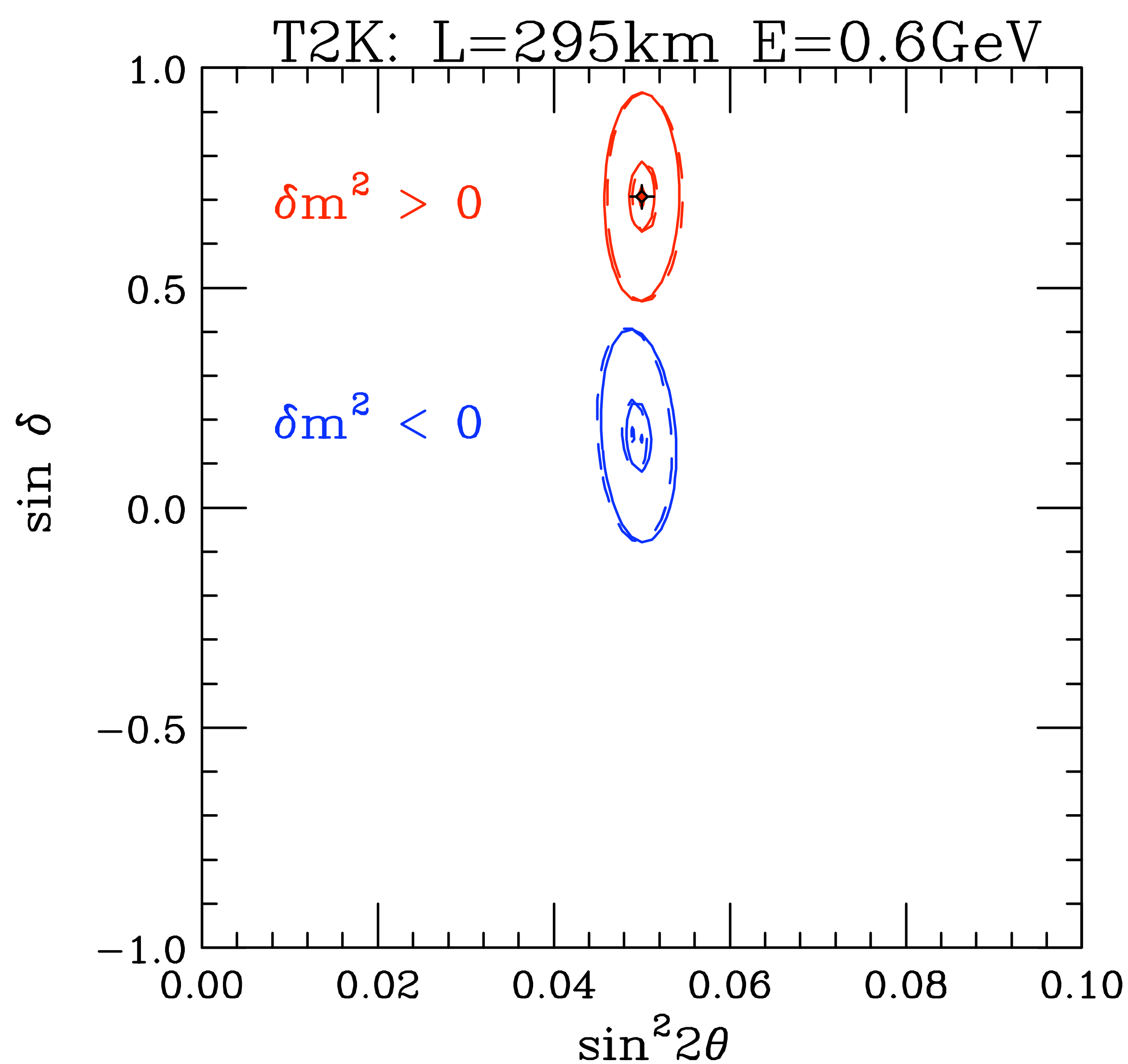
$$\sin\delta_+ = \sin\delta_- + 1.5\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

