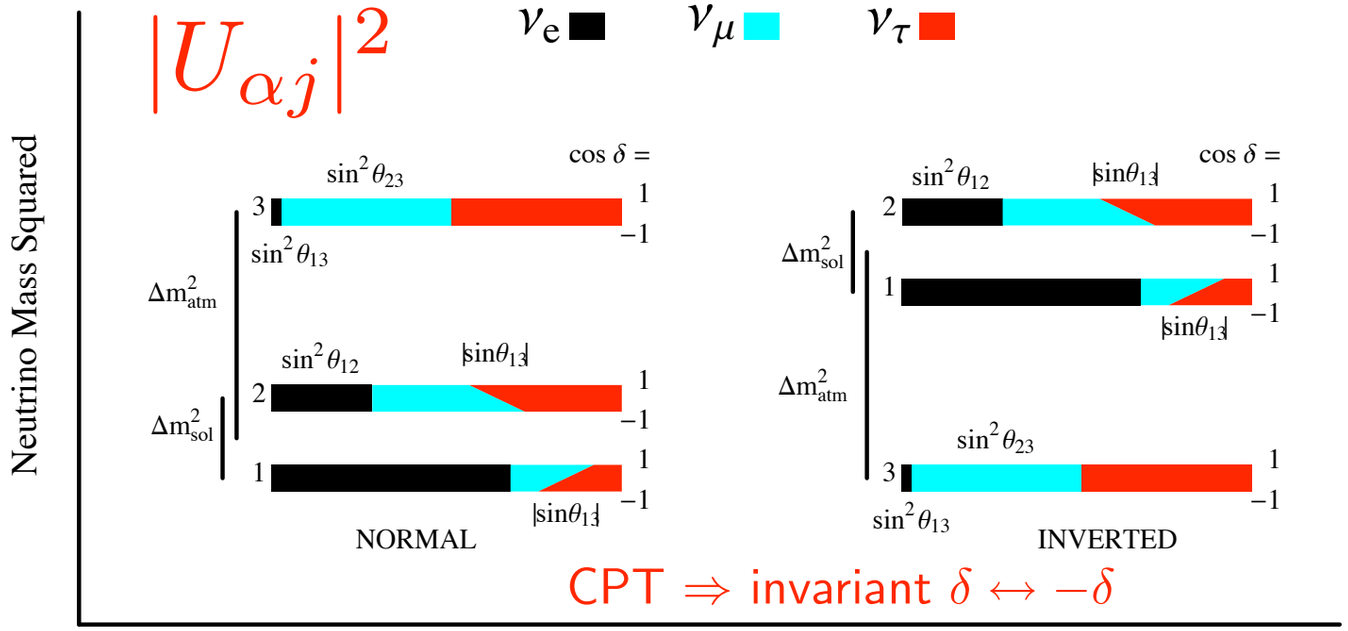
Implications for the high-precision oscillation programme:

Stephen Parke
Fermilab

- Theta_23
- Mass Hierarchy
- CPV
- NSI and Sterile Nus
- Summary & Conclusions

Masses & Mixings:



$$\sin^2\theta_{13} \approx 0.02 \pm 0.01$$

$$|\sin^2\theta_{12} - \frac{1}{3}| < 0.04$$

$$|\sin^2\theta_{23} - \frac{1}{2}| < 0.12$$

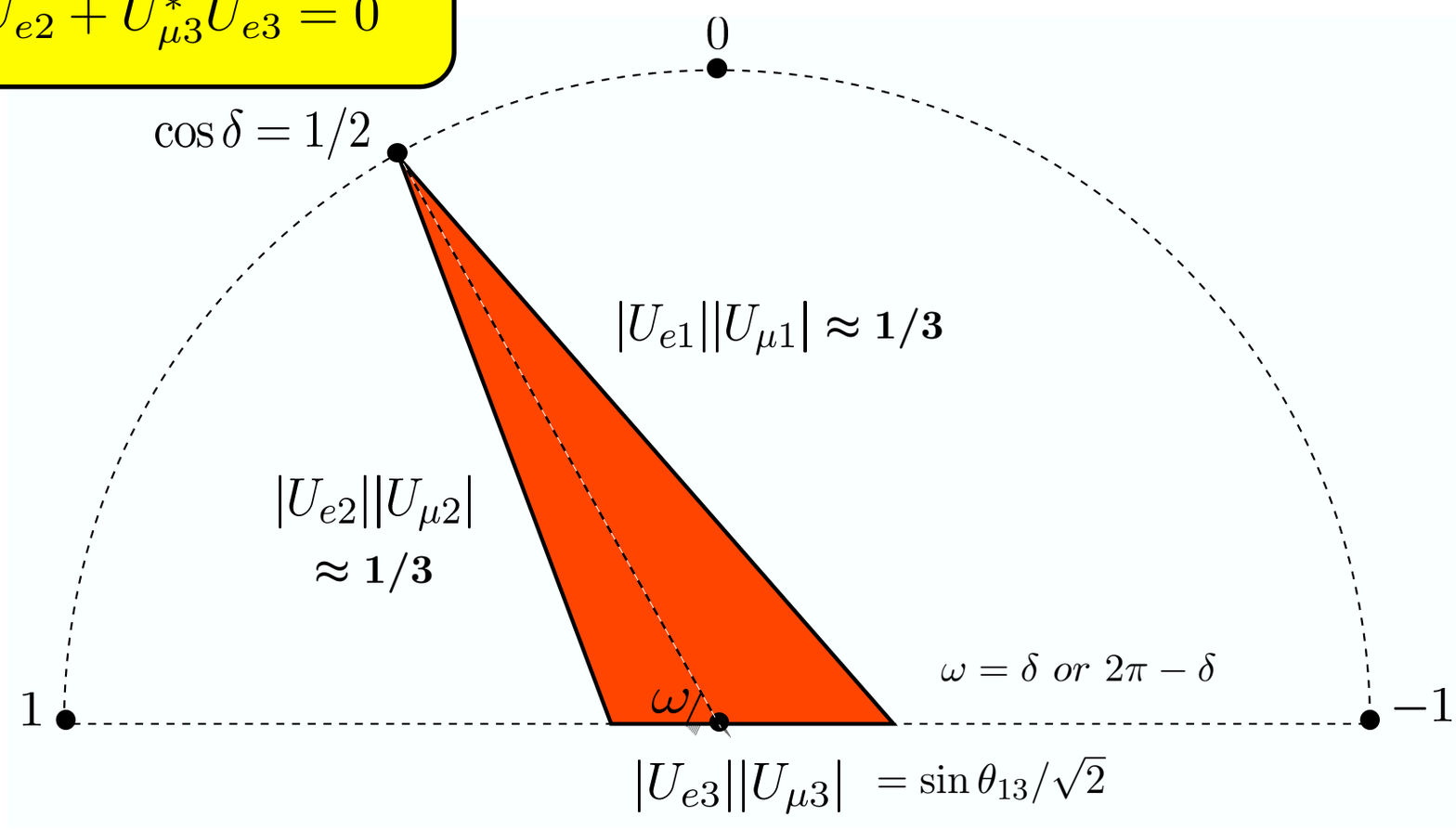
Are the deviations from TBM related?

Yes, of course!!!
(except HM et al)

Close to Tri-Bi-Maximal: Accident or Symmetry ?

