India-based Neutrino Observatory:

INO as an

atmospheric and magic-baseline detector

D. Indumathi

The Institute of Mathematical Sciences, Chennai

For the INO Collaboration

(http://www.ino.tifr.res.in)

A Schematic of Neutrino Properties

Neutrino masses are not well-known. Oscillation studies only determine the mass-squared differences: $\Delta m^2_{ij} = m^2_i - m^2_j$ and the mixing angles θ_{ij}. Phase(s) unknown.

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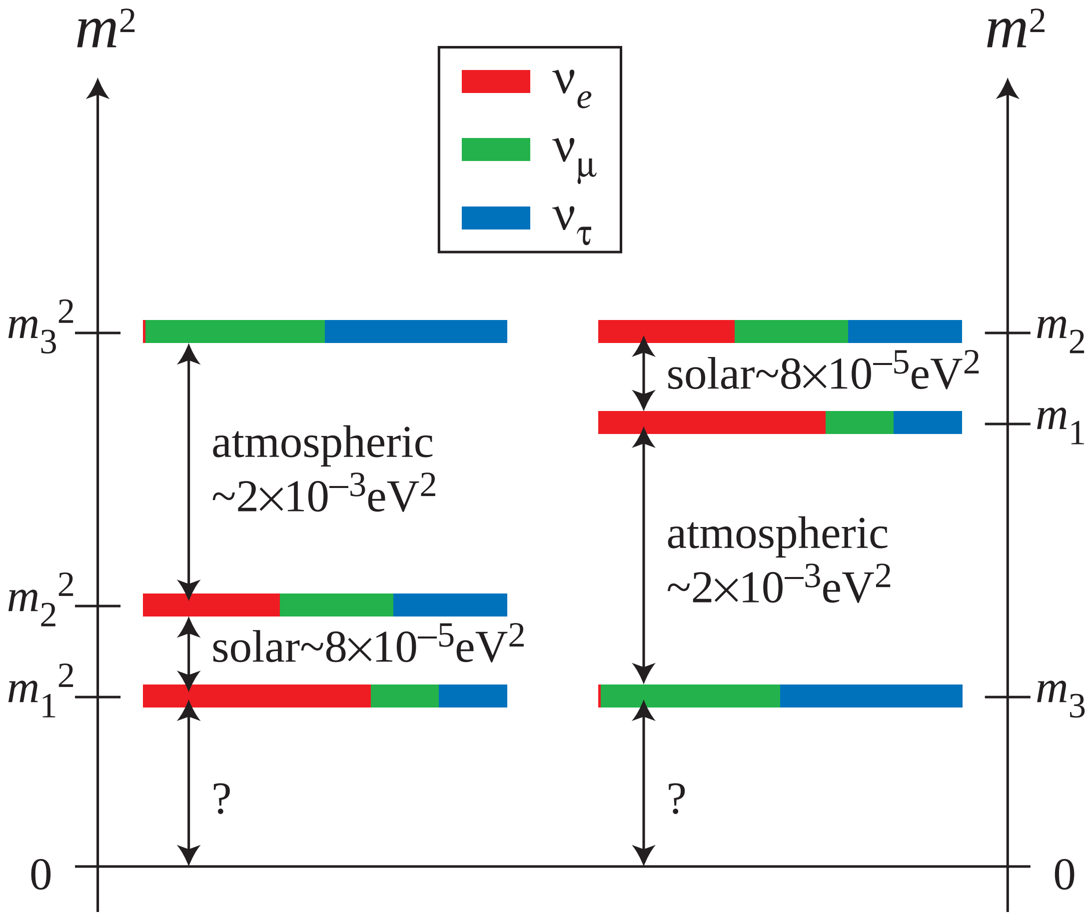

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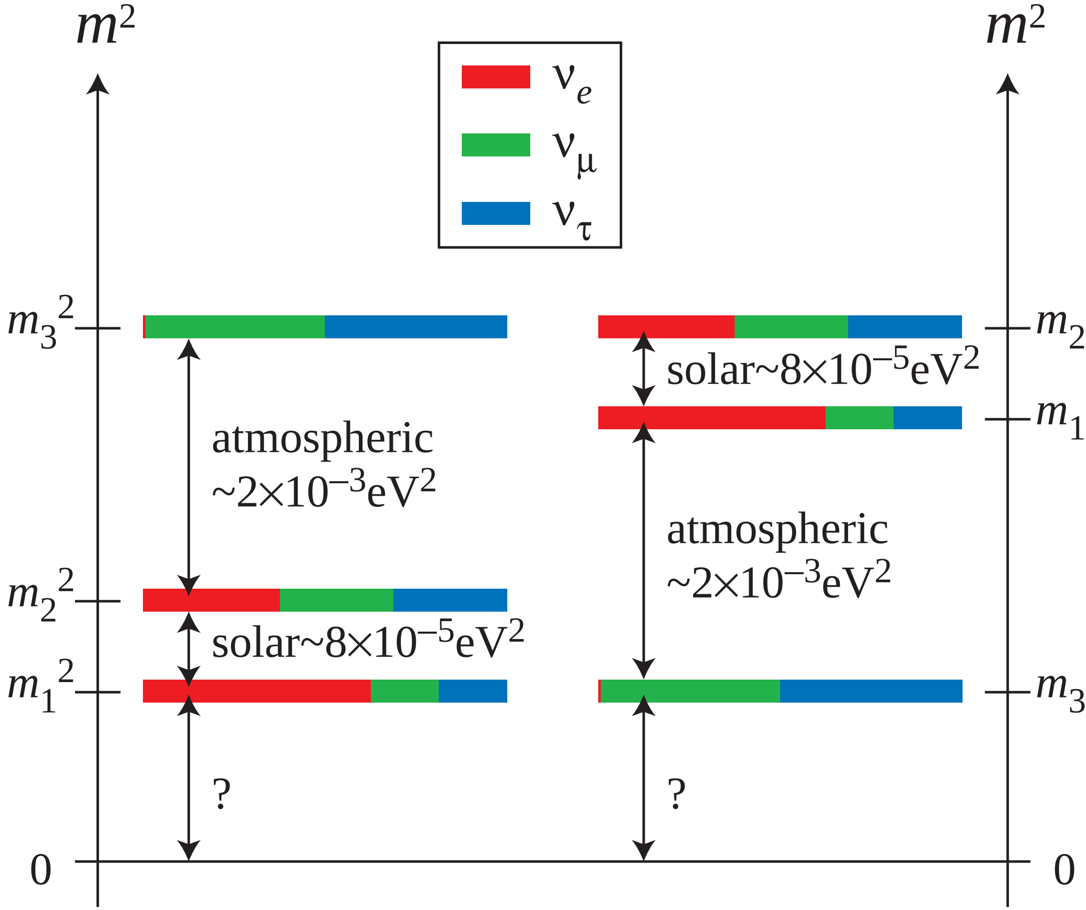
$|\Delta m_{32}^2| \sim 2.0 \times 10^{-3}$ eV^2 ;

$\sum_i m_i < 0.7$–2 eV.



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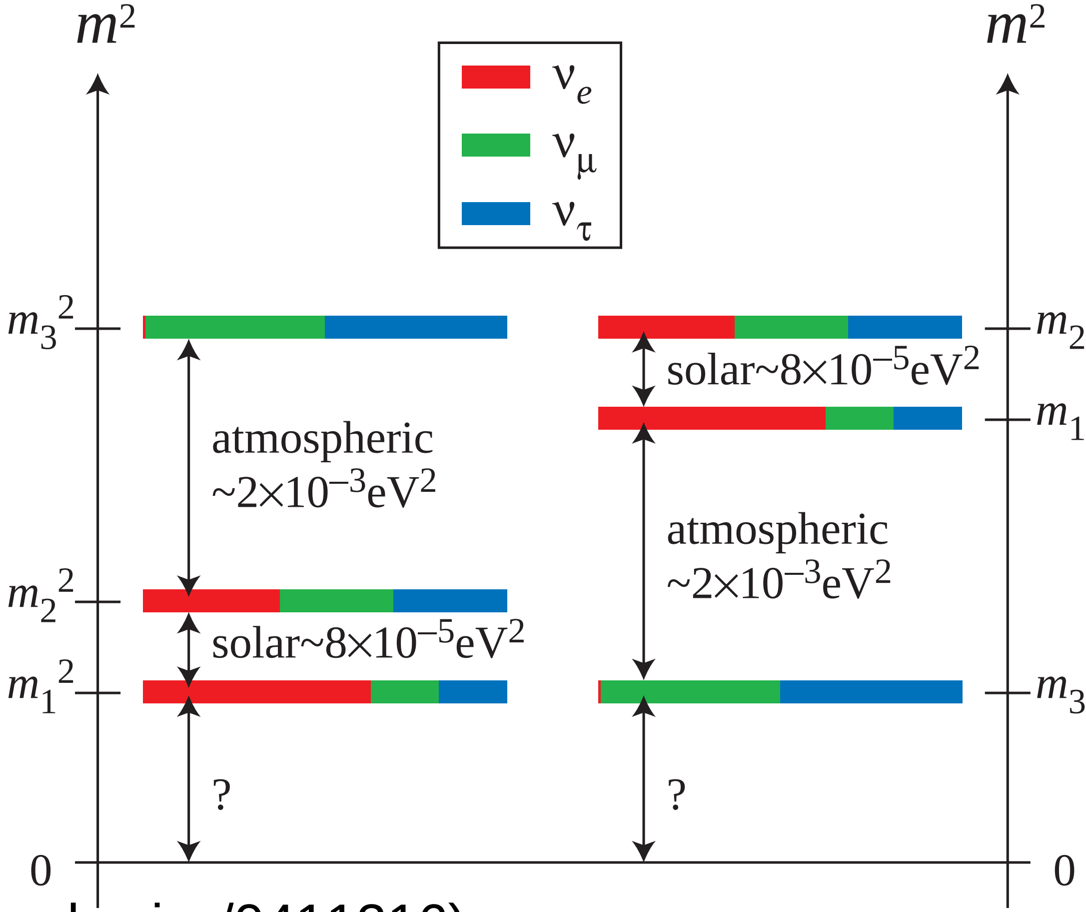


- $m_1 \sim m_2 \sim m_3 \sim 0.2$ eV
(Degenerate hierarchy)
- $m_1 < m_2 \ll m_3$
(Normal hierarchy)
- $m_3 \ll m_1 < m_2$
Inverted hierarchy

(APS multi-divisional neutrino study, physics/0411216)

INO Status, in brief

- Stage 0 : Site survey, clearances, construction; we are here
  - Site: Bodi West Hills, 100 km west of Madurai $9°58'$ N; $77°16'$ E.
  - Detector R & D facility: at Madurai
  - Awaiting formal clearances: AEC for financial sanction.
  - Detector R & D proceeding apace; 1/1000 prototype at Kolkata; to start work on 1/100 model (actually 1/40 scale of one module).
- Stage I : Study of atmospheric neutrinos with magnetised iron calorimeter detector, ICAL; focus of this talk
- Stage II : Study of long-baseline neutrinos, from a neutrino factory/beta beam; attractive future possibility
- Collaboration: From all over India and one member from U. Hawaii.
- This is an open collaboration: we welcome you to join!

