Measuring the deviation from maximal mixing of atmospheric neutrinos at INO

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- ICAL@INO
- ν-factfile and $D \equiv 1/2 - \sin^2\theta_{23}$
- $P_{\mu\mu}, P_{\bar{\mu}\bar{\mu}}$ and extrema
- Binned U/D and $(U/D)_N - (U/D)_A$ for atmospheric neutrinos
- Sensitivity to $|D|, sgn.D$
- Summary

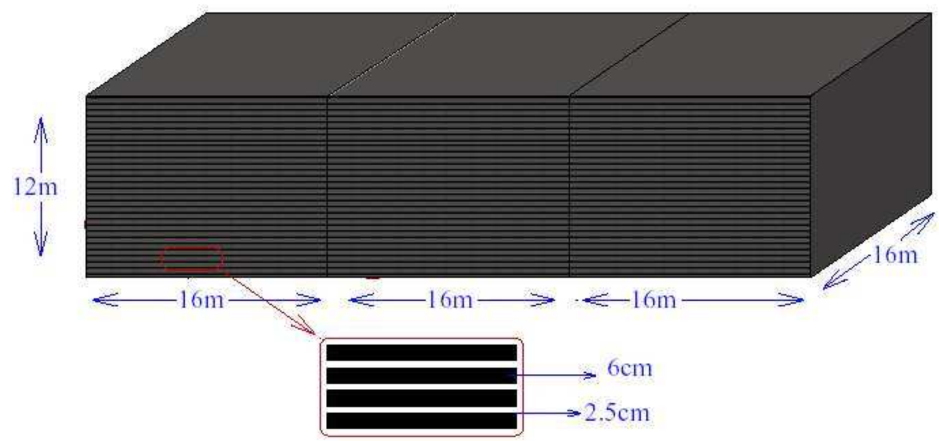
India-based Neutrino Observatory proposed at PUSHEP near Mysore in South India

(url : http : //www.imsc.res.in/~ino)

$\sim 2200m$ underground

$\sim 900m$ above MSL

Large magnetized iron calorimeter ICAL with 140 layers of iron plates.



Three modules. Total weight 50 ktons. Active detector element: RPC (?)

Neutrino factfile and focus on $D = 1/2 - \sin^2\theta_W$

3 weakly interacting ν's

- $\nearrow$ ν_e, ν_μ, ν_τ (flavor basis)
- $\searrow$ ν_1, ν_2, ν_3 (mass basis, eigenvalues $m_{1,2,3}$)

$$\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$$

$$\sum_i m_i \; < \; 0(1)\; eV \quad \text{from cosmology}$$

$$\sqrt{\Delta m_{21}{}^2} \; \sim \; 0.009\; eV \quad \text{(Solar \& KamLAND)}$$

$$\sqrt{|\Delta m_{32}{}^2|} \; \sim \; 0.05\; eV \quad \text{(atmospheric)}$$

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = U \leftrightarrow \begin{pmatrix}\nu_1\\ \nu_2\\ \nu_3\end{pmatrix}, \quad U \equiv U_{PMNS}(\underleftrightarrow{\theta_{12},\theta_{23},\theta_{13}},\delta)$$

$\uparrow$

definable
within first quadrant

$$\theta_{12} \sim 32^\circ, \theta_{23} \sim 45^\circ, \theta_{13} < 13^\circ, \delta = ?$$

$$|U_{PMNS}| \sim \begin{pmatrix} 0.8 & 0.5 & < 0.2 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}, \quad \text{contrast} \quad |V_{CKM}| \sim \begin{pmatrix} 0.97 & 0.22 & 0.003 \\ 0.22 & 0.97 & 0.04 \\ 0.01 & 0.04 & 0.99 \end{pmatrix}$$