Unitarity Triangle:

$$U^*_{\mu 1}U_{e1} + U^*_{\mu 2}U_{e2} + U^*_{\mu 3}U_{e3} = 0$$



$$|J| = 2 \times Area$$

$$J = s_{12}c_{12}s_{23}c_{23}s_{13}c^2_{13}\sin\delta$$

$\nu_\mu \rightarrow \nu_e$

In Matter:

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

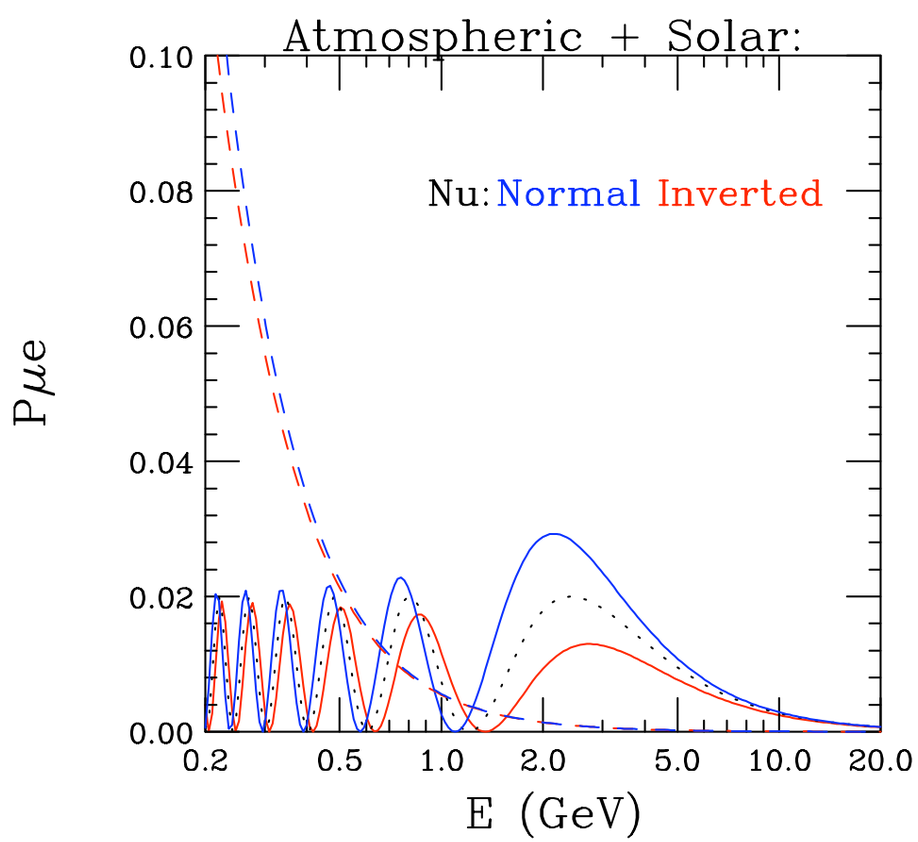
where $\sqrt{P_{atm}} = \sin\theta_{23} \sin 2\theta_{13} \frac{\sin(\Delta_{31} \mp aL)}{(\Delta_{31} \mp aL)} \Delta_{31}$

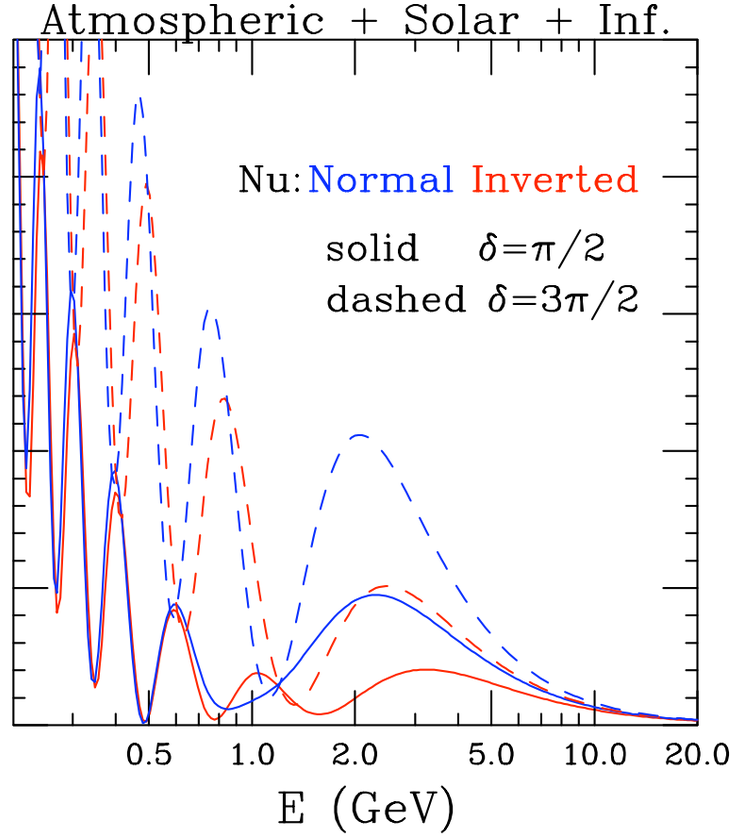
and $\sqrt{P_{sol}} = \cos\theta_{23} \sin 2\theta_{12} \frac{\sin(aL)}{(aL)} \Delta_{21}$

For $L = 1200\ km$
and $\sin^2 2\theta_{13} = 0.04$

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

Anti-Nu: Normal Inverted
dashes $\delta = \pi/2$
solid $\delta = 3\pi/2$





Theta_23:

$\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$

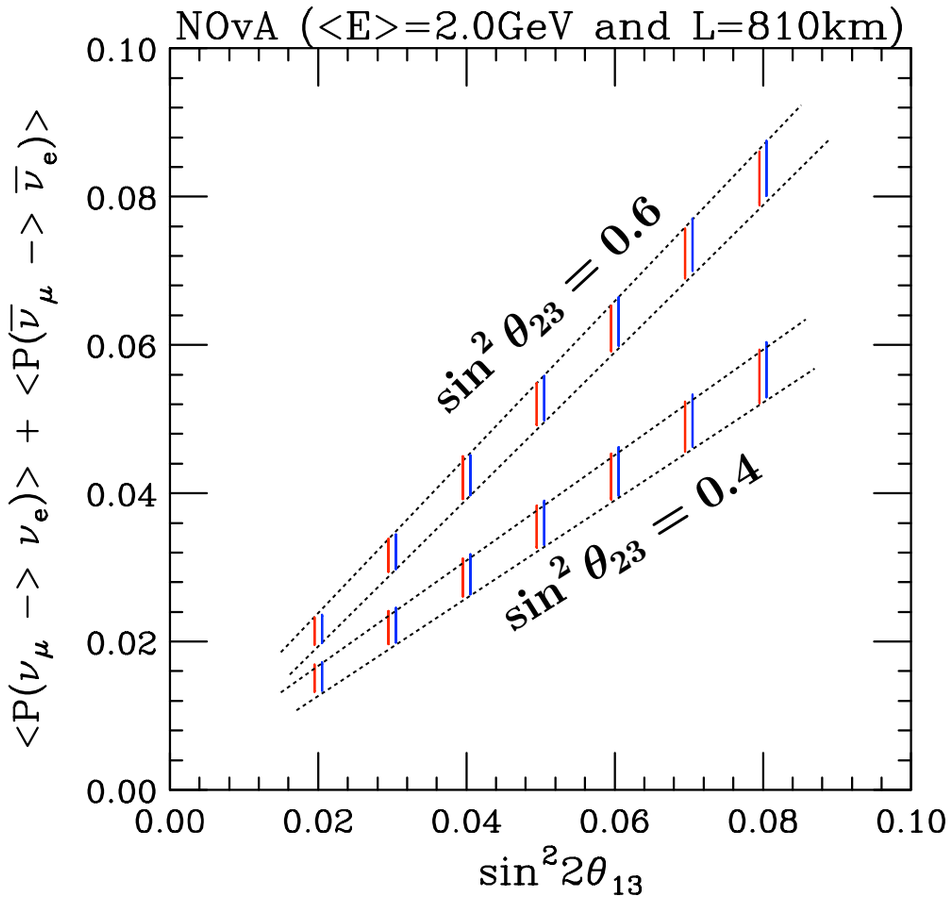
At Vac. Osc. Max. ($\Delta_{31} = \frac{\pi}{2}$)

$$P(\nu_\mu \rightarrow \nu_e) + P(\bar{\nu}_\mu \rightarrow \bar{\nu}_e) \approx 2 \sin^2\theta_{23} \sin^2 2\theta_{13} \quad + \quad \mathcal{O}[(aL)\sin\delta]$$