The choice of detector: ICAL

Use (magnetised) iron as target mass and RPC as active detector element. Reminder: KGF; MONOLITH detectors.

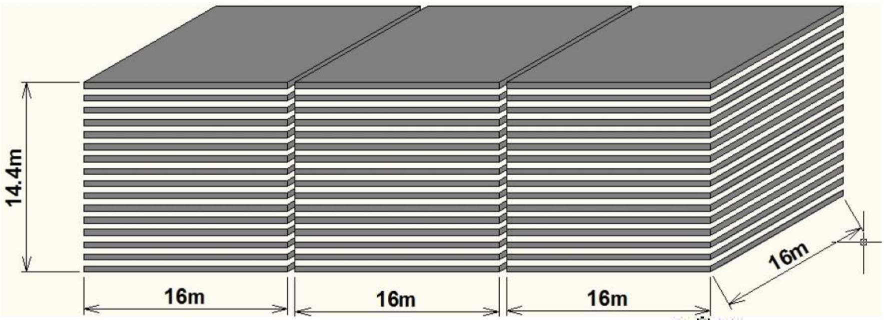
Atmospheric neutrinos have large L and E range. So ICAL has

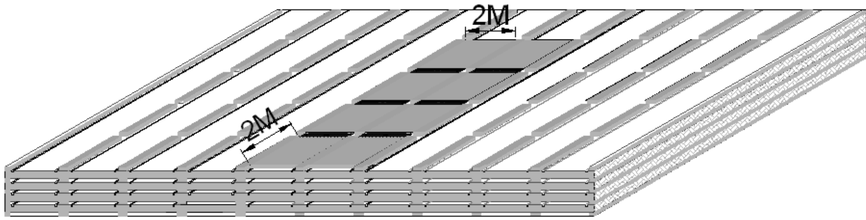
- Large target mass: current design 52 kton;
- Nearly 4π coverage in solid angle (except near horizontal);
- Upto ~ 20 GeV muons contained in fid. vol.: most interesting region for observing matter effects in 2–3 sector is 5–15 GeV;
- Good tracking and energy resolution;
- $\sim ns$ time resolution for up/down discrimination; good directionality;
- Good charge resolution; magnetic field ~ 1.5 Tesla;
- Ease of construction (modular; 3 modules of 17 kTons each).

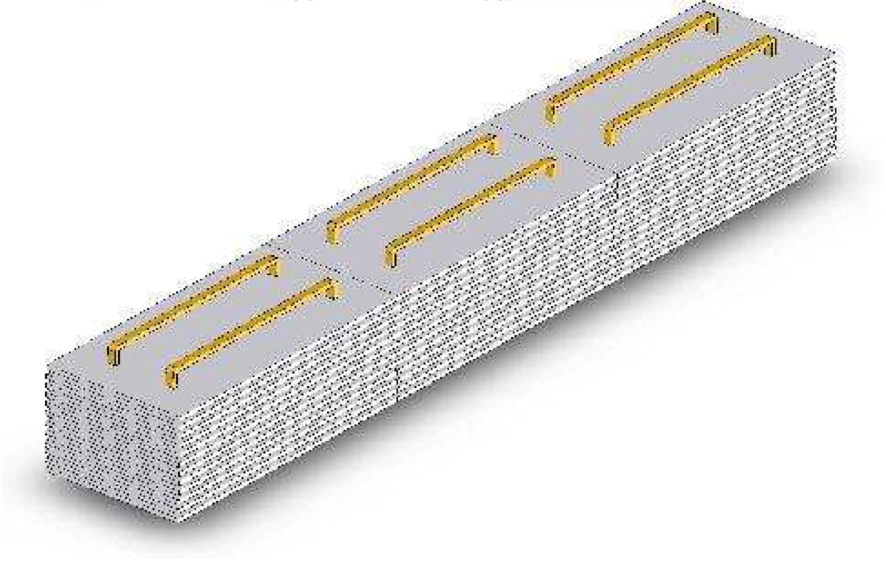
Note: Is sensitive to muons only, very little sensitivity to electrons.

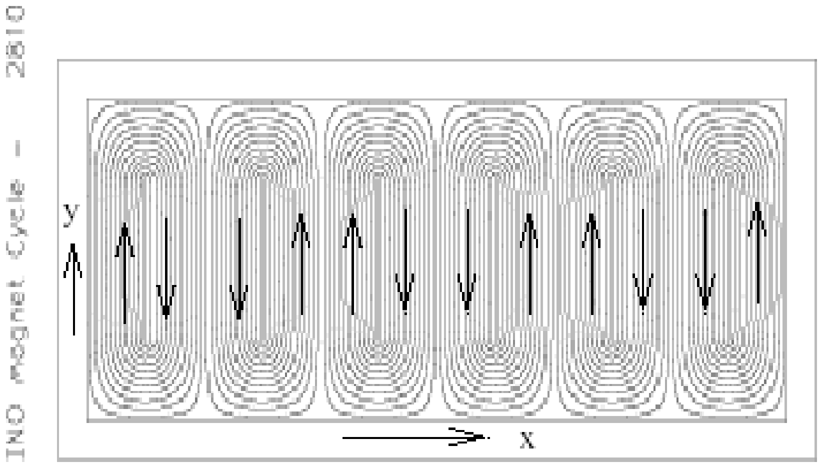
The ICAL detector

- 50 kton iron, magnetised to ~ 1.5 T with 150 layers of 5.6 cm plates in three modules
- Each module = $16 \times 16 \times 14.4$ m^3









Specifications of the ICAL detector

ICAL	
No. of modules	3
Module dimension	16 m × 16 m × 14.4 m
Detector dimension	48 m × 16 m × 14.4 m
No. of layers	150
Iron plate thickness	5.6 cm
Gap for RPC trays	4.0 cm
Magnetic field	1.5 Tesla
RPC	
RPC unit dimension	2 m × 2 m
Readout strip width	3 cm
No. of RPC units/Road/Layer	8
No. of Roads/Layer/Module	8
No. of RPC units/Layer	192
Total no. of RPC units	$\sim$ 30,000
No. of electronic readout channels	3.9 × 10^6

Needs large industry interface.

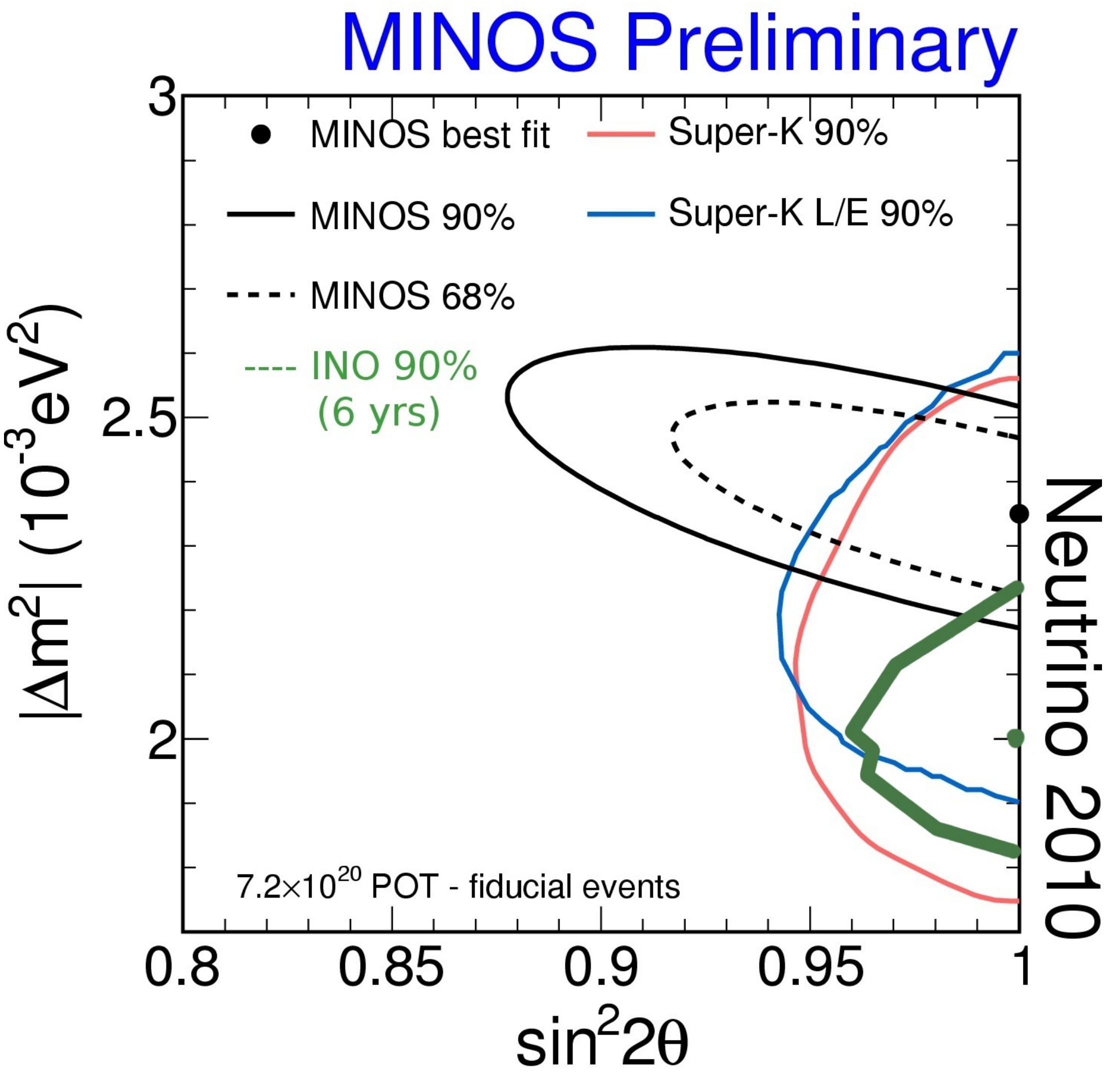
Physics Studies

- All results shown are old and appear in various documents, *including INO Report 2006*.
- Fully revised studies going on. Major changes in
  - detector coding ported from GEANT3 → GEANT4,
  - analyses for track reconstruction/fitting, esp. for muons,
  - neutrino generator.

