Physics with India-based Neutrino Observatory (INO)

Amol Dighe

Tata Institute of Fundamental Research, Mumbai, India

(For INO Collaboration)

All documents regarding INO are available at

http://www.imsc.res.in/$\sim$ino

ICHEP 06, Moscow, July 2006

India-based Neutrino Observatory: INO

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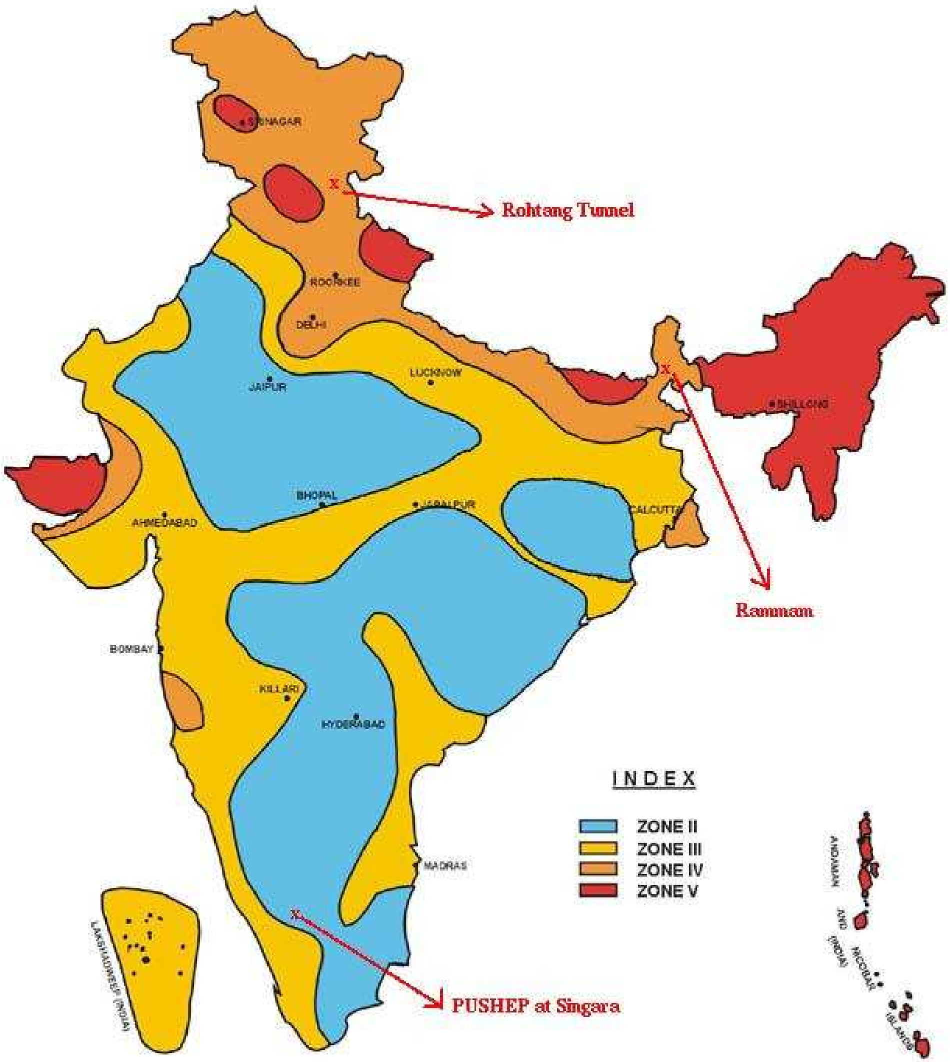