directly comparable to reactor

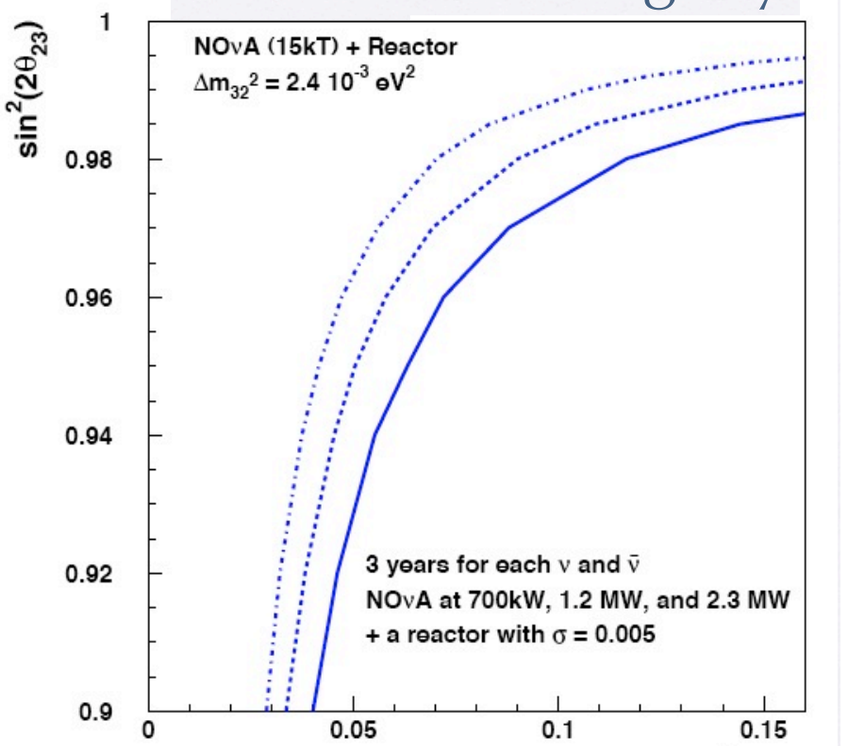
$$1 - P(\bar{\nu}_e \rightarrow \bar{\nu}_e) = \sin^2 2\theta_{13}$$

NOvA



For $\sin^2 2\theta_{23} = 0.96$
thus $\sin^2\theta_{23} = 0.4$ or 0.6 (4*0.4*0.6=0.96)

95% CL Resolution of the θ_{23} ambiguity



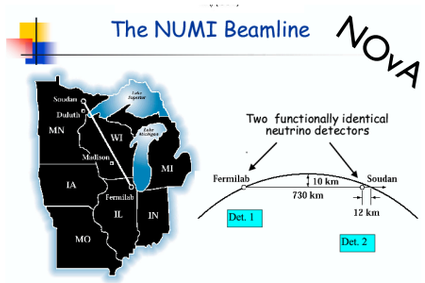
T2K could also do this, if they ran $\bar{\nu}_\mu$

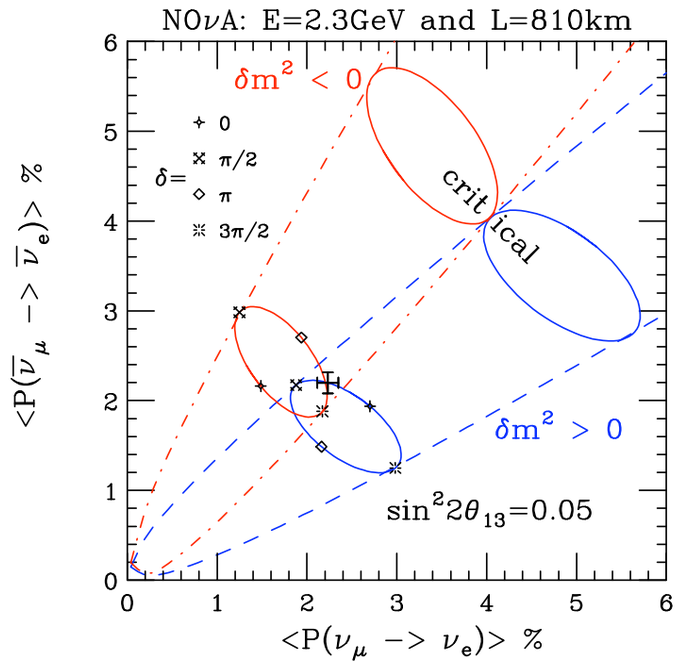
Mass Hierarchy:

Do we need to exclude Normal Hierarchy at a high CL than Inverted Hierarchy?

Does anybody care above 5 sigma?

Mass Hierarchy:





$$\sin^2 2\theta_{crit} = 0.10$$

$$\theta_{crit} = \frac{\pi^2}{8}\,\frac{\sin 2\theta_{12}}{\tan\theta_{23}}\,\frac{\delta m^2_{21}}{\delta m^2_{31}}\left(\frac{4\Delta^2/\pi^2}{1-\Delta\cot\Delta}\right)/(aL) \sim 1/6$$

$$\boldsymbol{\sin^2 2\theta_{crit} \sim 1/(aL)^{2+\epsilon}}$$

in the overlap region

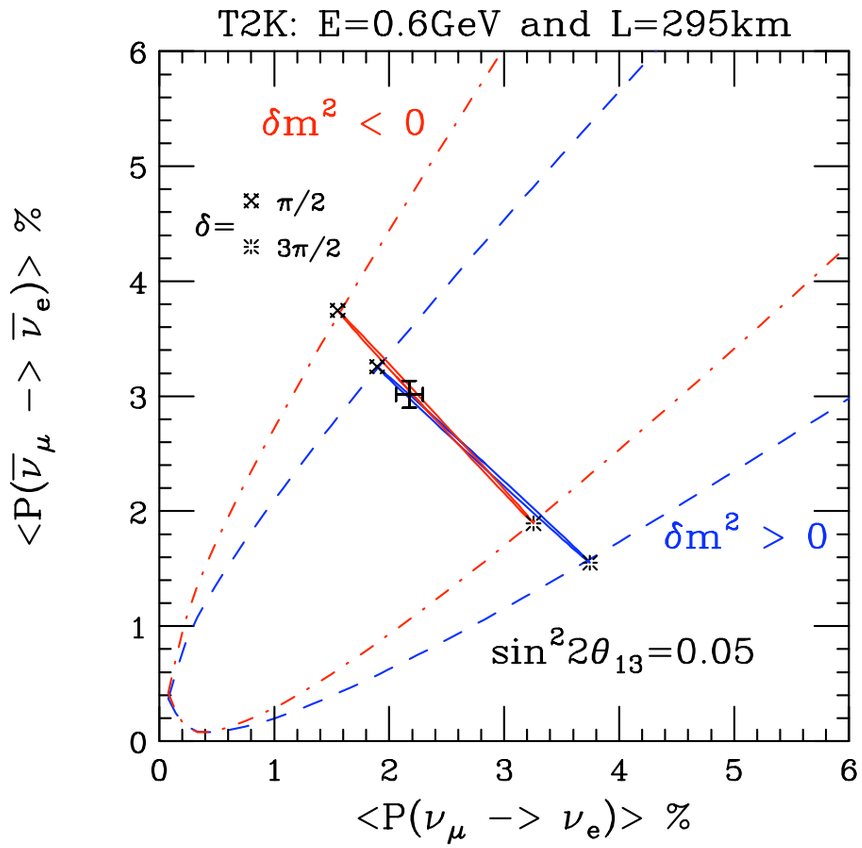
$$\langle \sin\delta\rangle_+ - \langle \sin\delta\rangle_- \;=\; 2\langle\theta\rangle/\theta_{crit} \;\approx\; 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

exact along diagonal --- approximately true throughout the overlap region!!!