3σ limits

$$7.2 \times 10^{-5}\ eV^2 < \Delta m^2_{21} < 8.9 \times 10^{-5}\ eV^2$$

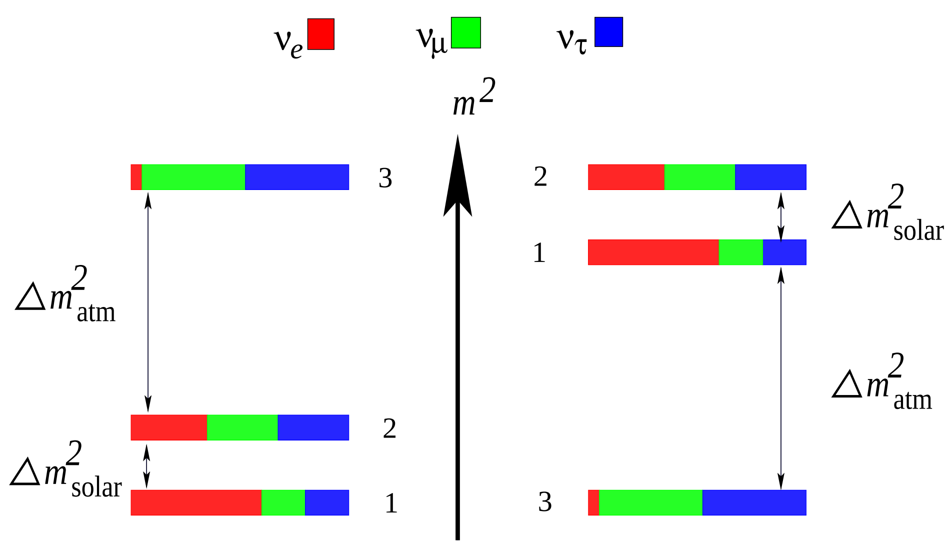
$$1.7 \times 10^{-3}\ eV^2 < |\Delta m^2_{32}| < 3.3 \times 10^{-3}\ eV^2$$

$$30^\circ < \theta_{12} < 38^\circ$$

$$36^\circ < \theta_{23} < 54^\circ \qquad -0.16 < D < 0.16$$

$$2\sigma: \ -0.10 < D < 0.10$$

$$1\sigma: \ -0.07 < D < 0.07$$



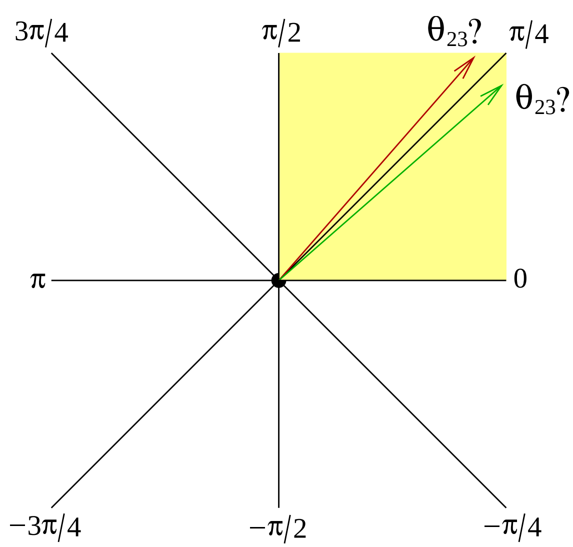
Maximality of $\theta_{23} = \pi/4$

Vacuum ν_μ 2-flavor oscillation $P \propto \sin^2 2\theta_{23}$

Models with $|D| \sim 0.005$ to $0.16 \leftrightarrow \begin{cases} \text{QLC (Minakata – Smirnov, 2003)} \\ \text{Broken } \mu - \tau \text{ exchange symmetry (Mohapatra, 2004)} \end{cases}$

(and sgn.$D >$ or < 0)