  So expect substantial improvement from older results.
- Primary focus on muon detection for E, L, with hadron energy reconstruction; all hadrons leave similar signature in ICAL.
- Electrons leave few traces (rad. length 1.8 (11) cm in iron (glass)).
- Reiterate that primary goals are
  - study of 2–3 mixing: magnitudes of Δm^2_{32} and θ_{23}
  - Challenge: the sign of Δm^2_{32} and octant of θ_{23}!
- Best scenario if Daya Bay/D-CHOOZ/MINOS/T2K find signs of non-zero θ_{13}.

Precision measurement of parameters

- Source: Atmospheric Neutrinos, 6 years' exposure, from Nuance neutrino generator. ICAL simulation with GEANT-3, $B_y = 1$ T.



Shown are 90 CL contours in comparison with Super-K and MINOS results. (Mar 2010)

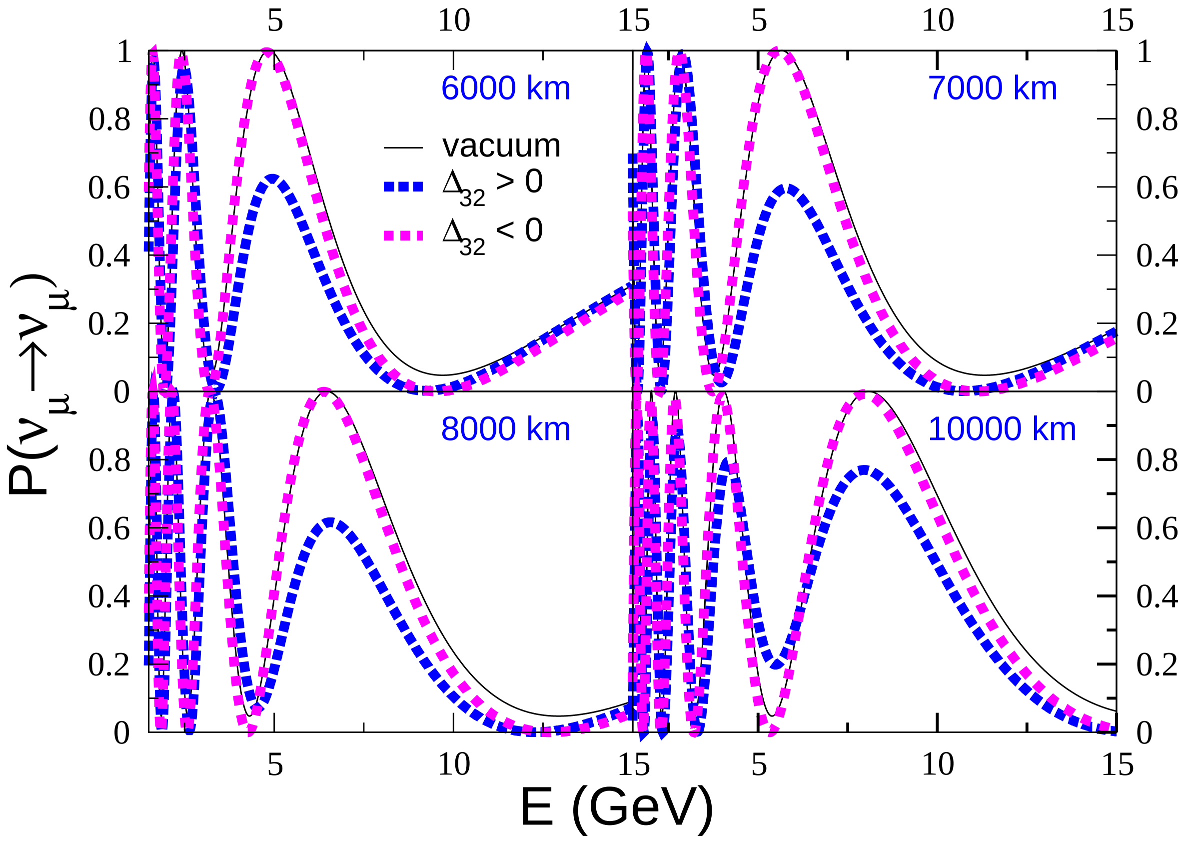
3σ precision:

$|\Delta m^2_{32}|$: 20%

$\sin^2_{23}$: 60%

Adapted from the MINOS Neutrino 2010 talk, with INO contours added by hand.

Matter effect with atmospheric neutrinos

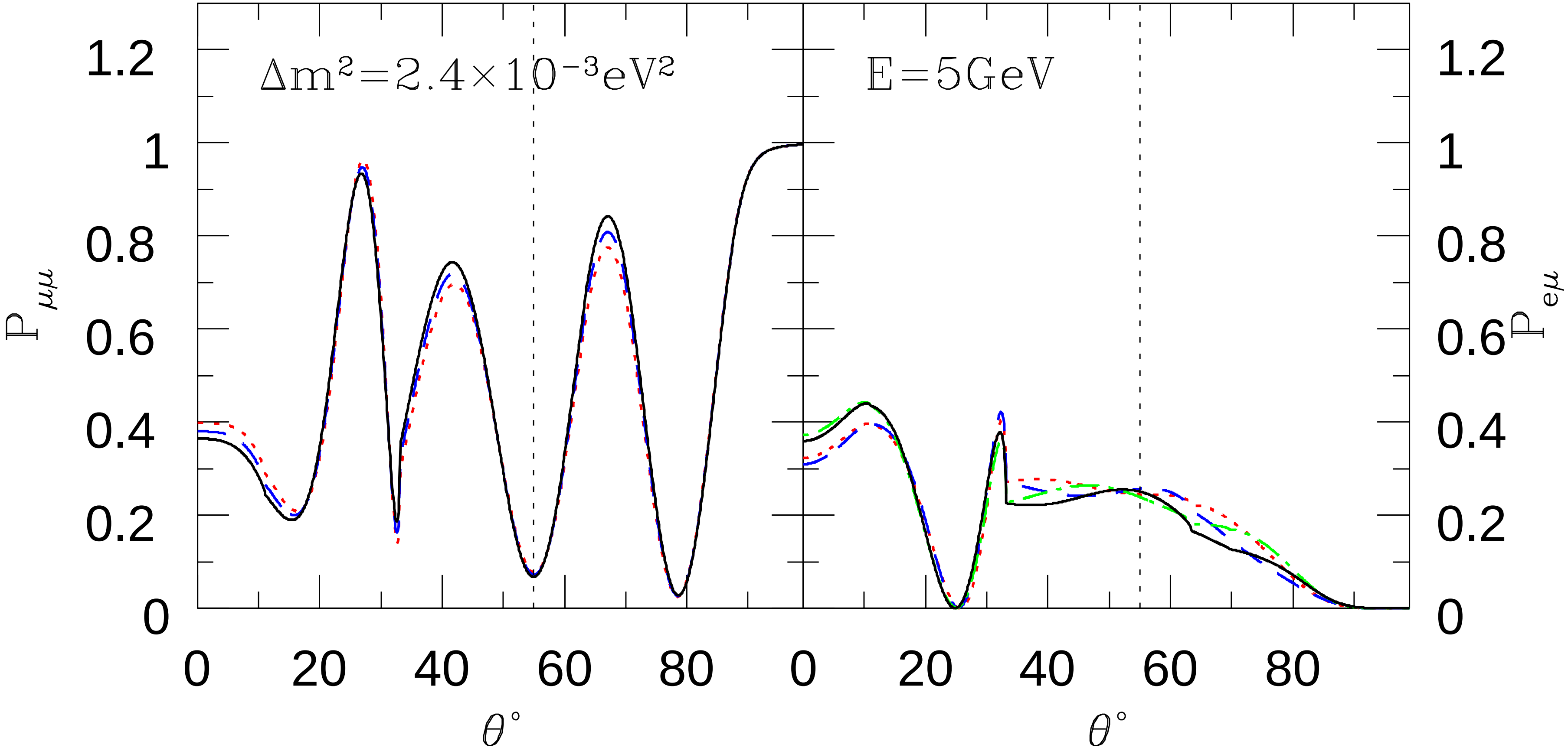


- Matter effects involve the participation of all three (active) flavours; hence involves both $\sin\theta_{13}$ and the CP phase $\delta_{\rm CP}$, in general.

R. Gandhi et al., Phys.Rev.Lett. 94 (2005) 051801; Phys.Rev. D73 (2006) 053001

Sensitivity to $\delta_{\rm CP}$

Variation of $P_{\mu\mu}$ as a function of nadir angle with the CP phase $\delta_{\rm CP}$ for $\theta_{13} = 9^\circ$.



- Mostly independent of the CP phase, $\delta_{\rm CP}$.
- Hence sensitive to the mass ordering of the 2–3 states, provided $\theta_{13} > 6^\circ$; however, needs large exposures.