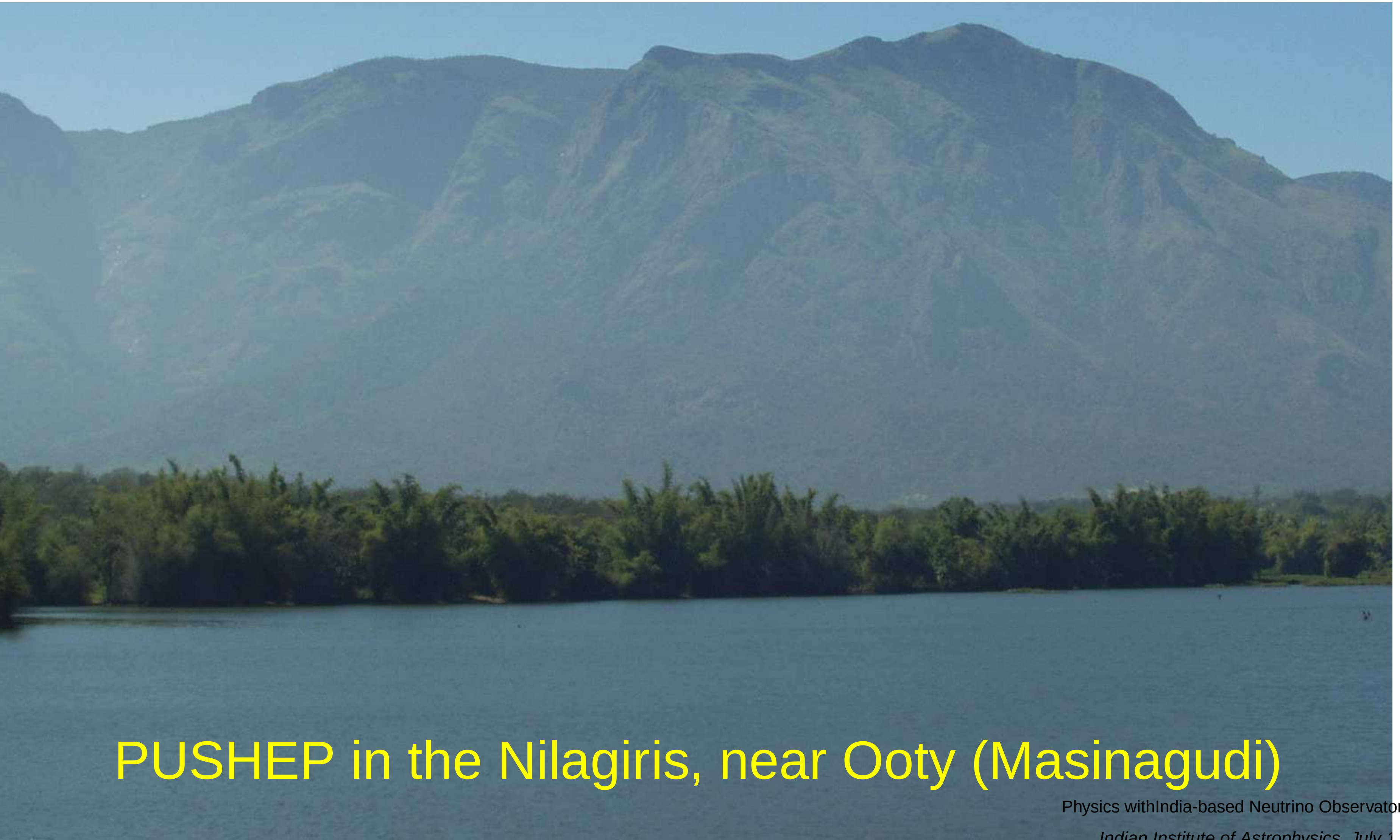
- INO will house 50 kiloton Iron CALorimeter (ICAL) capable of detecting atmospheric $\nu_\mu/\bar{\nu}_\mu$ interactions.
- May also host some smaller experiments (such as neutrinoless double beta decay searches) which require low cosmic ray background environments.