Octant ambiguity and sgn.D



$\nu_\mu, \bar{\nu}_\mu$ survival probability and spectral shape

Neutrino propagation in matter

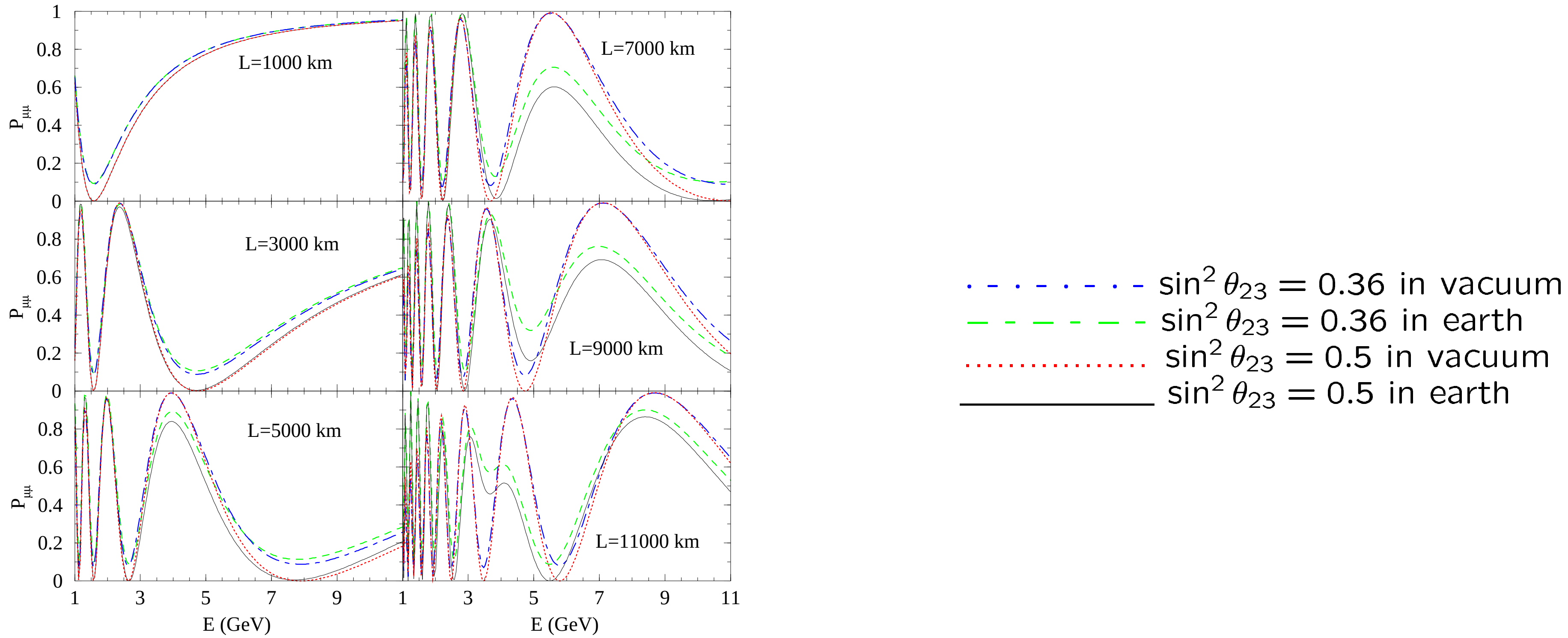
$$\begin{aligned} H &= \frac{1}{2E} U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger + \begin{pmatrix} \sqrt{2} G_F N_e(x) & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\ &= \frac{1}{2E} U_M \begin{pmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{pmatrix} U_M^\dagger, \; U_M = U\left(\theta_{ij} \to \theta^M_{ij}, \; \delta \to \delta^M\right). \end{aligned}$$

Survival probabilities

$$P_{\mu\mu}(L) = 1-4\Big[|U^M_{\mu 1}|^2|U^M_{\mu 2}|^2\sin^2\frac{\lambda_1-\lambda_2}{4E}L + |U^M_{\mu 2}|^2|U^M_{\mu 3}|^2\sin^2\frac{\lambda_2-\lambda_3}{4E}L$$
$$+|U^M_{\mu 3}|^2|U^M_{\mu 1}|^2\sin^2\frac{\lambda_3-\lambda_1}{4E}L\Big] = P^{\text{vac}}_{\mu\mu}(L) + P^M_\mu(A,\Delta,\alpha)$$

$$P_{\bar\mu\bar\mu}(L) = P_{\mu\mu}(L, G_F \to -G_F) = P^{\text{vac}}_{\mu\mu}(L) - P^M_\mu(A,\Delta,\alpha).$$

$$A = \frac{2\sqrt{2}G_F N_e E}{\Delta m^2_{31}}, \propto = \frac{\Delta m^2_{21}}{\Delta m^2_{31}}, \Delta = \frac{\Delta m^2_{31}L}{4E}.$$