D. Indumathi et al., Phys.Rev.D74 (2006) 053004.

The observable: the asymmetry

Hierarchy discriminator: difference in interactions between ν and $\overline{\nu}$.

$$\mathcal{A} = (U/D)_\nu - (\bar{U}/\bar{D})_{\bar{\nu}}$$

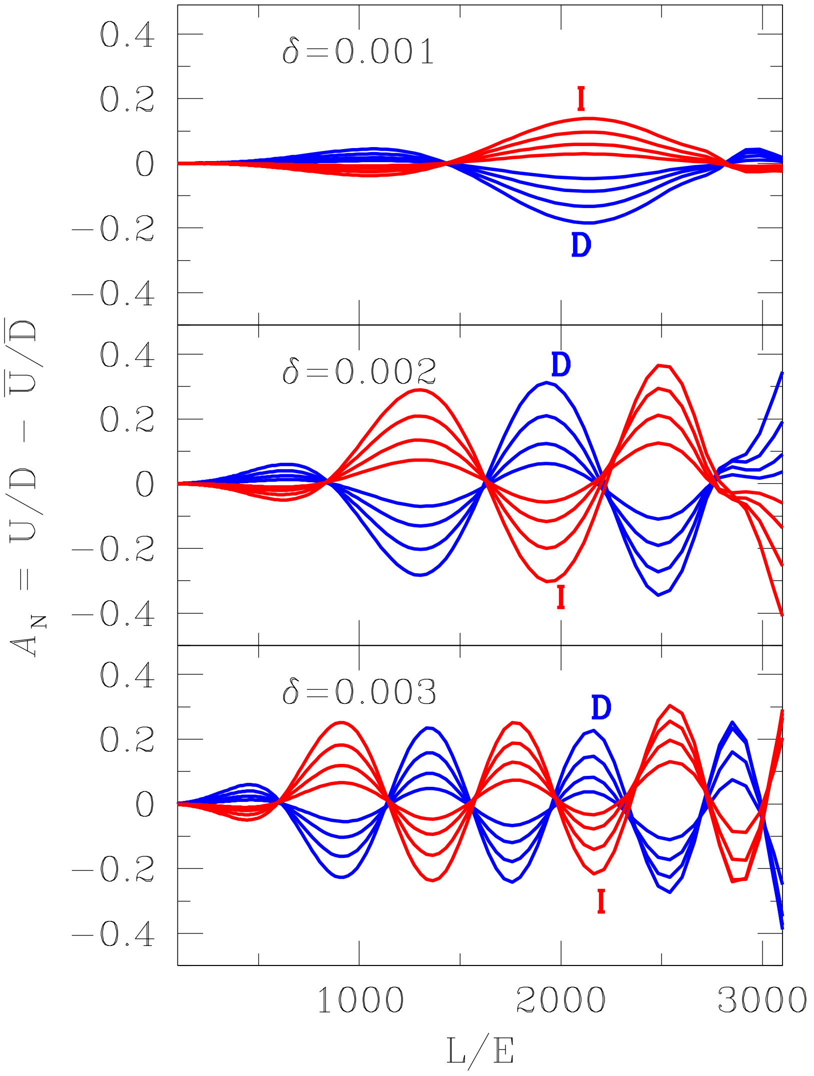
$$\begin{aligned} P^m_{\mu\mu}(A,\Delta) &\approx P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\ & \left[\frac{A}{\Delta - A} T_1 + \left(\frac{\Delta}{\Delta - A}\right)^2 \left(T_2 \sin^2[(\Delta - A)x] + T_3\right)\right] , \\ \overline{P}^m_{\mu\mu}(A,\Delta) &\approx P^{(2)}_{\mu\mu} - \sin^2\theta_{13} \times \\ & \left[\frac{-A}{\Delta + A} T_1 + \left(\frac{\Delta}{\Delta + A}\right)^2 \left(T_2 \sin^2[(\Delta + A)x] + T_3\right)\right] , \end{aligned}$$

where T_i are functions of the parameters. $A \propto \rho E$. **Changes sign between neutrinos and anti-neutrinos.**

So $\mathcal{A}(A,\Delta) \approx -\mathcal{A}(A,-\Delta) = -\mathcal{A}(-A,\Delta) = \mathcal{A}(-A,-\Delta)$.

A: The difference asymmetry

Asymmetry as a function of θ_{13} and L(km) / E(GeV)



Sign of $\delta \equiv \Delta m_{32}^2$ for

$\theta_{13} = 5, 7, 9, 11^\circ$

Hence sensitive to the mass ordering (red vs blue) of the 2–3 states;

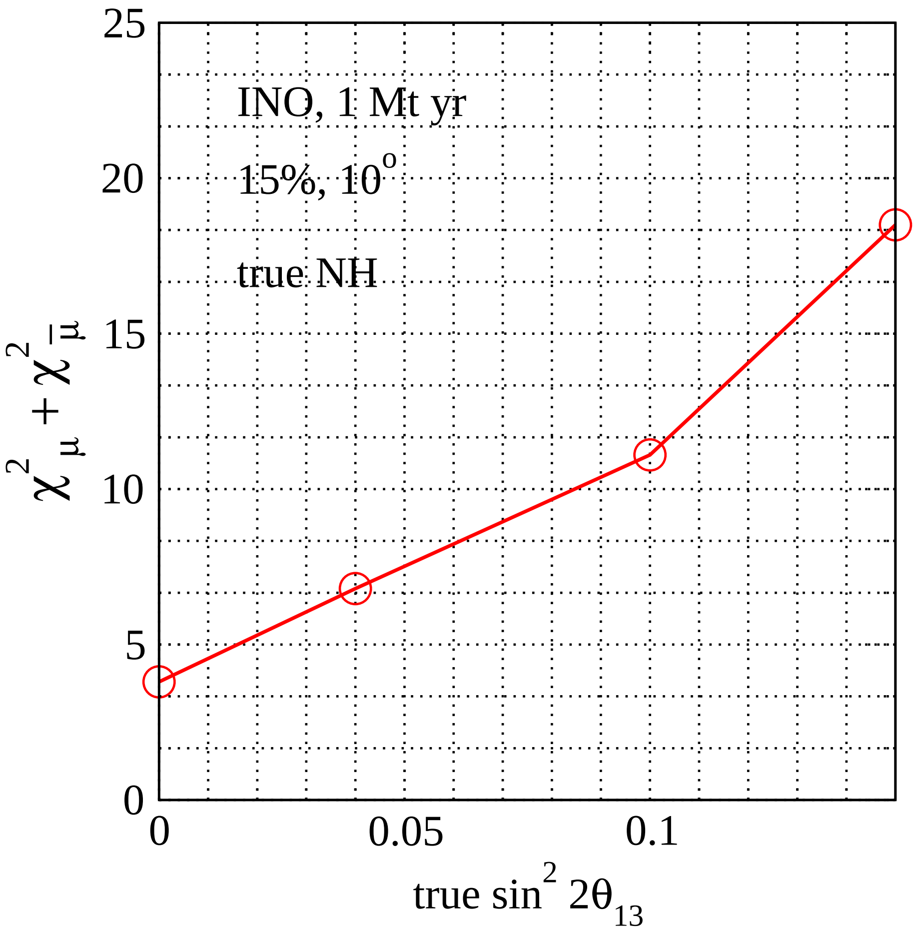
however, needs large exposures of about 500–1000 kton-years

(Resolutions determine error bars!)

D. Indumathi, M.V.N. Murthy, Phys.Rev. D71 (2005) 013001.

Hierarchy Reach

- Greater sensitivity in the case of Normal hierarchy
- Reiterate: Result independent of the CP phase $\delta_{\rm CP}$



- With exposures of 500 kton-years, can get a 90%CL result if

$\sin^2 2\theta_{13} > 0.09$ (10% R_θ, R_E)

$\sin^2 2\theta_{13} > 0.07$ (5% R_θ, R_E)

- However, needs large exposures of about 1000 kton-years for smaller θ_{13} or worse resolutions:

$\sin^2 2\theta_{13} > 0.07$ (10% R_θ, 15% R_E)

$\sin^2 2\theta_{13} > 0.05$ (5% R_θ, R_E)

S.T. Petcov, T. Schwetz, Nucl.Phys. B740 (2006) 1.

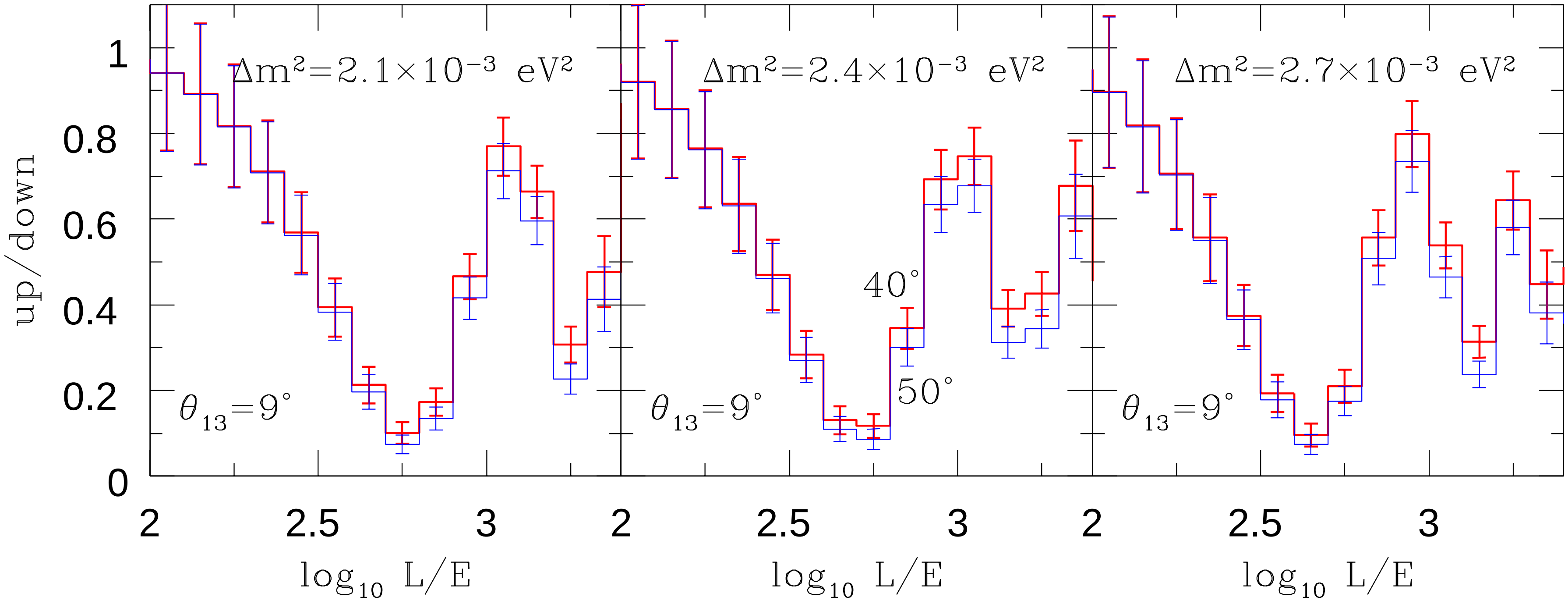
R. Gandhi et al., Phys.Rev.D76:073012,2007.