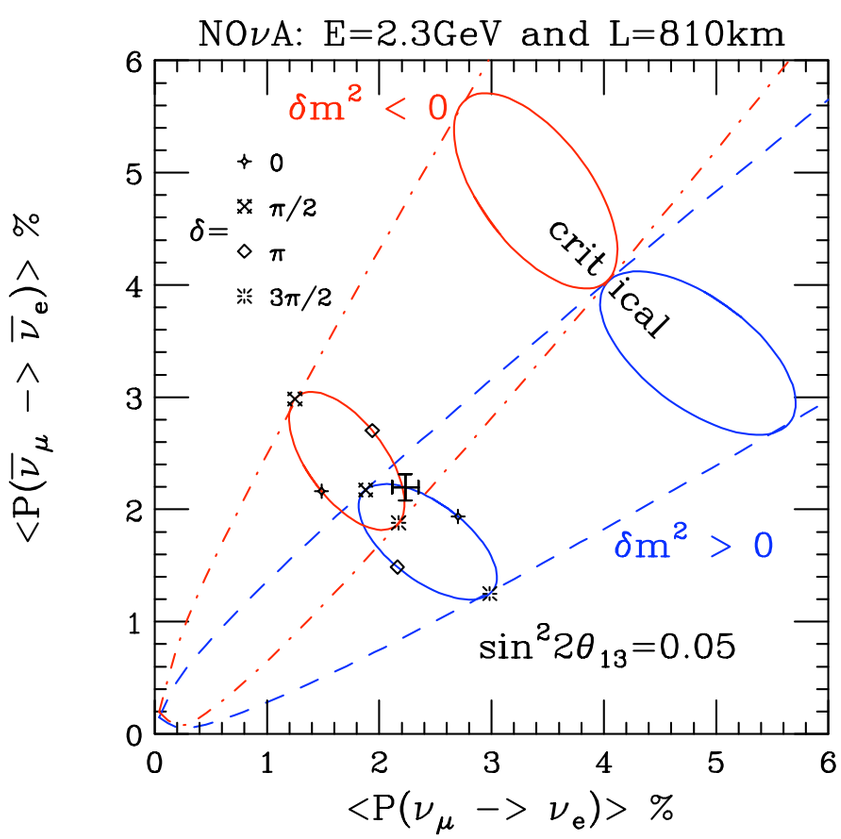
O. Mena + SP
hep-ph/0408070

T2K + NOvA:

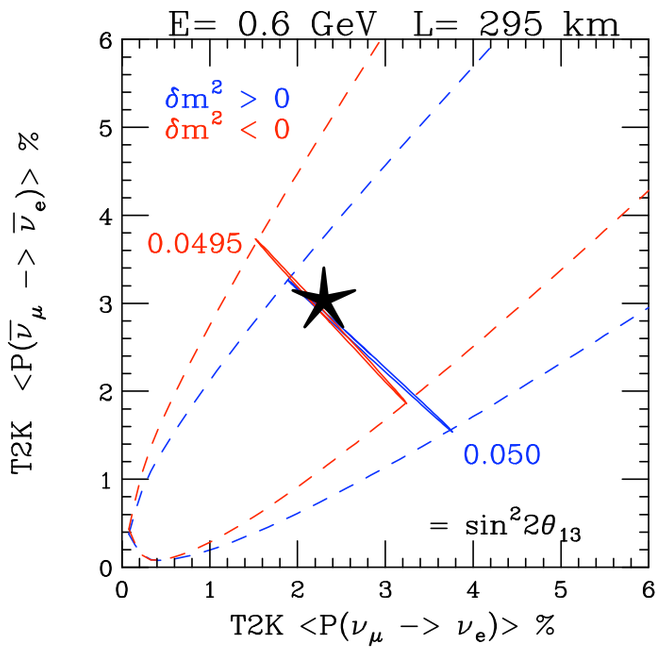
T2K:

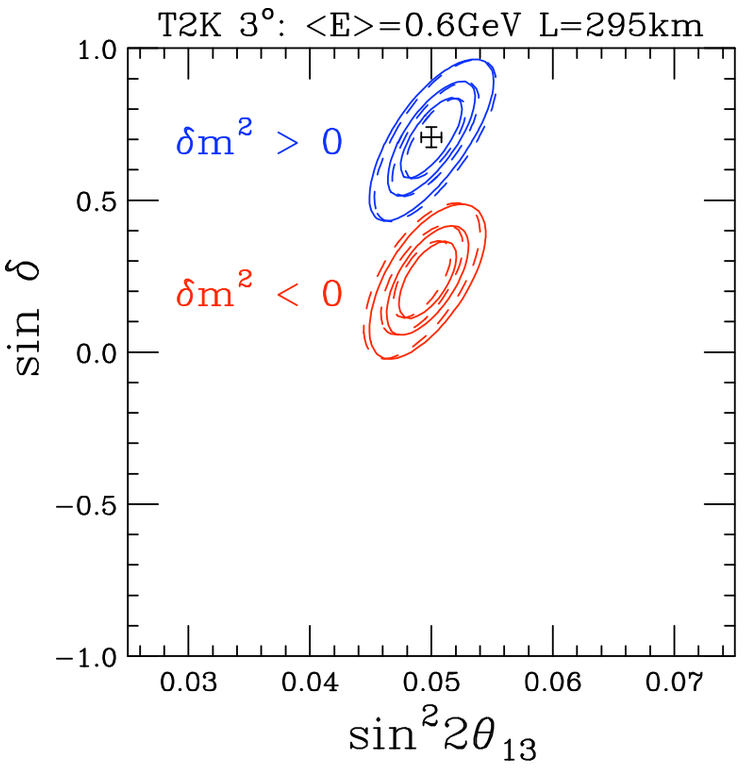


NOvA:

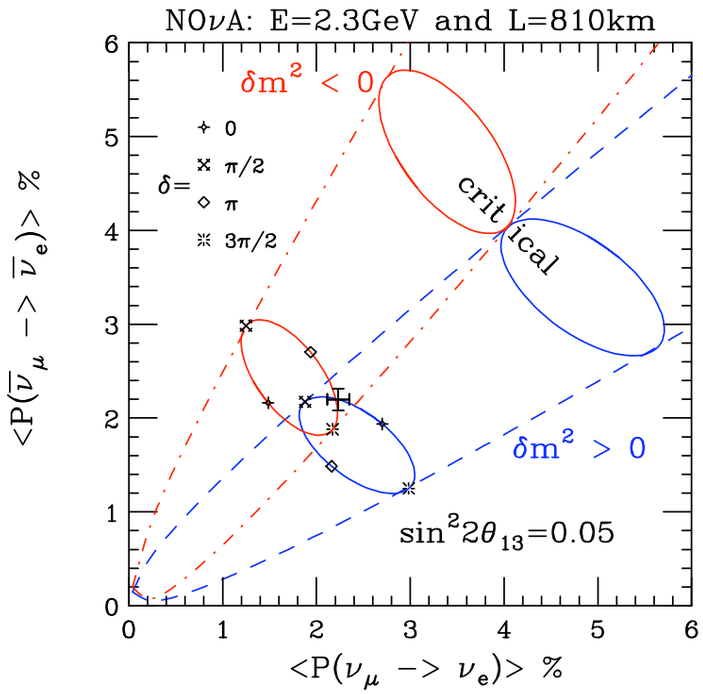


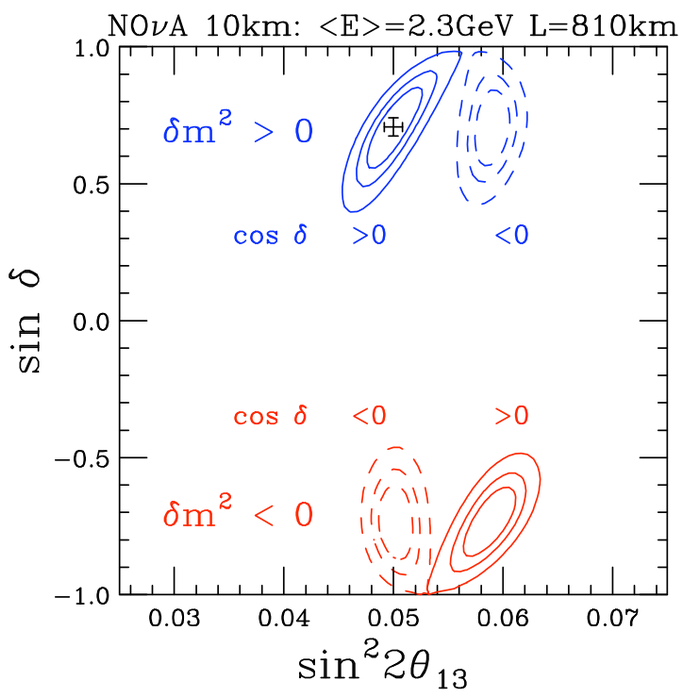
"T2K" + "NOvA"





$$\langle \sin\delta \rangle_+ \quad - \quad \langle \sin\delta \rangle_- \approx 0.47\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