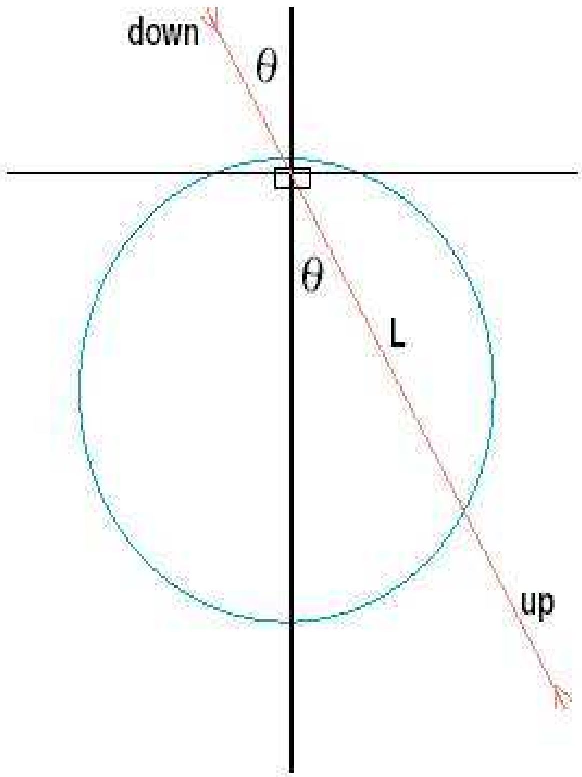


SPMIN 1, SPMAX, SPMIN 2

Binned U/D and $(U/D)_N - (U/D)_A$ for atmospheric neutrinos

Benchmark values for simulation

Δm^2_{31}	$=$	$2 \times 10^{-3}\ eV^2$
Δm^2_{21}	$=$	$8 \times 10^{-5}\ eV^2$
$\sin^2\theta_{12}$	$=$	0.28
δ	$=$	0
$\sin^2\theta_{23}$	$=$	0.36 and 0.5
$\sin^2\theta_{13}$	$=$	0.00, 0.02, 0.04



Flux : HONDA et al. (2004)

Energy and zenith angle resolution functions: gaussian with parameters from INO report

$$\text{Total \# of events} \begin{array}{l} \nearrow \mu^-: 15K \\ \searrow \mu^+: 7K \end{array}$$

Binning in **Both** E and $\cos\xi$ is the key new feature and improvement on earlier work.

$$\begin{array}{ccccccc} 5 & \times & 12 & \times & 2 & = & 120 \text{ bins} \\ \uparrow & & \uparrow & & \uparrow & & \\ \text{E} & & \xi & & \nu, \bar{\nu} & & \end{array}$$

Indumathi-Murthy (2004)