The octant of θ_{23}

$$\begin{aligned} P^m_{\mu\mu} &\approx 1 - \sin^2 2\theta_{23} \left[\sin^2\theta^m_{13}\sin^2\Delta^m_{21} + \cos^2\theta^m_{13}\sin^2\Delta^m_{32}\right] \\ & \quad -\sin^4\theta_{23}\sin^2 2\theta^m_{13}\sin^2\Delta^m_{31} \ , \\ P_{e\mu} &\approx \sin^2\theta_{23}\sin^2 2\theta^m_{13}\ \sin^2\Delta^m_{31} \ , \end{aligned}$$

- Deviations of 20% from maximality at 99% CL provided $\sin^2\theta_{13} > 0.015$ and 1000 kton-yr exposure
- Results much poorer for inverted hierarchy and solution in second octant.
- Will be strongly improved using neutrino-factory beams.

Rates at ICAL: $E = 5$–10 GeV



- Contributions from both $P_{e\mu}$ and $P_{\mu\mu}$.
- Events ratio for $\theta_{23} < 45^\circ$ is systematically larger than that for $\theta_{23} > 45^\circ$, provided θ_{13} is large enough.
- This cannot be confused with the deviations in the ratio due to effects of θ_{13} (where peaks and troughs are systematically away from extremal).

Other physics possibilities

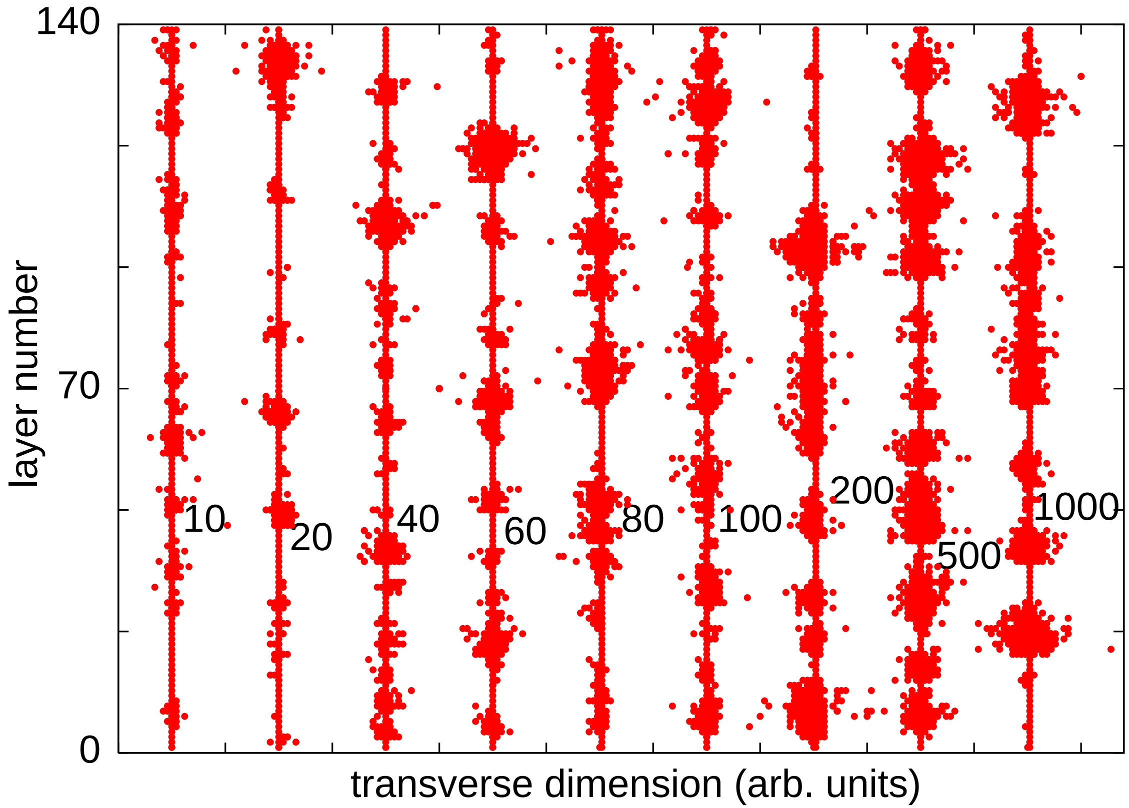
. . . with atmospheric neutrinos

- Reminder: Both hierarchy and discrimination of octant of θ_{23} require $\theta_{13} > 7^\circ$ $(\sin^2 2\theta_{13} > 0.06)$; hard
- Discrimination between oscillation of ν_μ to active ν_τ and sterile ν_s from up/down ratio in “muon-less” events?
- Probing CPT violation from rates of neutrino to rates of anti-neutrino events in the detector: either from separate analysis of neutrino and anti-neutrino data (recent MINOS results) or via sensitivity to the δb term which adds to $\Delta m^2_{32}/(2E)$ in oscillation probability expression (LSND/MiniBooNe?)
- Constraining long-range leptonic forces by introducing a matter-dependent term in the oscillation probability even in the absence of U_{e3}, so that neutrinos and anti-neutrinos oscillate differently.

  Only $L_e - L_\mu, L_e - L_\tau, L_\mu - L_\tau$ can be gauged in anomaly-free way. If neutrinos are massive, then these are broken and have light relevant gauge bosons. This would influence nu-osc.

Cosmic Ray Muons

are a signal, not background, at high energies, due to pair-production (pair meter technique).

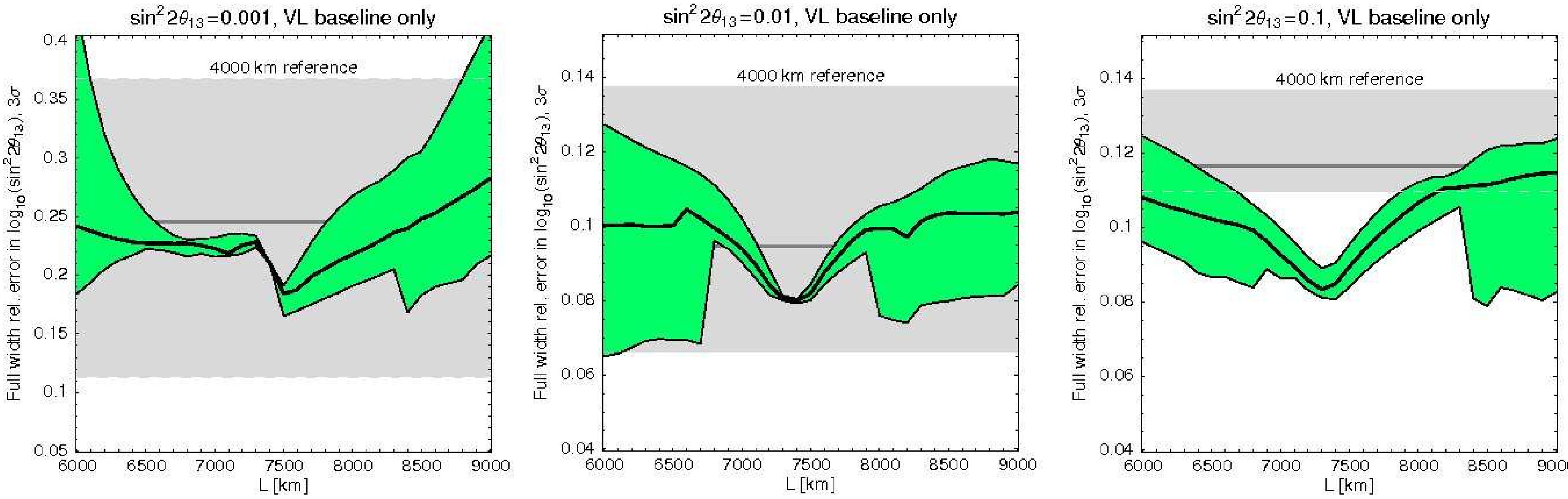


- Muon charge ratio gives information on meson production by primary cosmic rays. Example: π^+/π^-, K^+/K^-, etc.
- MINOS results in *P. Schreiner, XVI Int. Symp. very high energy cosmic interactions, (ISVHECRI 2010), July 2010.*

Stage II: Neutrino factories and INO

- The magic baseline, where the event rate is independent of the CP phase $\delta_{\rm CP}$, occurs at $\sqrt{2} G_F n_e L = n\pi$. So $L \sim 7400$ km. (*P. Huber, W. Winter, Phys.Rev.D68 (2003) 037301.*)
- The degeneracies associated with $\delta_{\rm CP}$ and $\delta_{\rm CP}$–$\sin^2\theta_{13}$ are lifted. Implies greater sensitivity to both θ_{13} and the magnitude and sign of Δm^2_{32}.
- Standard route: *wrong sign* muons as a signal of oscillation.
- Technical point: the uncertainties will be reduced compared to atm. experiment because there is no uncertainty in L.