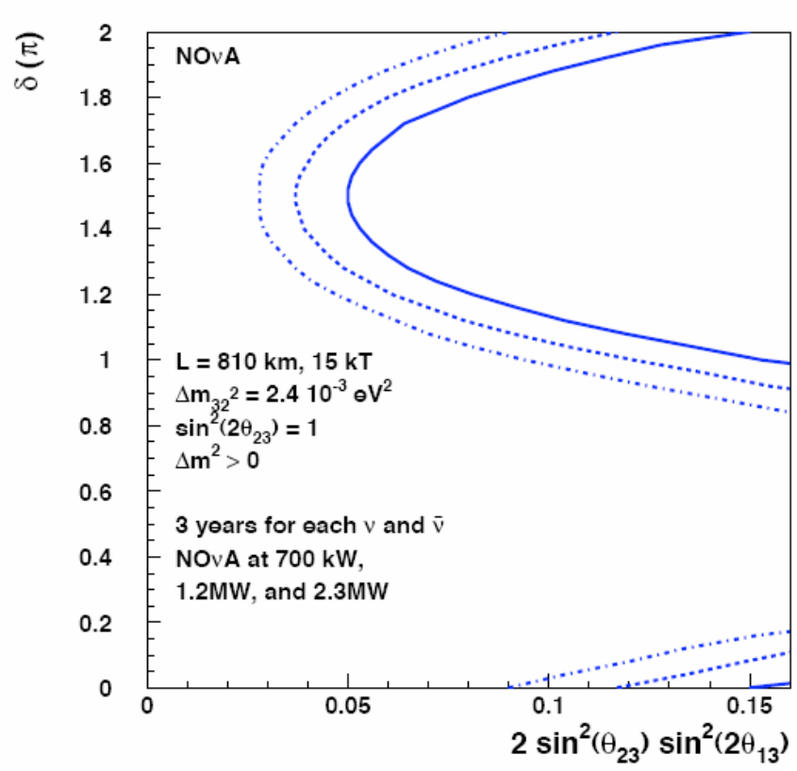




$$\langle \sin\delta \rangle_+ \quad - \quad \langle \sin\delta \rangle_- \approx 1.4\sqrt{\frac{\sin^2 2\theta_{13}}{0.05}}$$

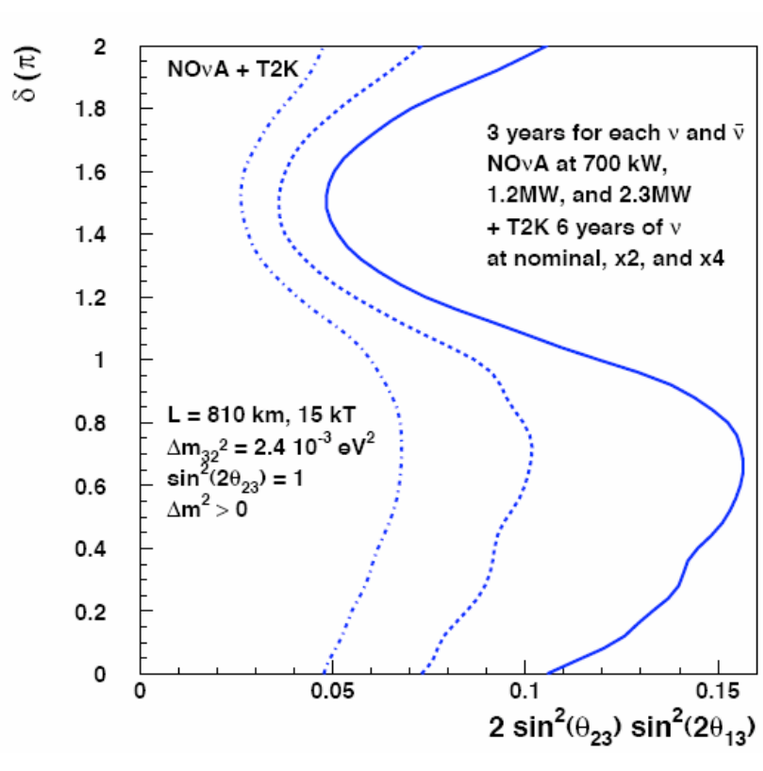
NOvA + T2K nuetrinos:

95% CL Resolution of the Mass Ordering
NOvA Alone



Normal Ordering

95% CL Resolution of the Mass Ordering
NOvA Plus T2K

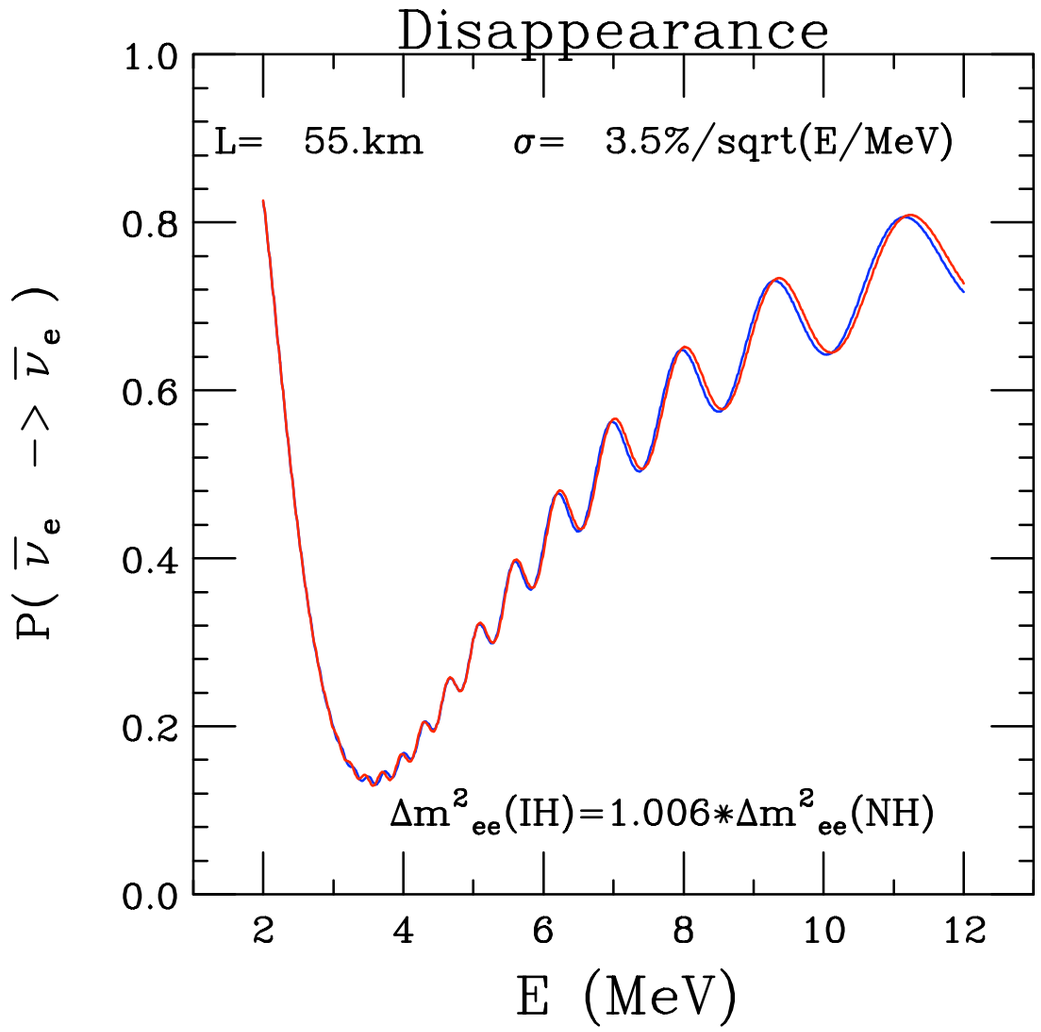


Normal Ordering

for Inverted Hierarchy $\delta \to \pi - \delta$

Mass Hierarchy from Reactor Nu:

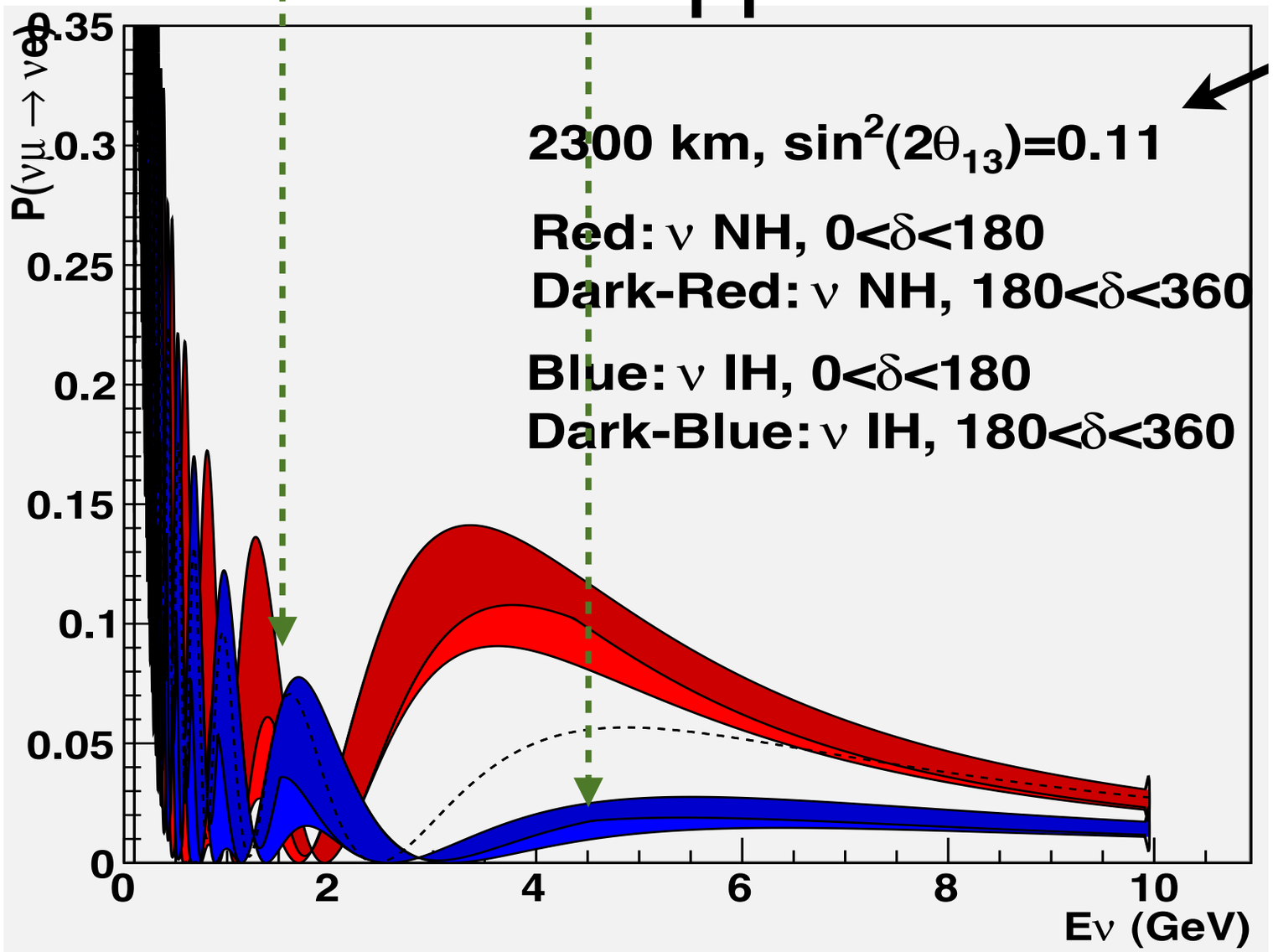
Neutrinos from 2-8 MeV:



% diff < 2% !!!

bi-Magic Baseline:

Electron appearance

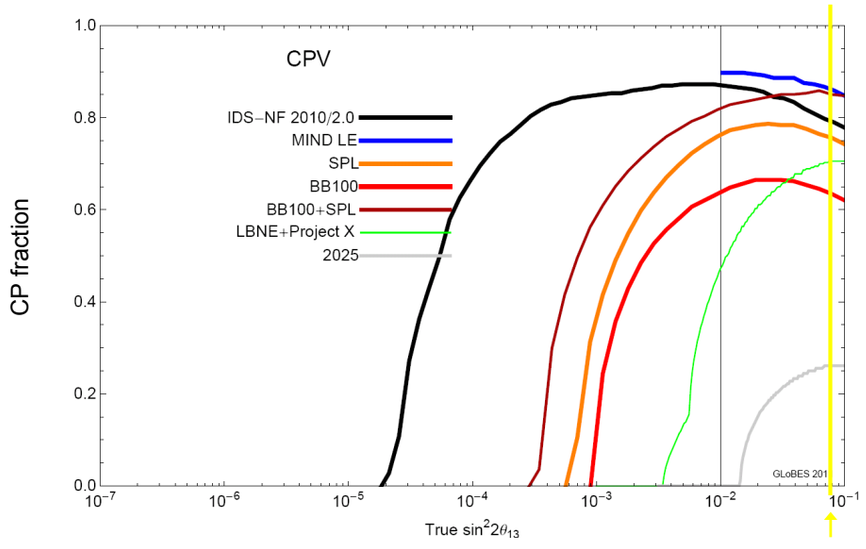


A. Ruddia 10th ICFA Seminar on

Not obviously required for mass hierarchy determination for large Theta_13 !

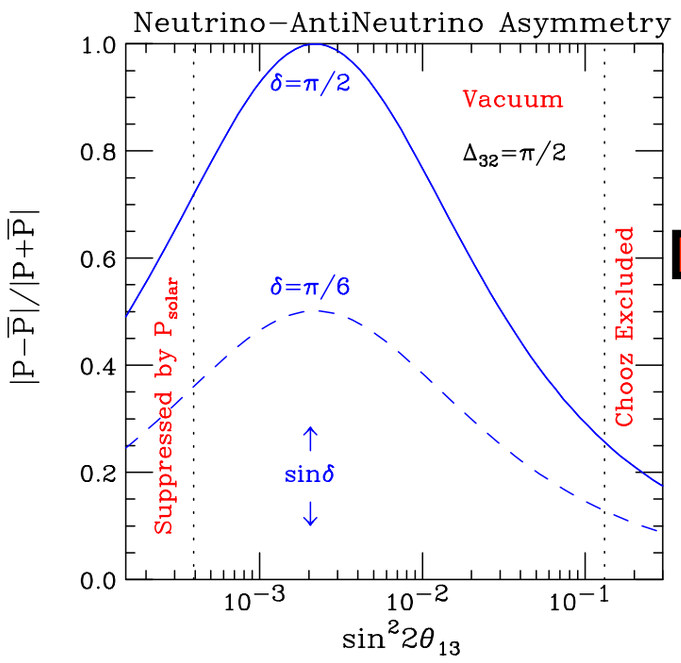
CP Violation:

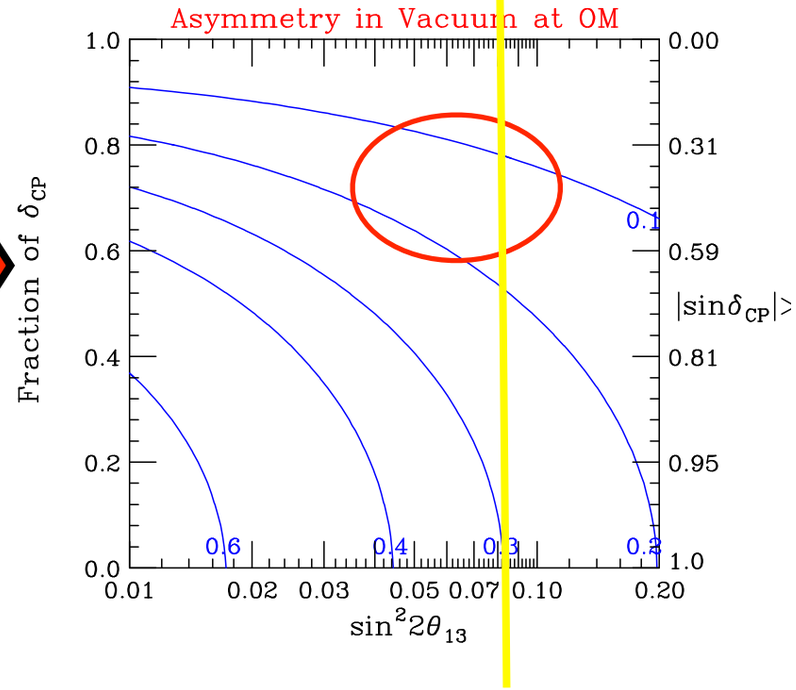
Asymmetry:



$$A_{vac} \approx \frac{1}{11} \frac{\sin 2\theta_{13} \sin \delta}{(\sin^2 2\theta_{13} + 0.002)}$$