Location of PUSHEP

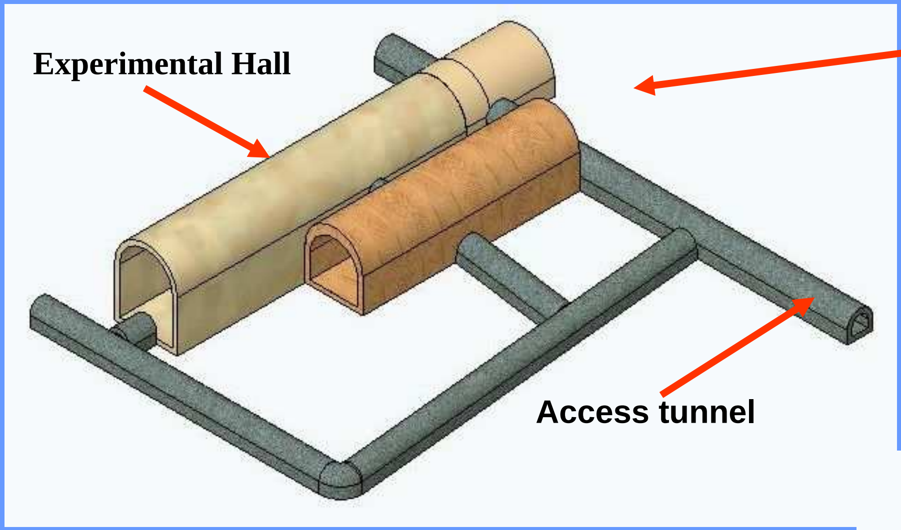


A view of PUSHEP



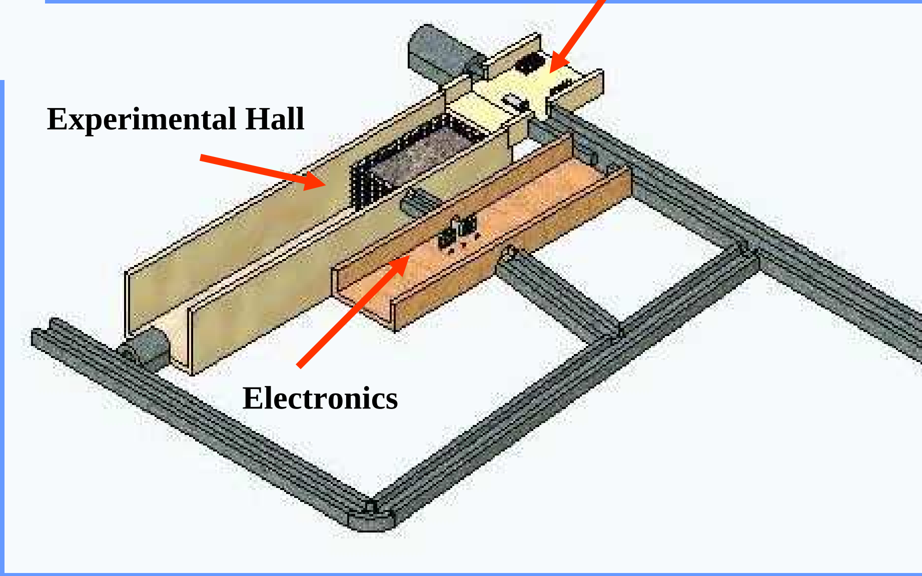
PUSHEP in the Nilagiris, near Ooty (Masinagudi)