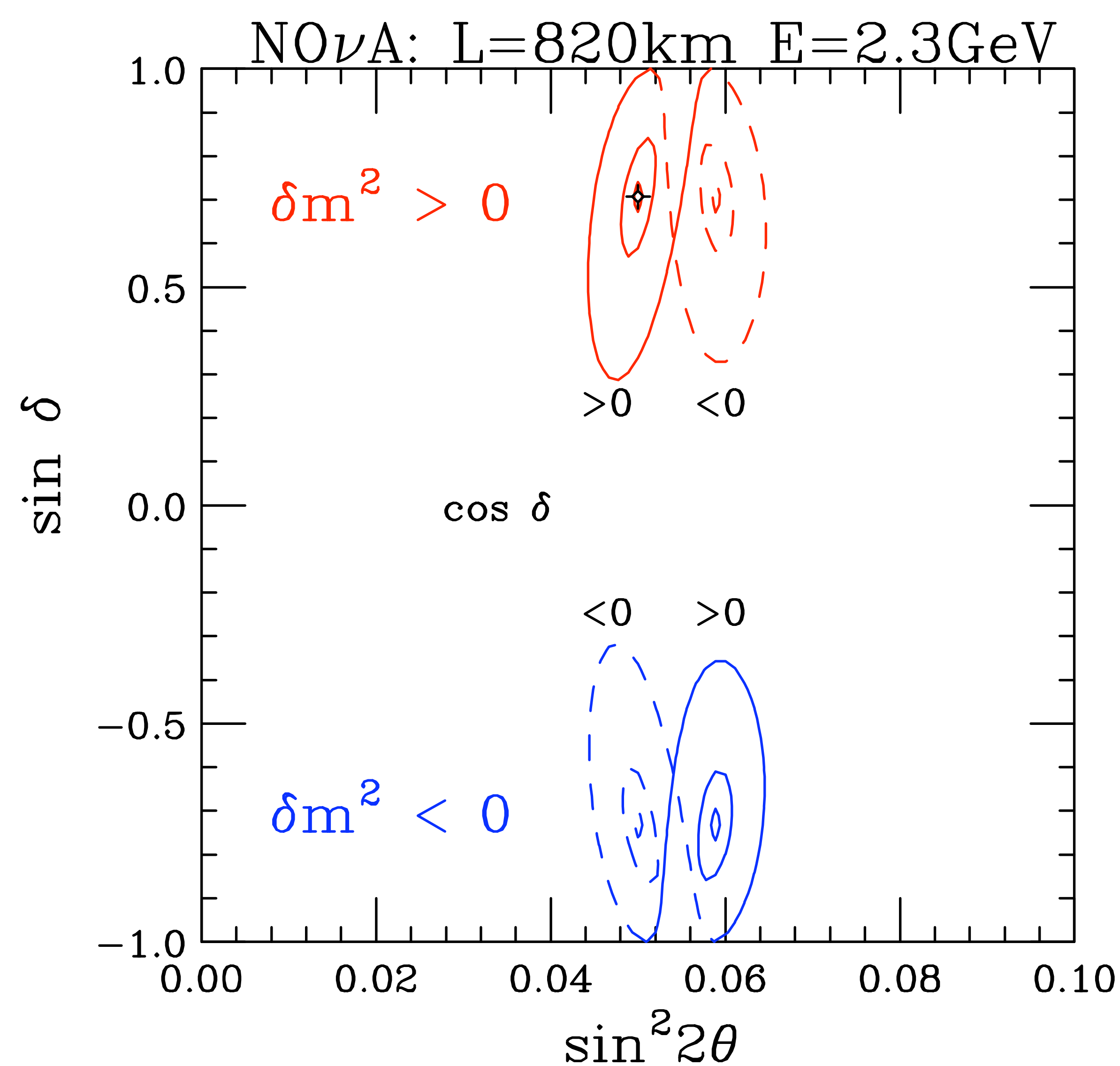




sensitive to sign of $\cos\delta = \pm\sqrt{1-\sin^2\delta}$

T2K + NOvA





with sufficient events
T2K plus NOvA determines

sign of δm^2_{31} =hierarchy

$\sin\delta$ =CPV

Hierarchy: T2K Nu v. NOvA Nu

sign δm^2_{32}

At Vac. Osc. Max., $\Delta_{32} = \frac{\pi}{2}$

$$P_{mat} = \left(1 \pm 2\frac{E}{E_R}\right) P_{vac}$$

where $E_R \simeq 12$ GeV.