Vacuum, at 1st oscillation maximum





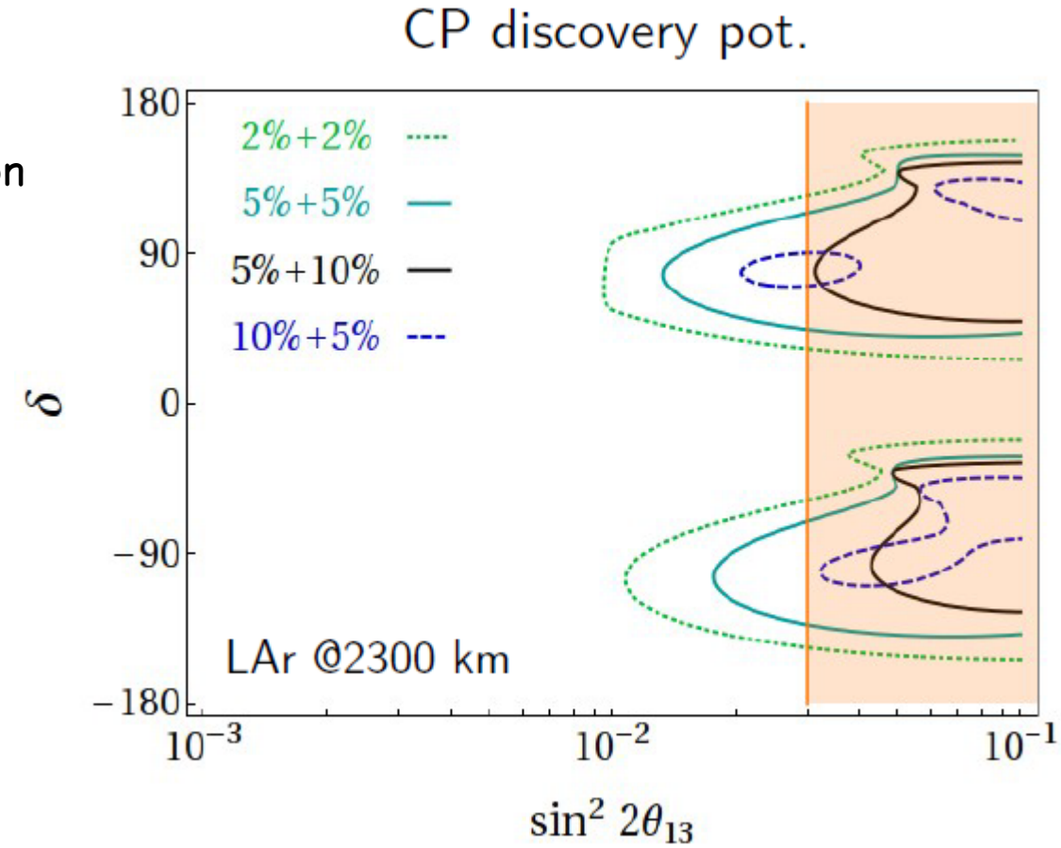
Status of WP6

E. Fernández-Martínez, A. Donini, P. Hernández

WP6 Task 2

3) Impact of large θ_{13} (ongoing effort)

Performance comparison of LAGUNA baselines and dependence on experimental variables



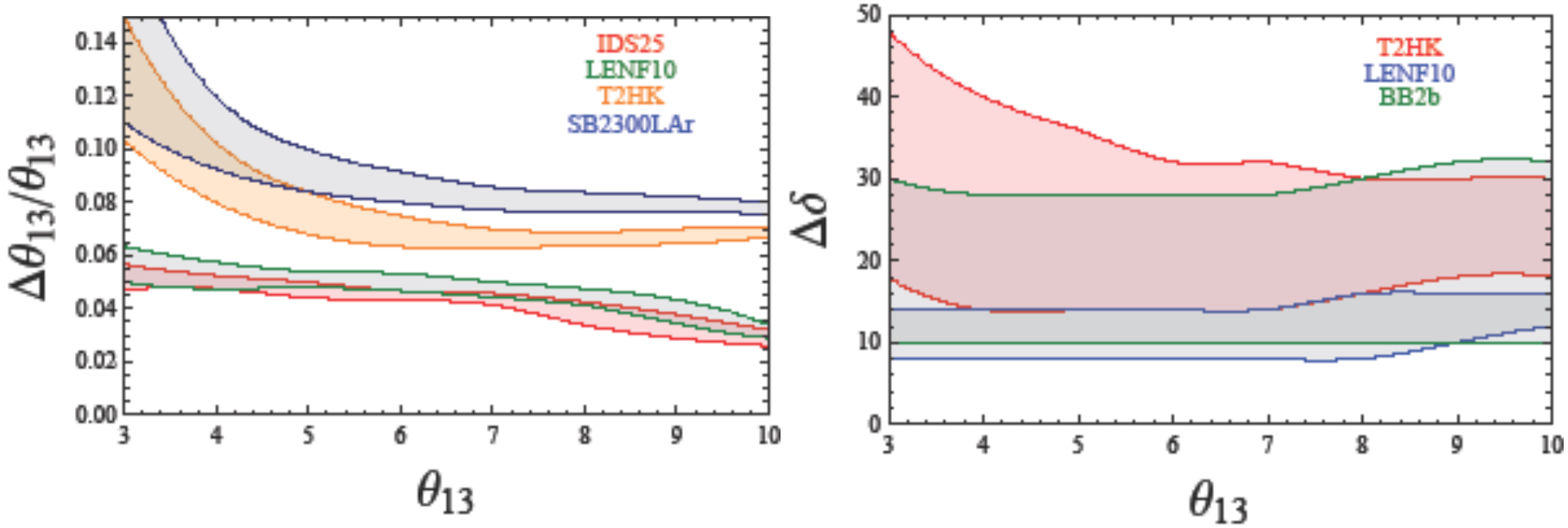
P. Coloma PhD Thesis

WP6 Task 2

3) Impact of large θ_{13} (ongoing effort)

Exclusion plots not very informative if θ_{13} is known-> need to quantify precision