Underground Cavern



Layout of the Underground Cavern

Size of the experimental hall
150 m X 22 m X 30 m



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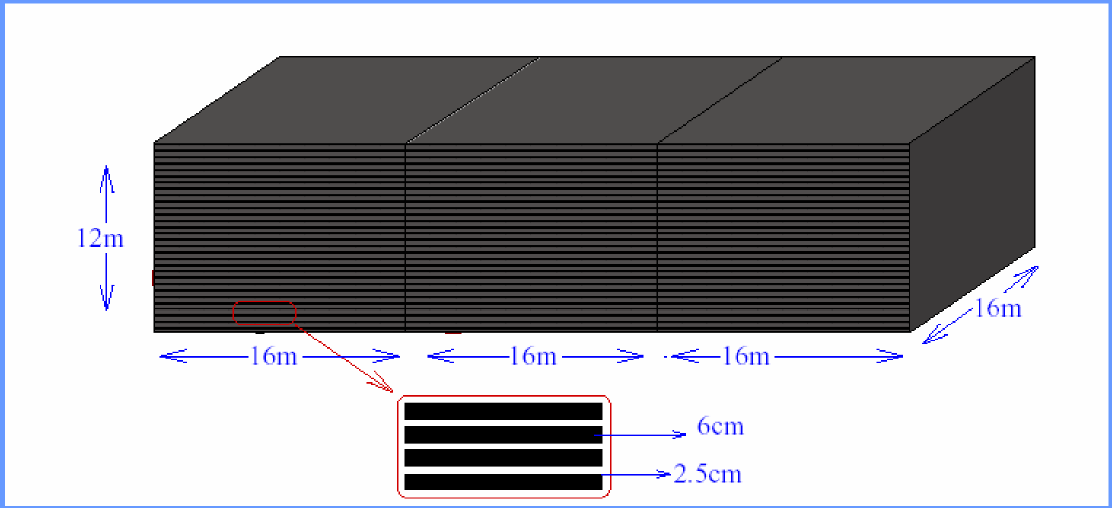
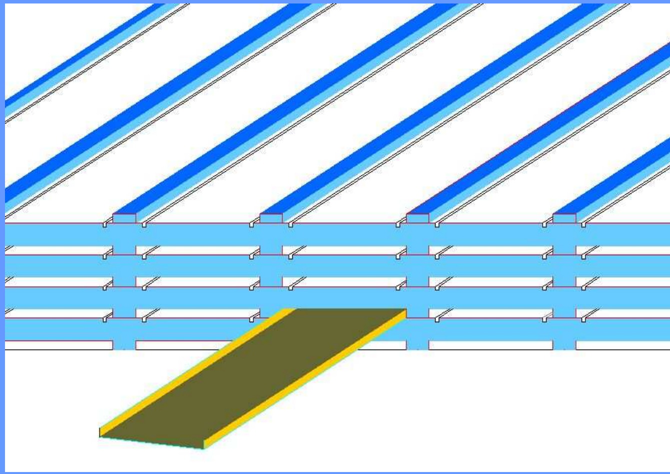
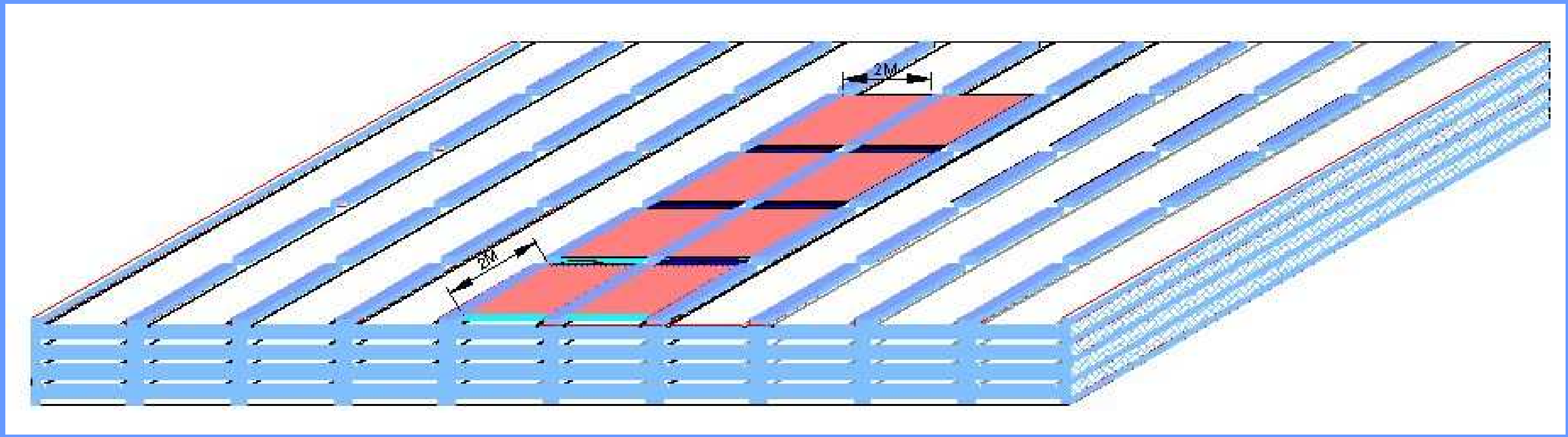
- Similar to the earlier Monolith proposal.