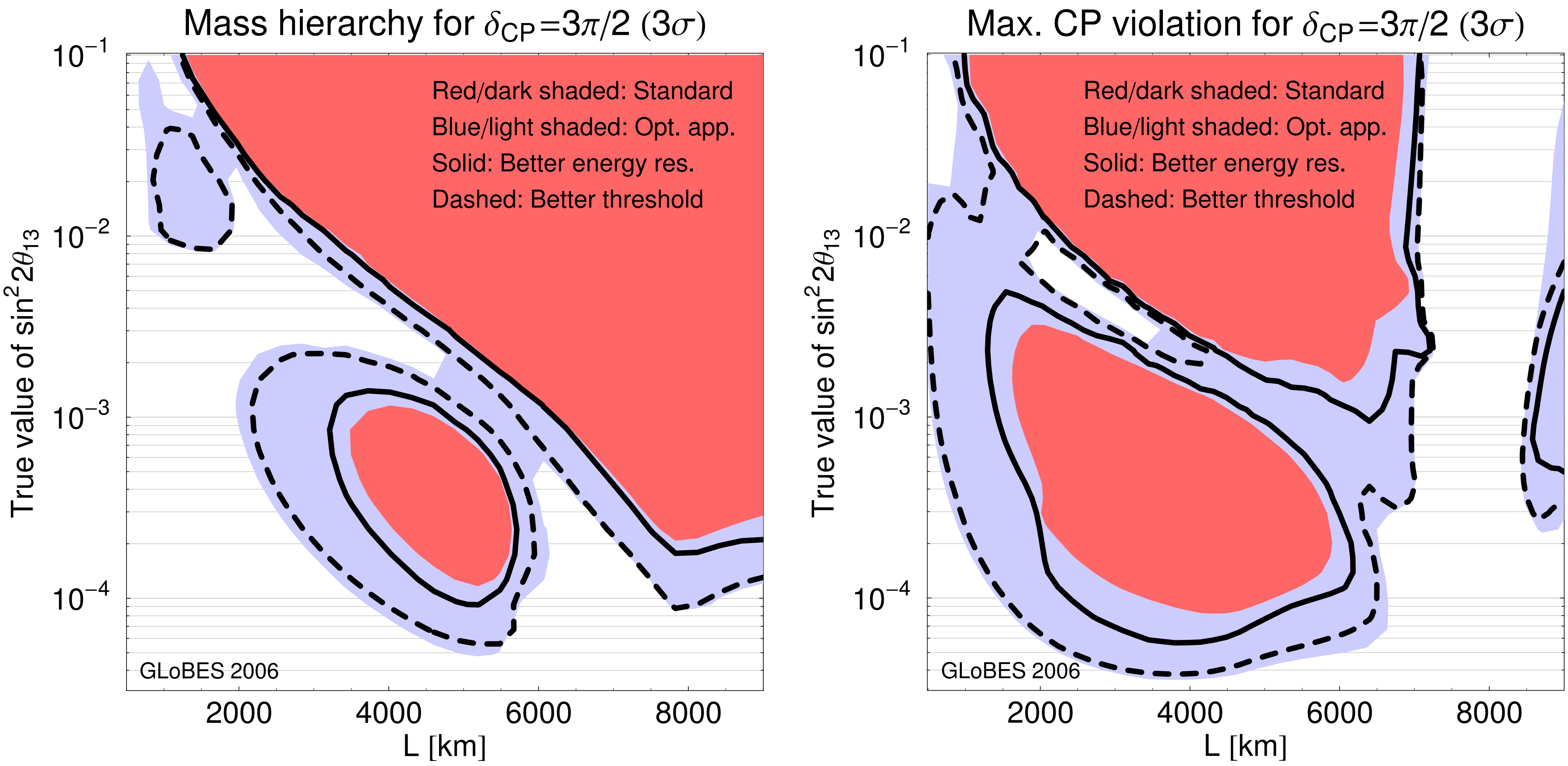
θ_{13} Sensitivity



- Case: $10^{-4} < \sin^2 2\theta_{13} < 10^{-2}$. Mass hierarchy determined for all $\delta_{\rm CP}$; may be sensitive to matter profile.
- Case: $\sin^2 2\theta_{13} > 10^{-2}$. Max. sensitivity to matter profile; helps unfold degeneracies with shorter baselength detector.

R. Gandhi, W. Winter, Phys.Rev.D75:053002, 2007.

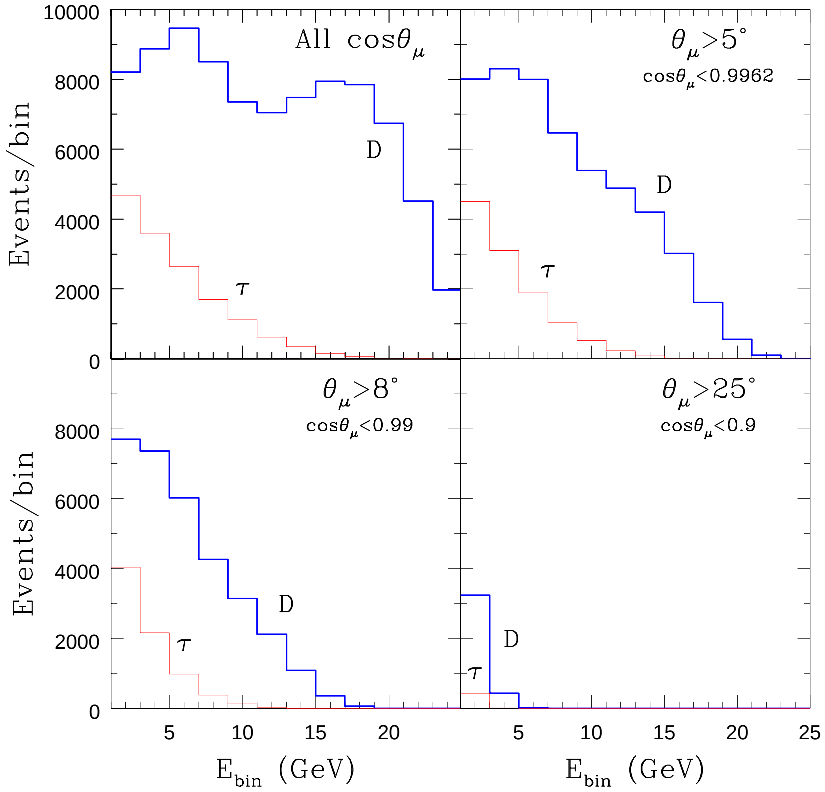
Hierarchy Sensitivity

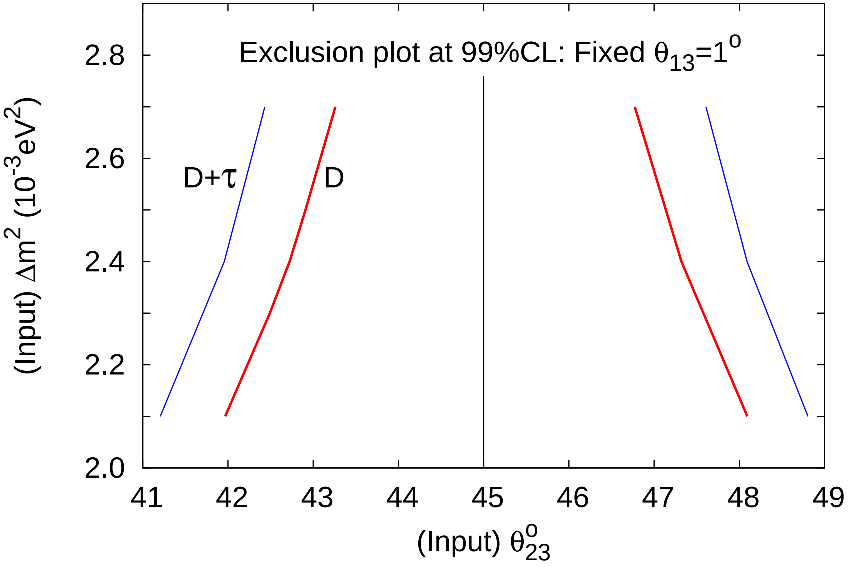


Sensitivity to hierarchy and CP violation as a function of baselength with a 50 GeV muon factory beam.

P. Huber et al., Phys.Rev.D74, 073003.

Sensitivity to θ_{23}



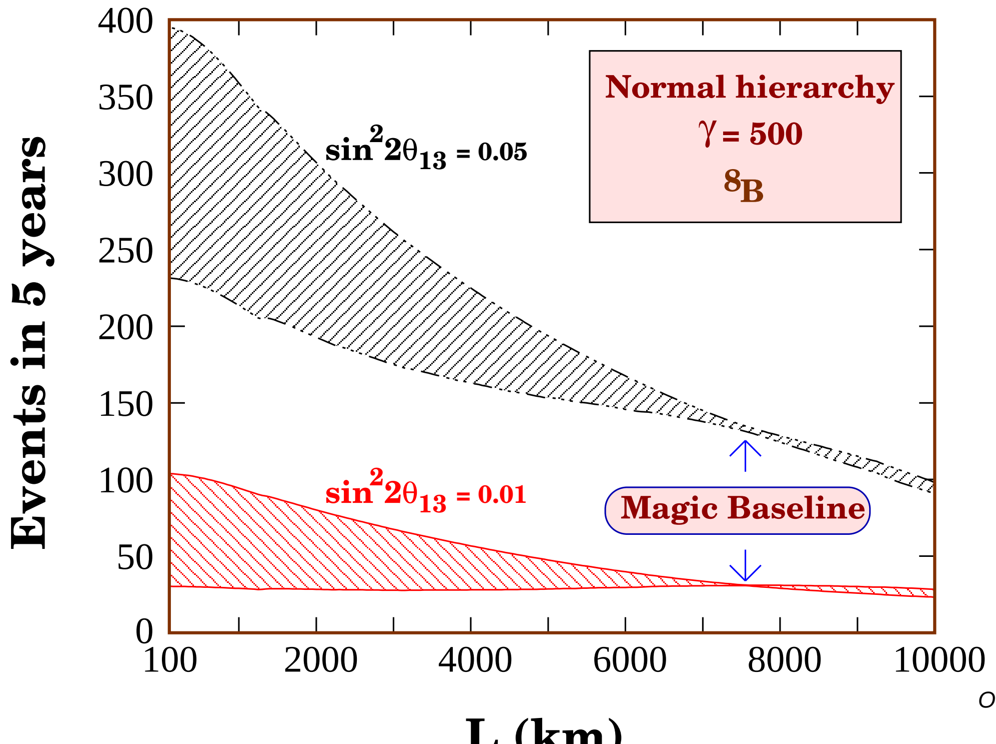


- 25 GeV muon beam of both signs; 5×10^{20} useful decays per year; 50 kton detector, 5 year sample, $\Delta E_\mu =$ 7%.
- Note contamination due to tau decays into (right sign) muons.