Eg: $\Delta\theta_{13}/\theta_{13}$, $\Delta\delta$



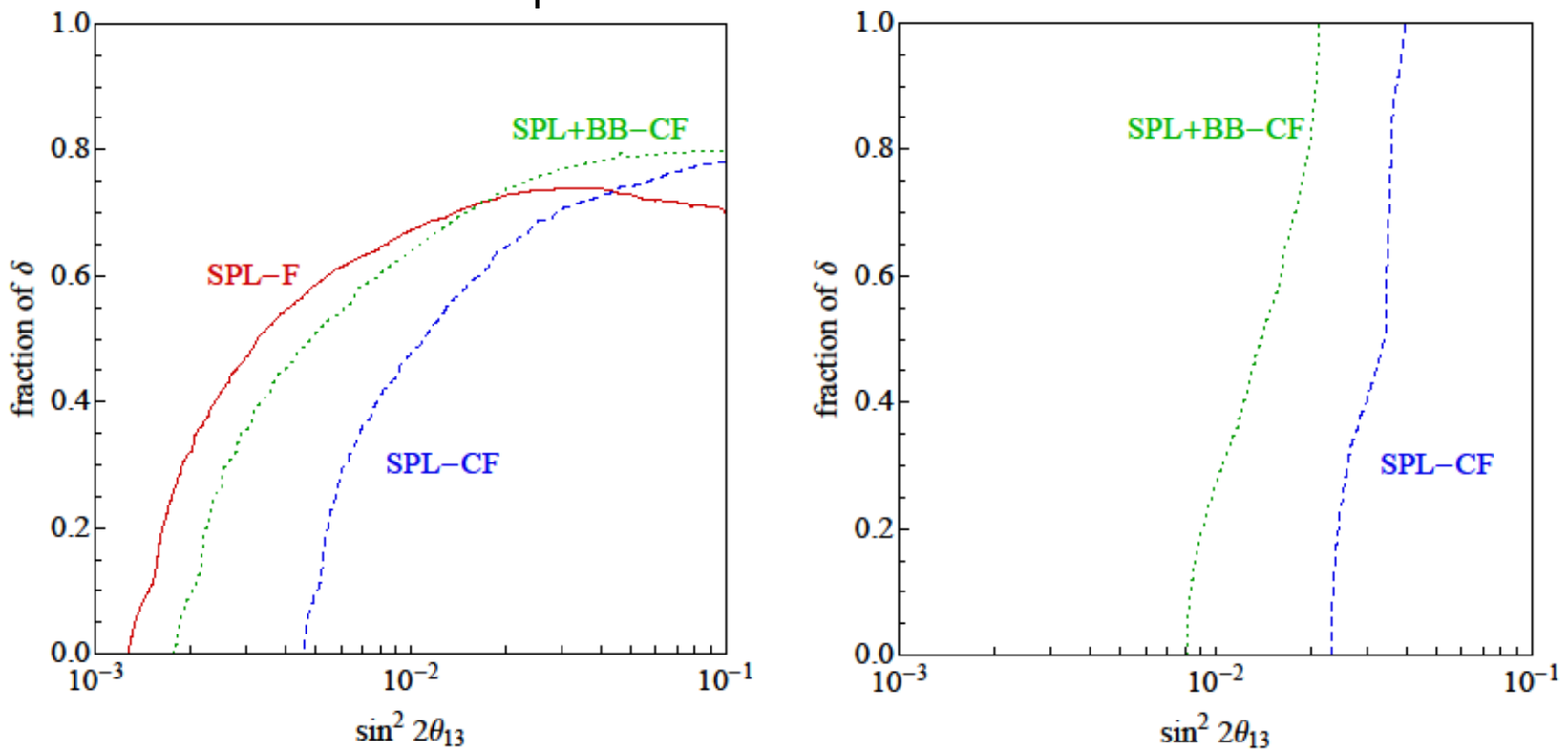
P. Coloma, A. Donini and P. Hernández, work in progress

WP6 Task 2

3) Impact of large θ_{13} (ongoing effort)

Multiple CLs needed !
say 2,3 5 sigma

SPL @ second oscillation peak

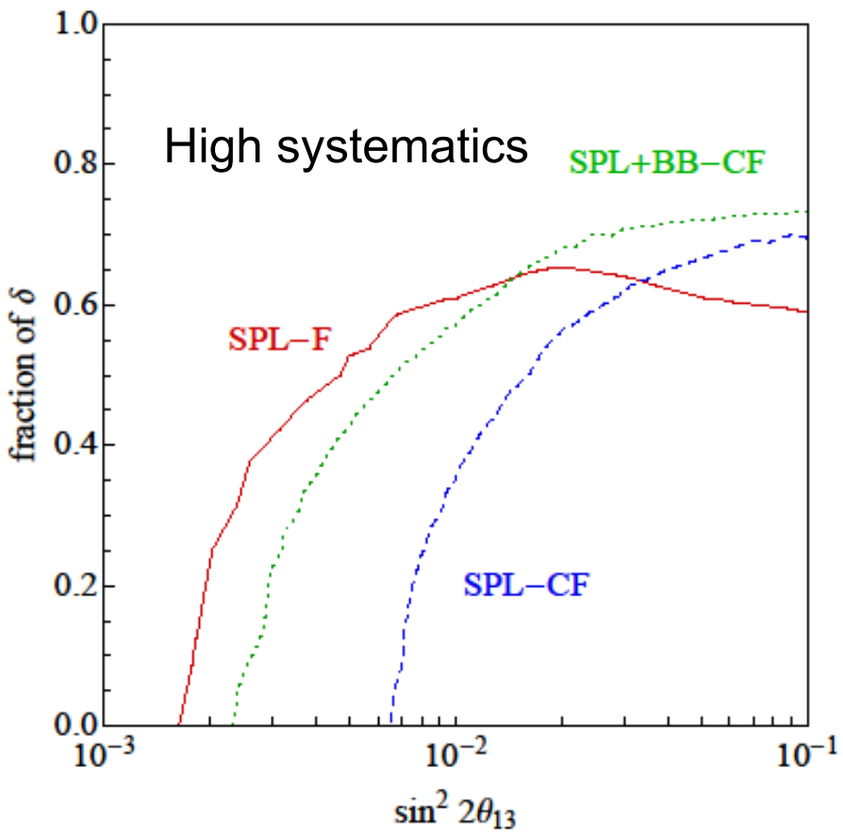


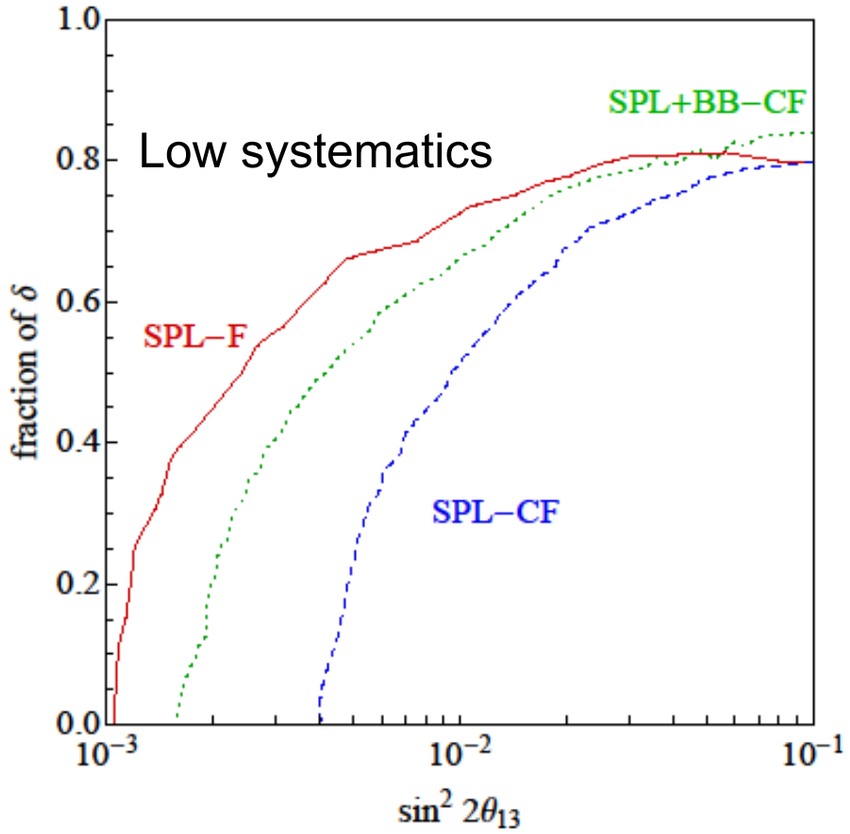
P. Coloma and EFM work in progress

E. Fernández-Martínez,

WP6 Task 2

4) Systematic uncertainties (will become more critical for large θ_{13})





P. Coloma and EFM work in progress

NF constraints on NSI

Model independent approach. Mild experimental constraints:

$$|\varepsilon^{\oplus}_{\alpha\beta}| < \begin{pmatrix} 4.2 & 0.33 & 3.0 \\ 0.33 & 0.068 & 0.33 \\ 3.0 & 0.33 & 21 \end{pmatrix}$$

Sterile Neutrinos less likely to effect Theta_13, MH and CPV determination:

Summary & Conclusions:

- Large Theta_13, if confirmed
  - wonderful opportunity for all !!!
    - Double Chooz, Daya Bay and Reno, T2K, NOvA ....
    - precision determination of Theta_13
    - exclude wrong Hierarchy at high CL
    - CPV, precision dominated by systematic effects!
    - New Physics less likely to be entangled with Theta_13 effects !