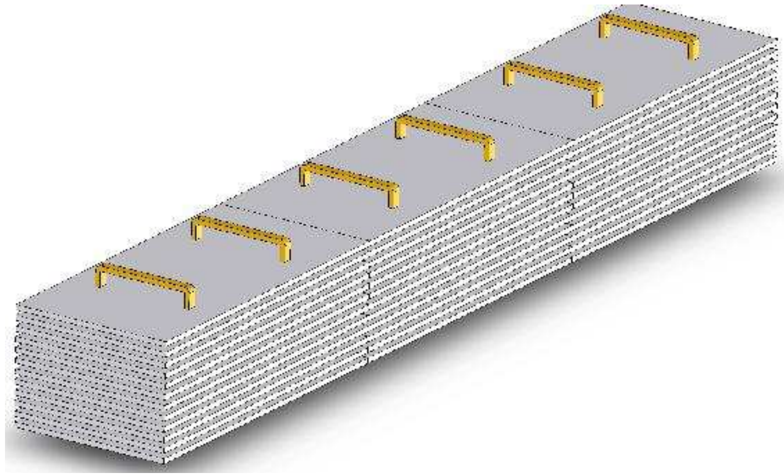
INO Detector Concept

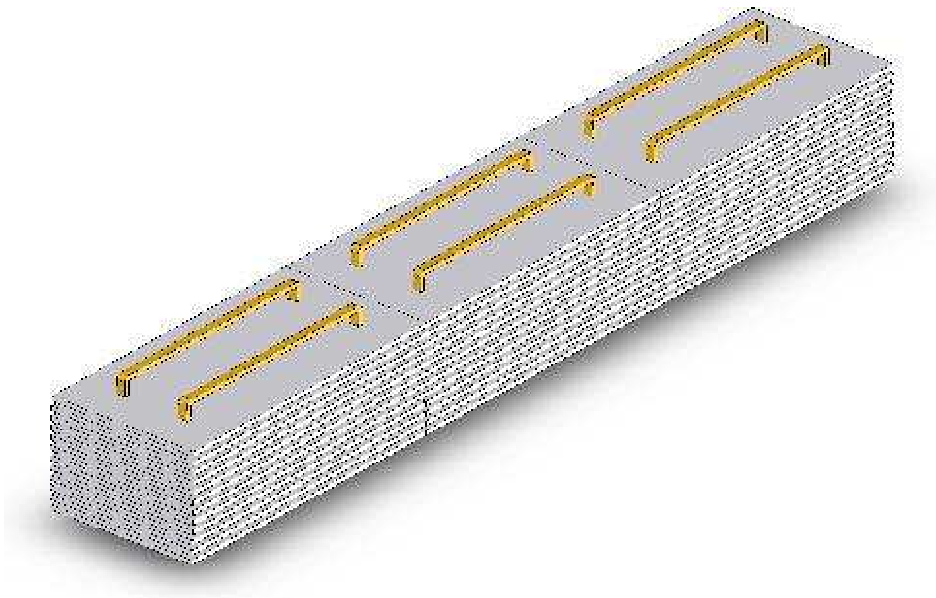






Two possible magnet designs





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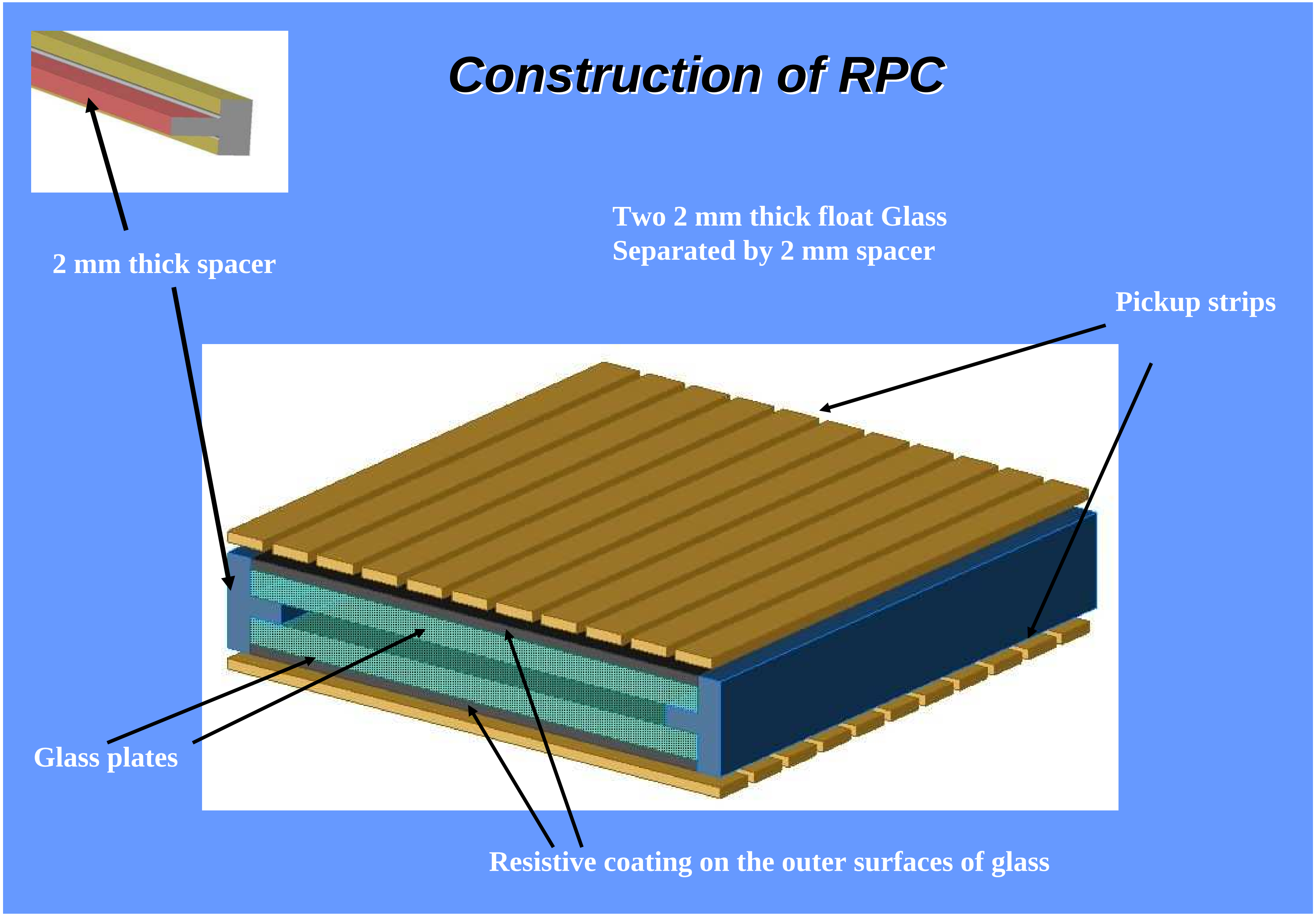
- Pick-up strips, 3 cm wide, above and below each RPC for the determination of x and y coordinates of the passage of charged particle
- The z coordinate is provided by the location of RPC itself.
- Good reconstruction of energy and direction of charged particles.