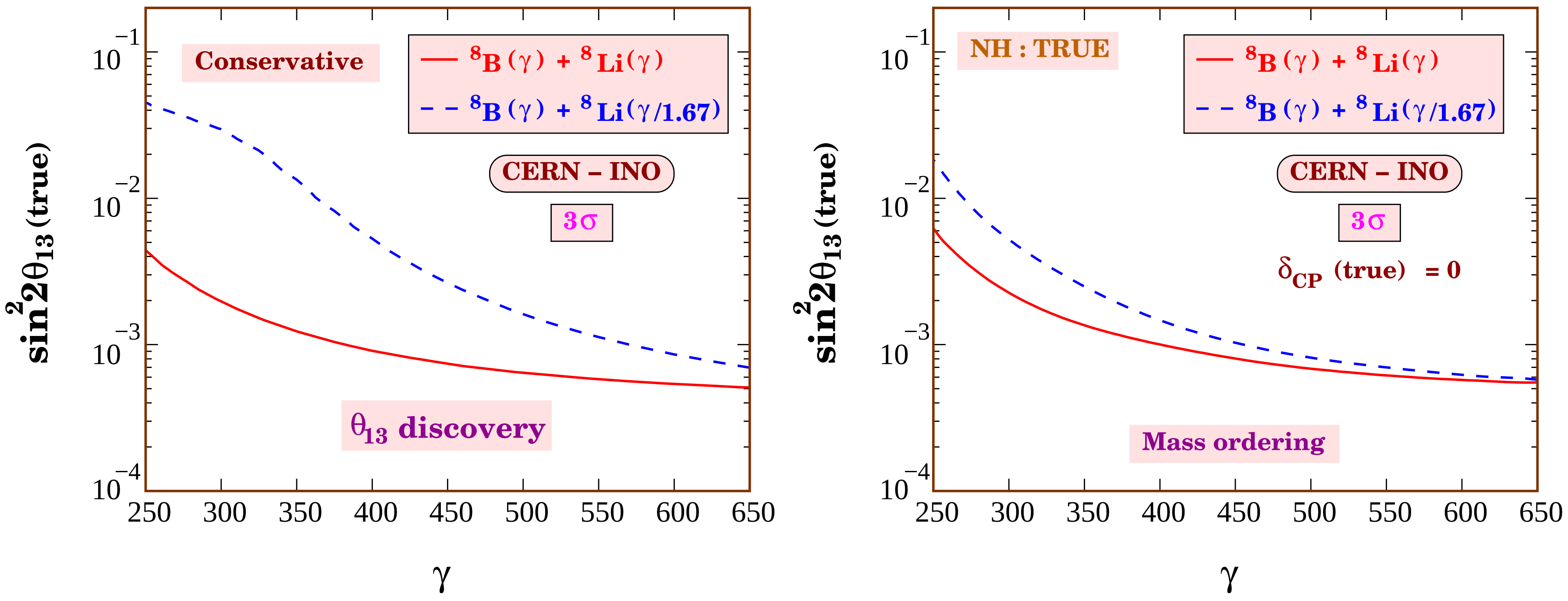
Nita Sinha, talk in this meeting.

Magic baseline beta beams

- Beta beams are pure ν_e ($\overline{\nu}_e$) (^{8}B, ^{8}Li) beams, so muons clearly indicate oscillation.
- End-point energies are low: ~ 13 MeV; so large boosts needed. $\gamma \sim 500$ for B and Li. So challenging.
- Since muons are already a signal for oscillation, much less dependent on charge identification.



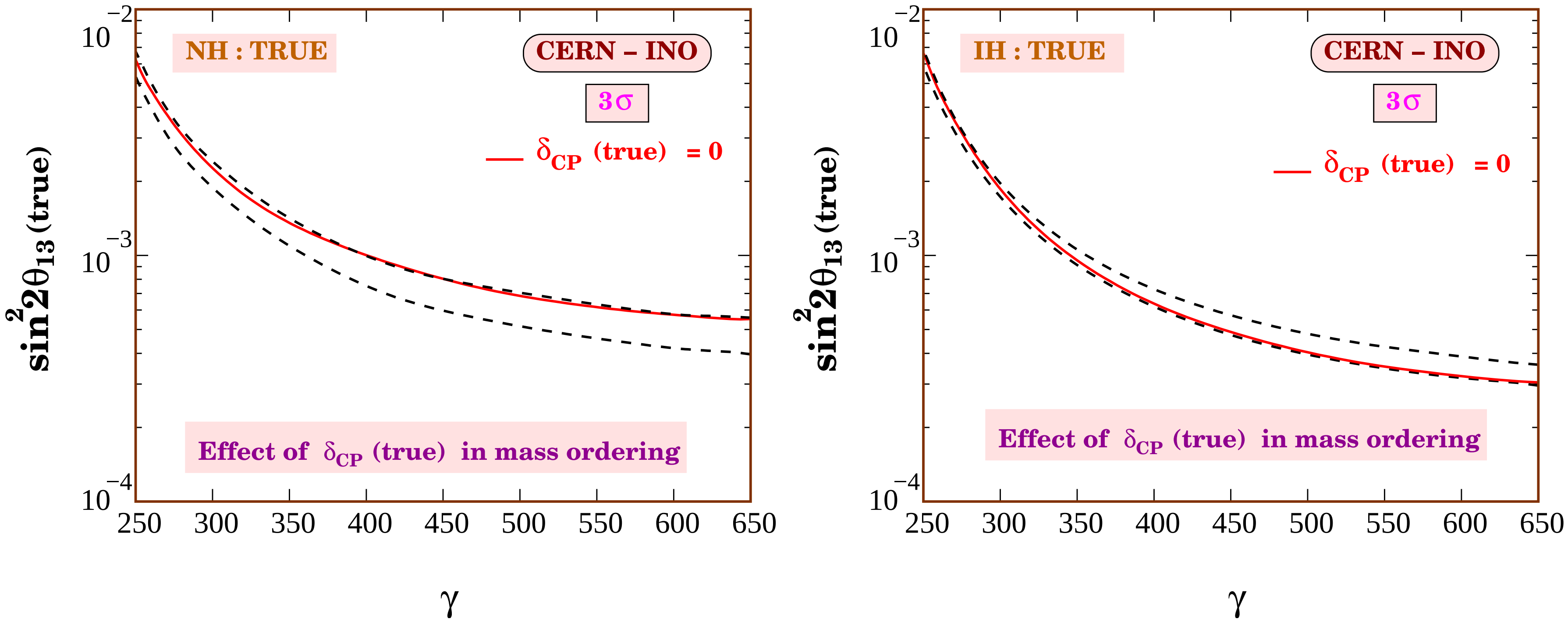
Sensitivity of beta beams



- 3σ sensitivity/discovery reach with 1.1(2.9) $\times 10^{18}$ useful decays/year.
- 5 years, both ν and $\overline{\nu}$ data.

S.K. Agarwalla, S. Choubey, A. Raychaudhuri, Nucl.Phys.B798:124, 2008.

How magical is it?



- Effect of adding both neutrino and antineutrino channels is to constrain θ_{13} in such a way that the wrong sign hierarchy is rejected to values of $\sin^2 2\theta_{13}$ more than 15–20 times smaller!

- Figure shows effect of varying $\delta_{\rm CP}$ from 0–2π at $L = 7150$ km (old CERN–INO baseline).

- So need to redo the results for new baselines.

Outlook

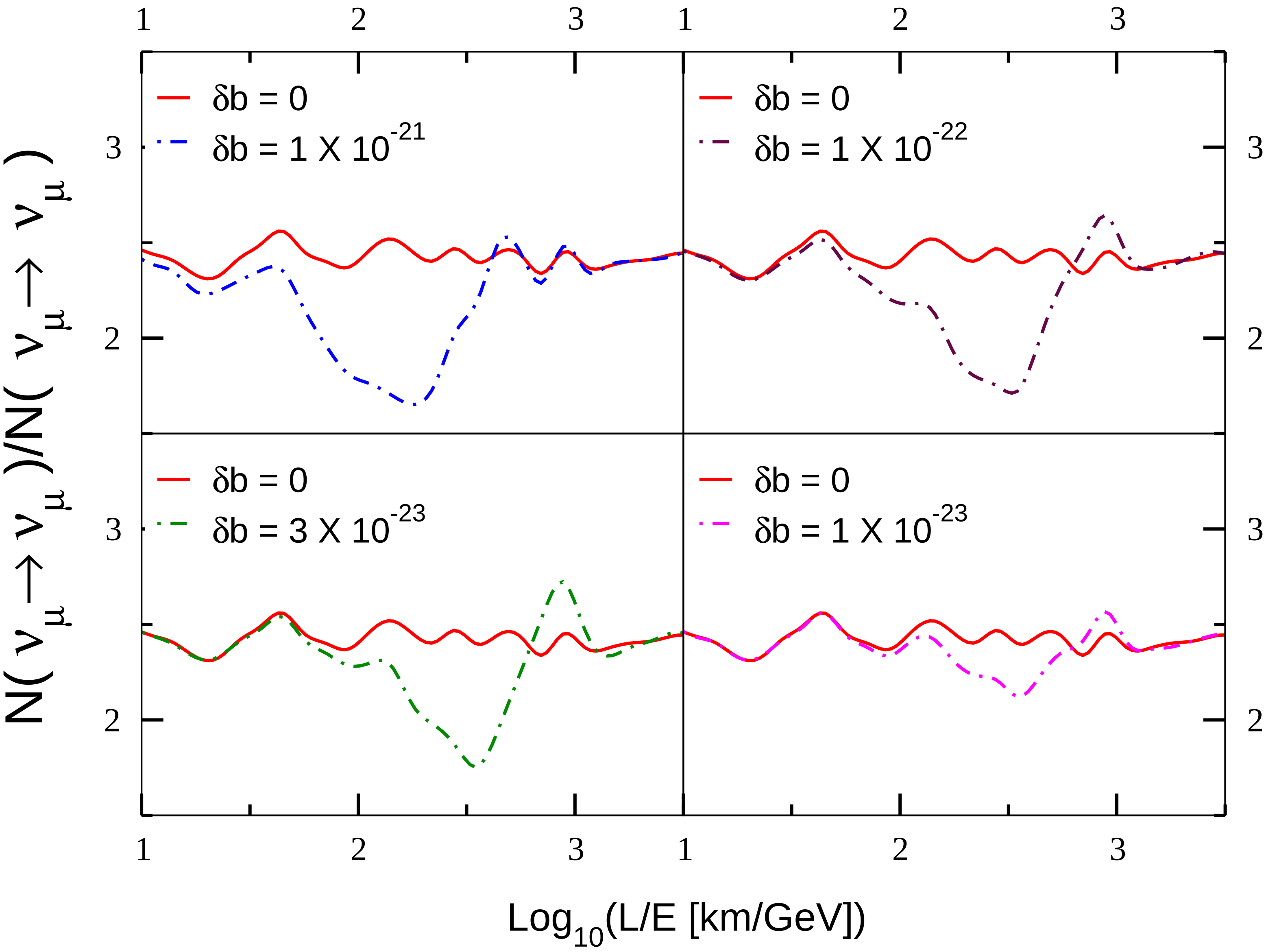
- Hoping for quick clearances and movement on INO construction front
- The physics case looks good: needs strengthening by detailed simulations, which are now in progress.
  - Atmospheric neutrinos provide sensitivity to 2–3 mixing parameters, although not to θ_{13}.
  - Non-oscillation physics is possible via study of high energy cosmic rays muons.
  - ICAL at INO is well-suited (both because of its physical characteristics such as charge identification capability and its large mass, as well as its unique near-magic-baseline location) to be a far-end detector for a future beam facility.
  - Hence there is also a good case to explore the physics of ICAL with muon factory beams and/or beta beams.