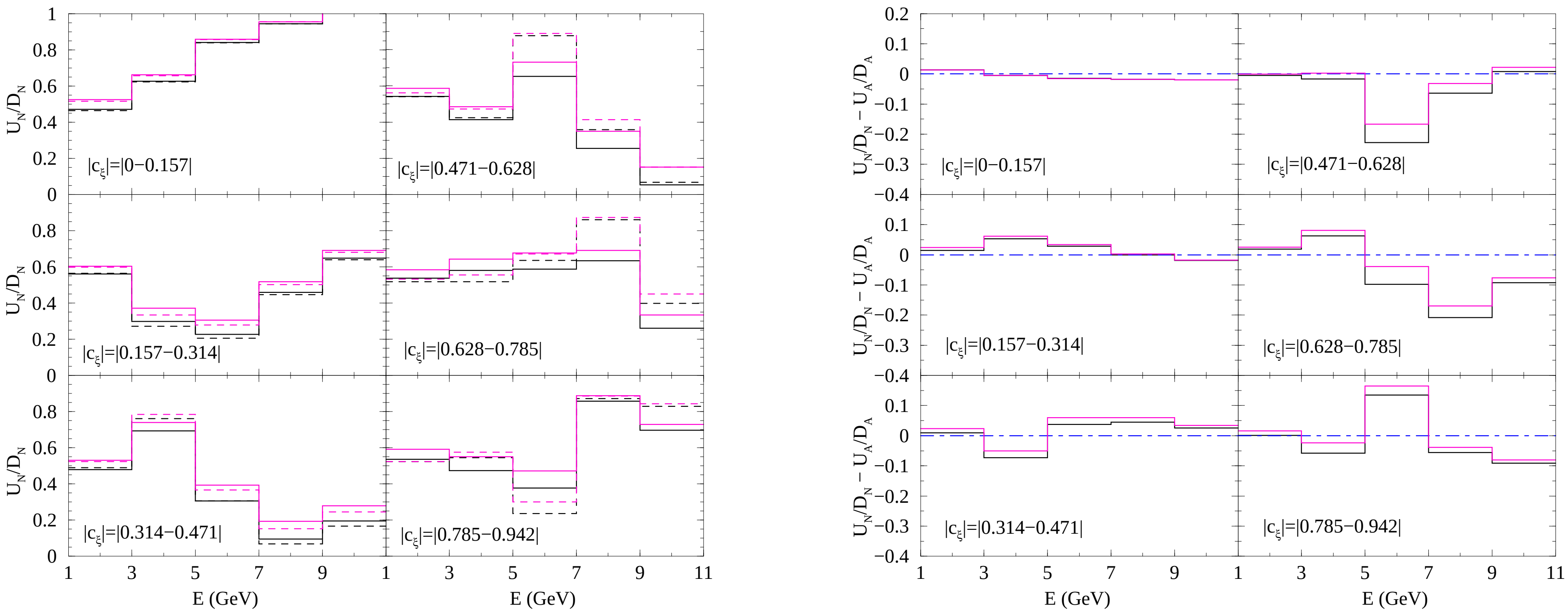
Gandhi, Ghoshal, Goswami, Mehta (2005)

$\sin^2\theta_{23} = 0.36$ in earth

$\sin^2\theta_{23} = 0.36$ in vacuum

$\sin^2\theta_{23} = 0.5$ in earth

$\sin^2\theta_{23} = 0.5$ in vacuum



Normal ordering: matter effects decrease / increase U_N/D_N at SPMAX / SPMIN making $\frac{U_N}{D_N} - \frac{U_A}{D_A}$ negative / positive

Sensitivity to $|D|$ and sgn. D

Error analysis

Stump et al. (2001)
Strumia, Visani (2001)
Fogli et al. (2002)

$$\chi^2_{atm} \equiv \min_{\xi_k} \left[\sum_{n=1}^{120} \left(\frac{\tilde{N}_n^{\text{th}} - N_n^{\text{data}}}{\sigma_{\text{stat}}} \right)^2 + \sum_{k=1}^{k} \xi_k^2 \right]$$

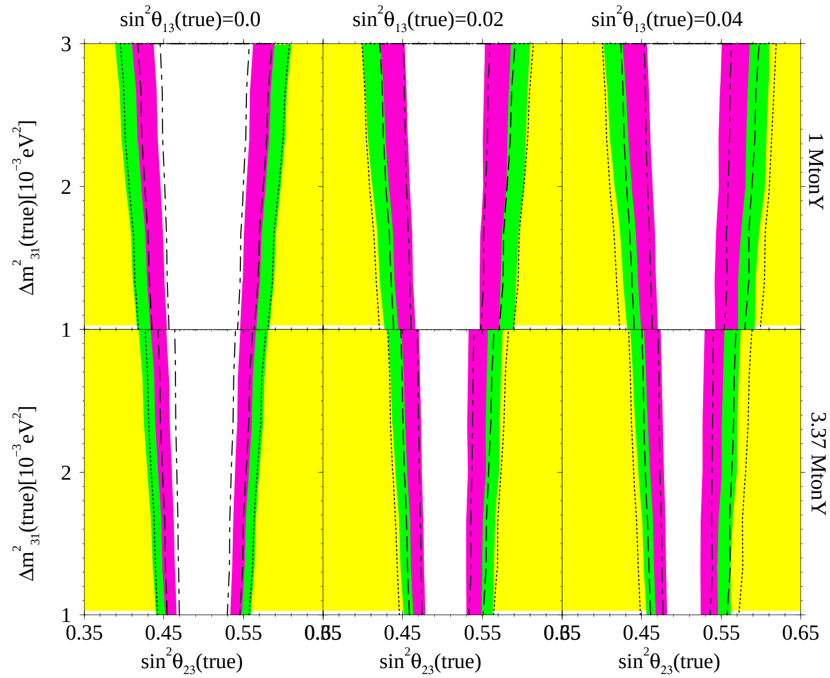
N_n^{th} = expected # of events in bin n with 'true' parametric values