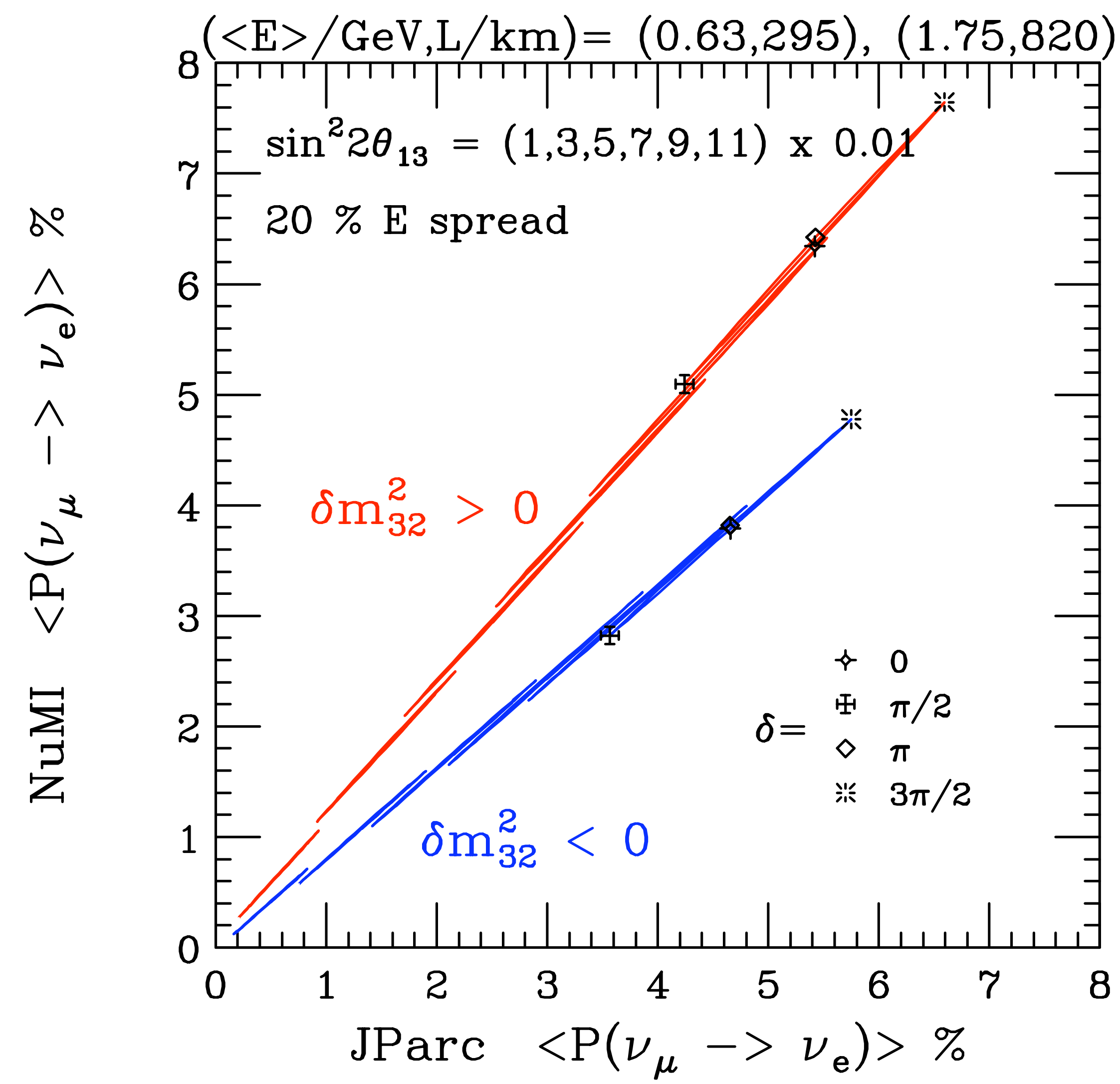
Therefore, if NuMI and JParc both run Neutrinos at Vac. Osc. Max.

$$P_N = \left(1 \pm 2\frac{(E^N - E^J)}{E_R}\right) P_J$$

i.e. $P_N \approx (1.2 \; or \; 0.8) P_J$

Need about 100 events in each expt.

(signal)



Separation degraded for $E^N > E_{vom}$.

Minakata, Nunokawa and SP – hep-ph/0301210

Conclusions:

- $\sin^2 2\theta_{13}$: Can be measured by

  Reactor Exp.(~ 0.01),

  Long Baseline Exp.(~ 0.005),

  Nu Factories ($\sim 10^{-4}$).

- sign of δm^2_{31} and $\sin\delta$:

  $\Rightarrow$ Mass Hierarchy and CP Violation.

  $\nu_\mu \rightarrow \nu_e$ Superbeam Long Baseline Exp. running BOTH ν and $\bar{\nu}$.

- θ_{23}: To break the $\theta_{23} \leftrightarrow \frac{\pi}{2} - \theta_{23}$ degeneracy.

  Combination of Reactor and Long Baseline Exps.

  $\sin^2 2\theta_{13}$ v. $2\sin^2\theta_{23}\sin^2 2\theta_{13}$.

If the size of θ_{13} is in range of the LBL/Reactor expts, $\sin^2 2\theta_{13} \geq 0.005$, then a few carefully choosen counting experiments with sufficient statistics can determine

θ_{13}, δ_{CP}, sign of δm^2_{31}, θ_{23}.

A Fabulous Opportunity in the Neutrino Osc. Sector!!!

Leaving the Questions of:

Majorana v Dirac?,

Steriles? and

Absolute Mass Scale, M_{lite}?