- Total number of RPC units: 27000
- Number of electronic readout channels: 3.6 million

Physics Motivations

- Reconfirm the first oscillation dip as a function of L/E in atmospheric neutrinos (to a greater significance level)
- Measure $|\Delta_{31}|$ and $\sin^2 2\theta_{23}$ precisely
- Determine neutrino mass hierarchy (normal/inverted)
- Resolve the θ_{23} octant ambiguity
- Distinguish between $\nu_\mu \leftrightarrow \nu_\tau$ and $\nu_\mu \leftrightarrow \nu_s$
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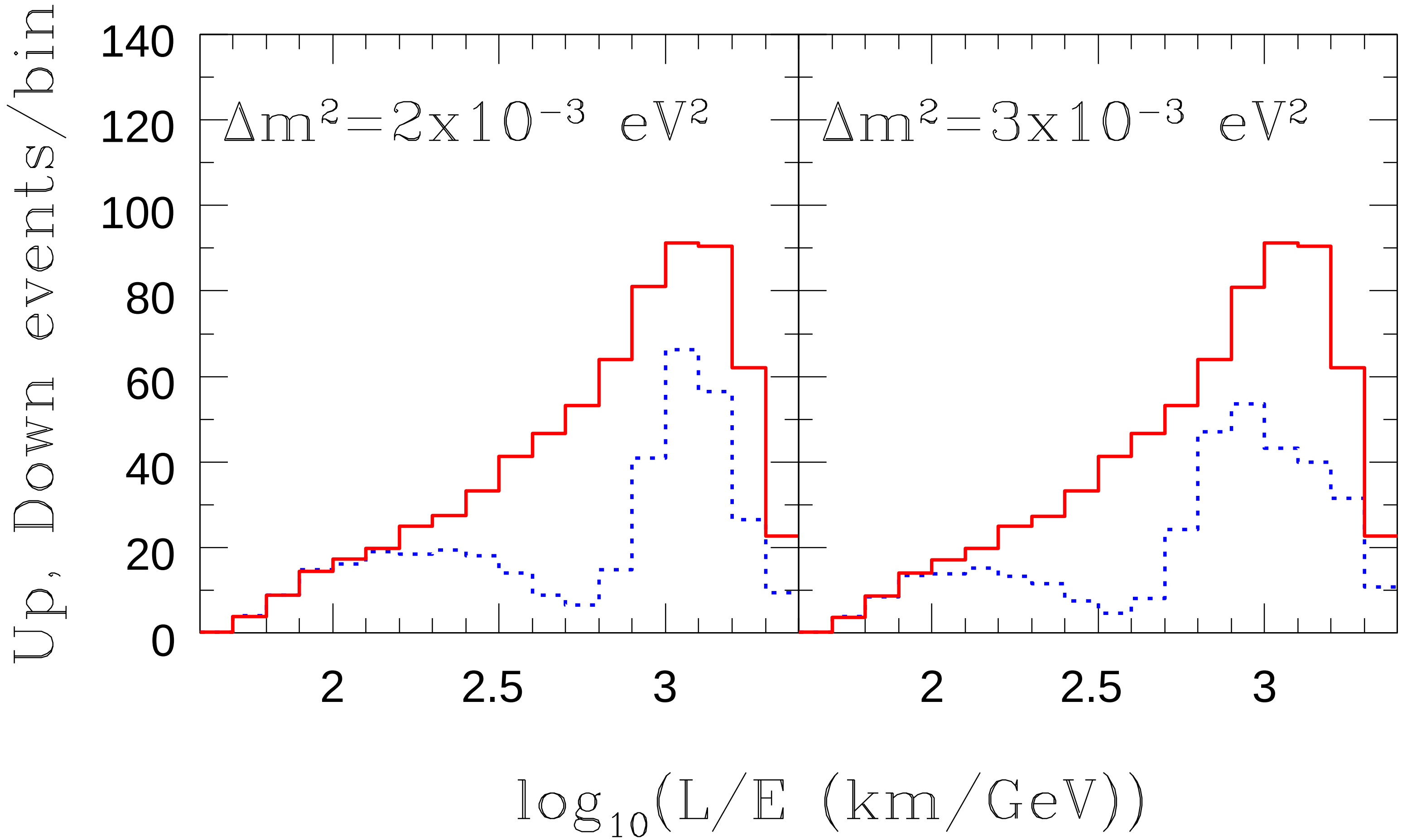
All results are generated assuming 15% resolution in L as well as E, unless specified otherwise.