N_n^{data} = expected # ofevents in bin n with parameters varying over allowed ranges

σ_{stat} = stat. error in bin n

ξ_k = kth "pull' i.e. systematic error

$\tilde{N}_n^{\text{th}}$ = $N_n^{\text{th}} \left[1 + \sum_{k=1}^{k} \Pi_n^k \xi_k \right] + \mathcal{O}(\xi_k^2)$.



← 1 MTY

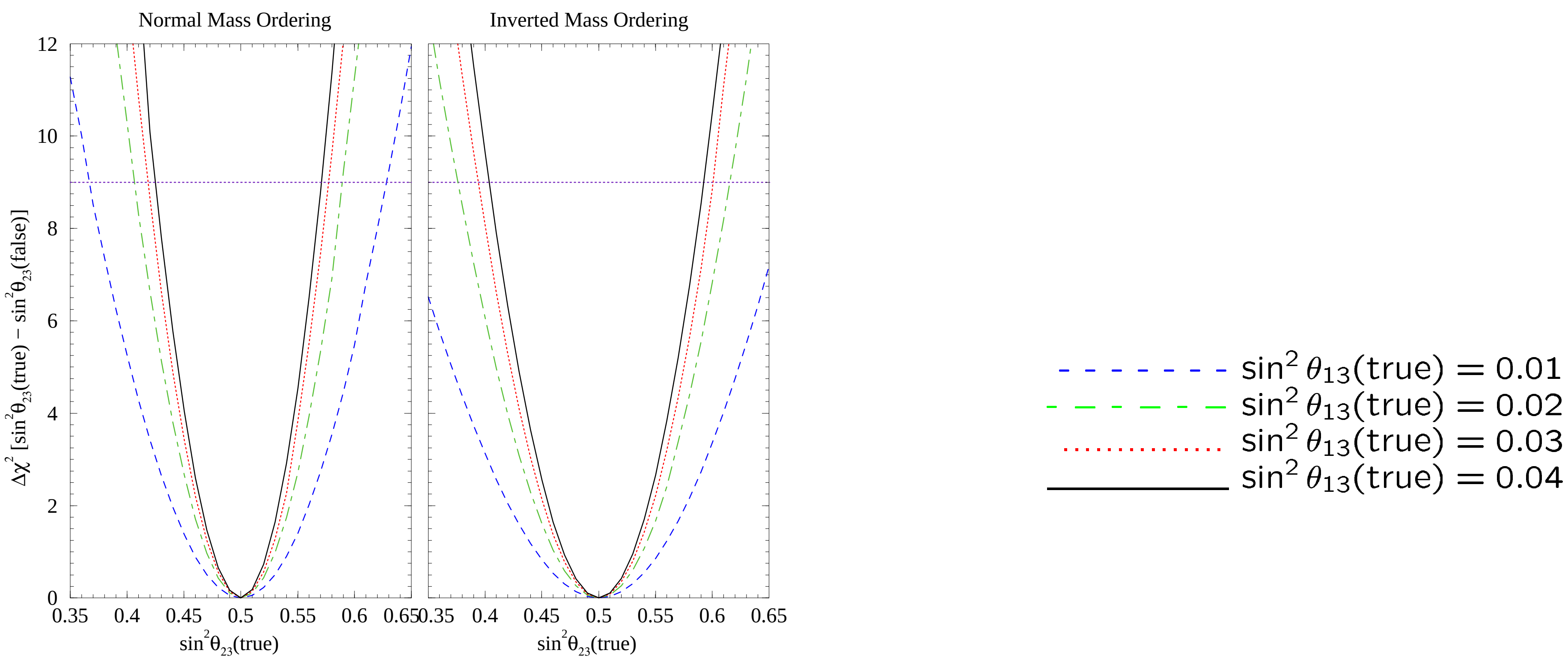
← 3.37 MTY

$|D|$ sensitivity comparable to 20 SK from water Cherenkov detector
18% vs. 23% at 3σ.

Octant ambiguity resolution better at ICAL for $\sin^2\theta_{13} \geq 0.01$.

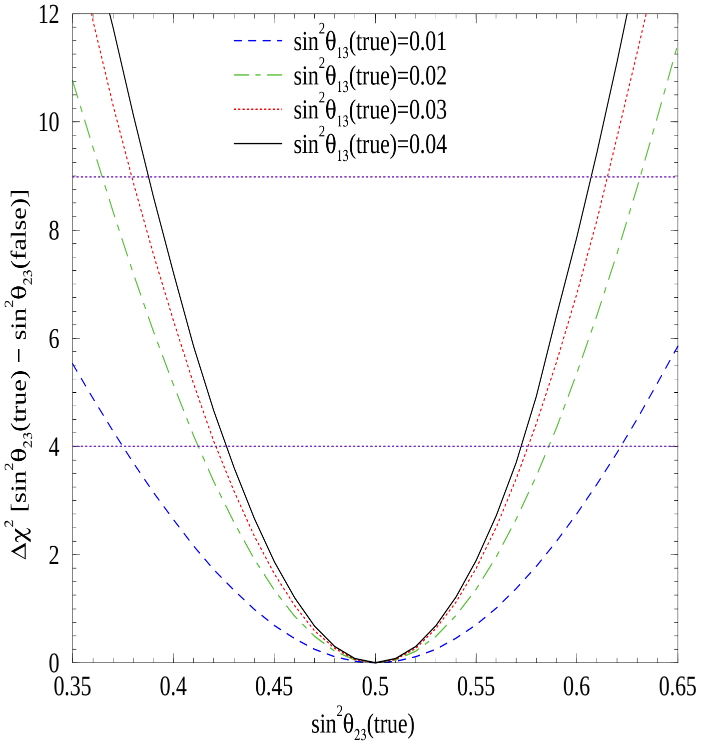
$$\Delta\chi^2 \equiv \chi^2\left[\sin^2\theta_{23}(\text{true}), \text{others}\right] - \chi^2\left[\sin^2\theta_{12}(\text{false}), \text{others}\right] \text{ vs } \sin^2\theta_{23}(\text{true})$$

1 MTY at ICAL



0.5 MTY of data at ICAL

If $\theta_{13} > 5.7^\circ$, $\theta_{23} < 37.8^\circ$ or $> 52.2^\circ$ can be resolved.
$\theta_{13} > 8.1^\circ$, $\theta_{23} < 40.0^\circ$ or $> 50.0^\circ$
$\theta_{13} > 10.0^\circ$, $\theta_{23} < 40.5^\circ$ or $> 49.5^\circ$
$\theta_{13} > 11.5^\circ$, $\theta_{23} < 40.9^\circ$ or $> 49.1^\circ$



For normal hierarchy,

90% c.l. resolution of octant ambiguity possible from 0.5 MTY at ICAL

Summary

- Established feasibility of statistically significant measurement of $D \equiv 1/2 - \sin^2\theta_{23}$ from 1 MTY of INO data.

- Binning in both energy and zenith angle essential; effect largest at SPMAX.

- Range of $|D|$ significantly sharpened over SK, comparable to capability of 20 SK.

- θ_{23} octant resolution sensitivity significantly better than megaton water Cherenkov detectors, provided $\theta_{13} > 5^\circ$.