Additional Slides

3σ Precision of parameters

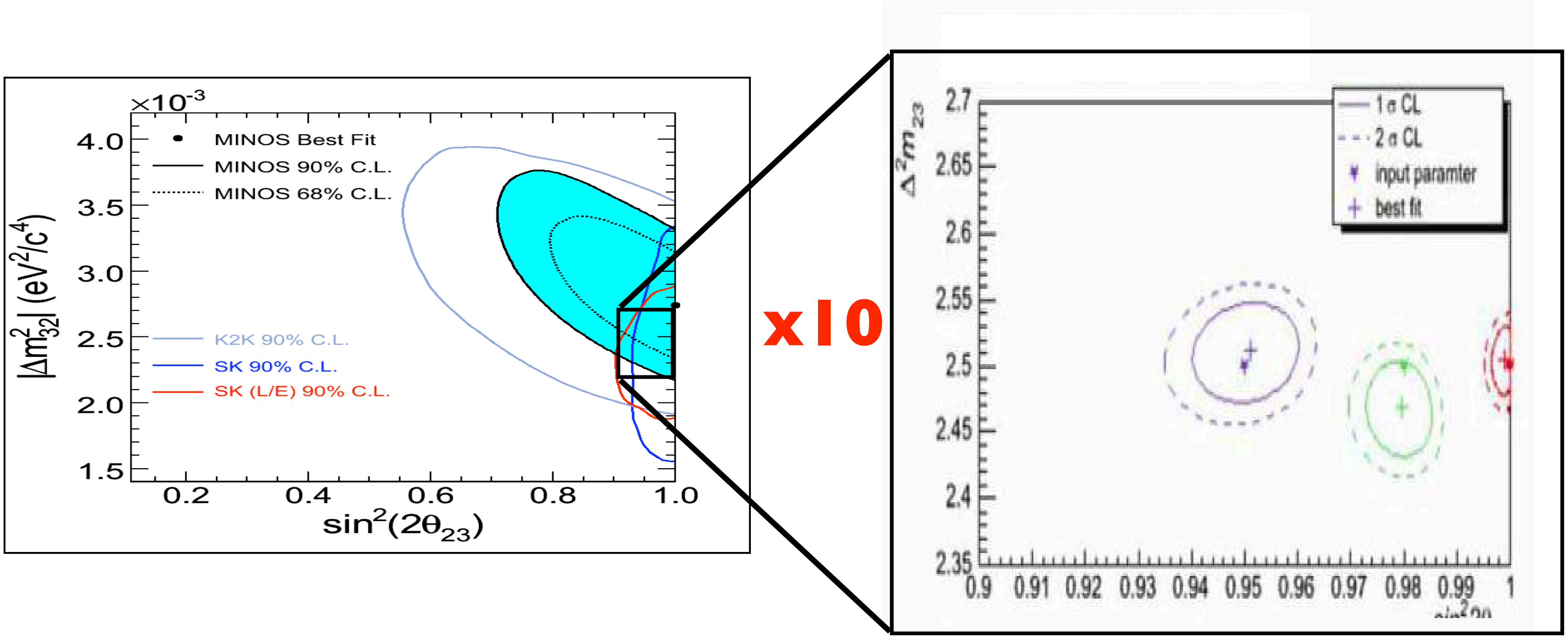
at $\Delta m^2_{32} = 2.0 \times 10^{-3}$ eV^2 and $\sin^2\theta_{23} = 0.5$

Experiment	P($\lvert\Delta m^2_{32}\rvert$)	P($\sin^2\theta_{23}$)	hierarchy
Current	88%	79%	–
MINOS	17%	65%	–
CNGS	37%	–	–
NOνA (6×10^{21} pot)	$\sim$ 5%	$\sim$ 9%	in comb
T2K (Super-K, 0.75 MW)	12%	46%	
ICAL (50 kton)	20%	60%	$\sin^2 2\theta_{13} > 0.06$


δb = 0
δb = 1 X 10^-21
δb = 0
δb = 1 X 10^-22
δb = 0
δb = 3 X 10^-23
δb = 0
δb = 1 X 10^-23
N(ν_μ → ν_μ)/N(ν̄_μ → ν̄_μ)
Log10(L/E [km/GeV])
1
2
3
1
2
3
2
3
2
3

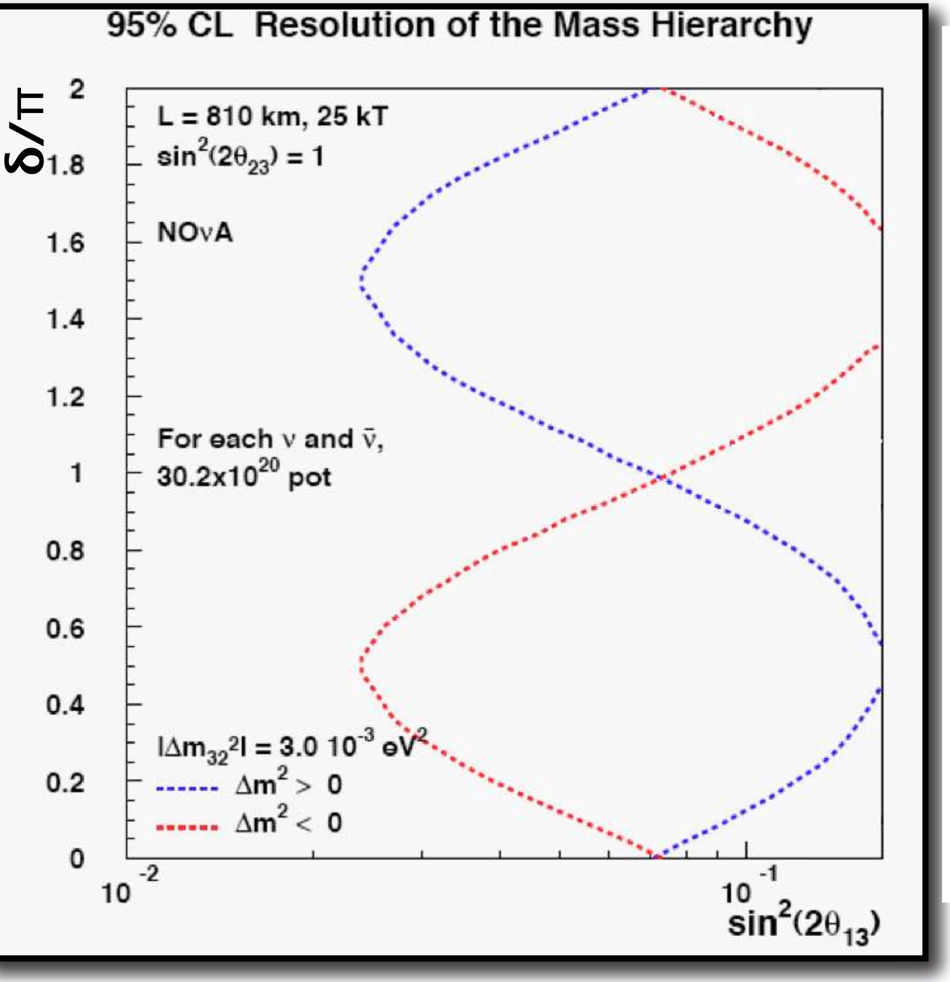
δ_δ Disappearance Measurement

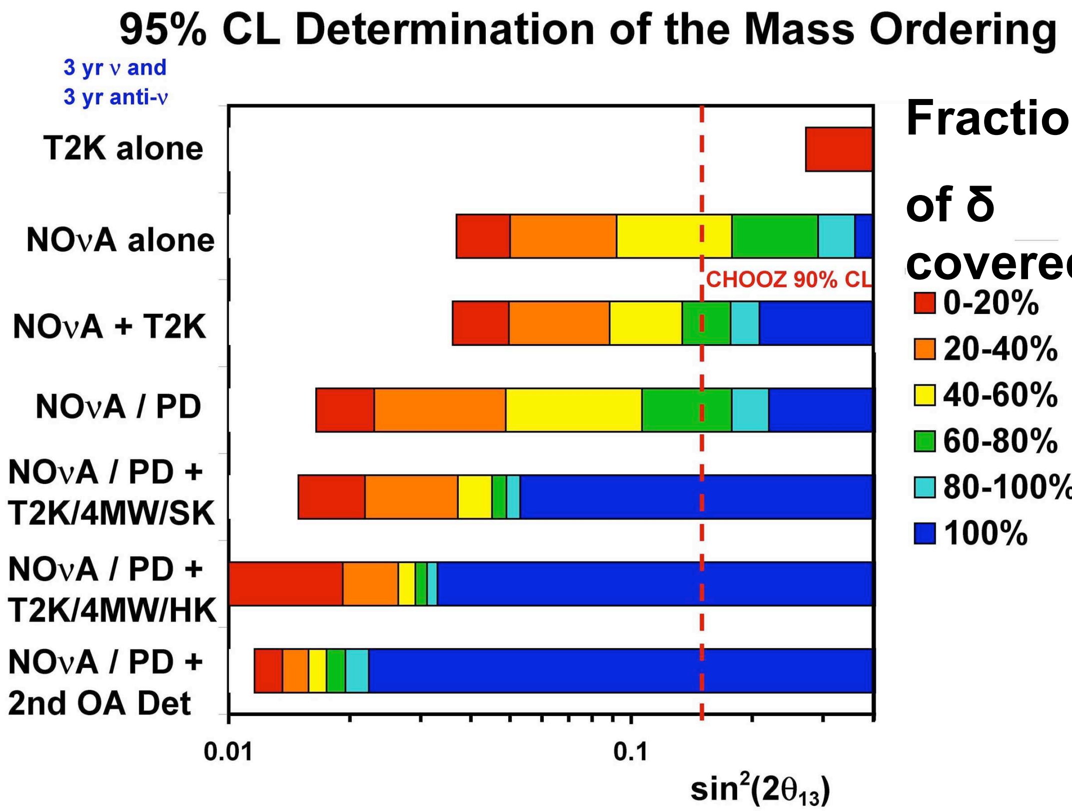
- **NOδA can still do** **δ_δ disappearance measurement**, **measure the mixing angle δ_{23} and δm^2_{23}.**



Measure $\sin^2 2\delta_{23}$ to 0.5-1%

Hierarchy Sensitivity





Measurement unique to NOδA