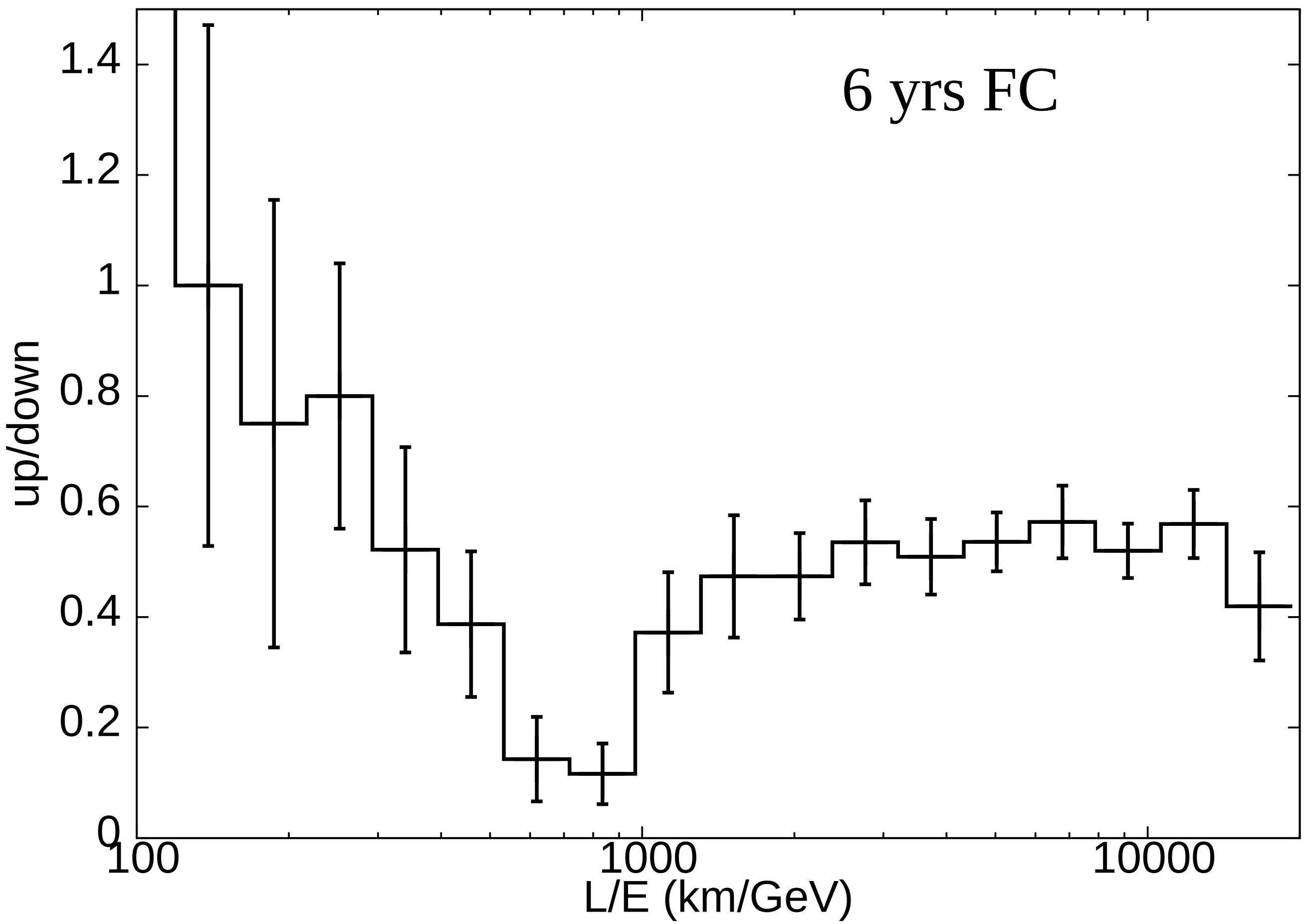
L/E distribution of muon events



red: down-going, blue: up-going

Exposure 250 kt-years, $\theta_{23} = \pi/4$, $E_\mu > 5$ GeV

Up/Down ratio of muon events



$E_\mu > 1$ GeV

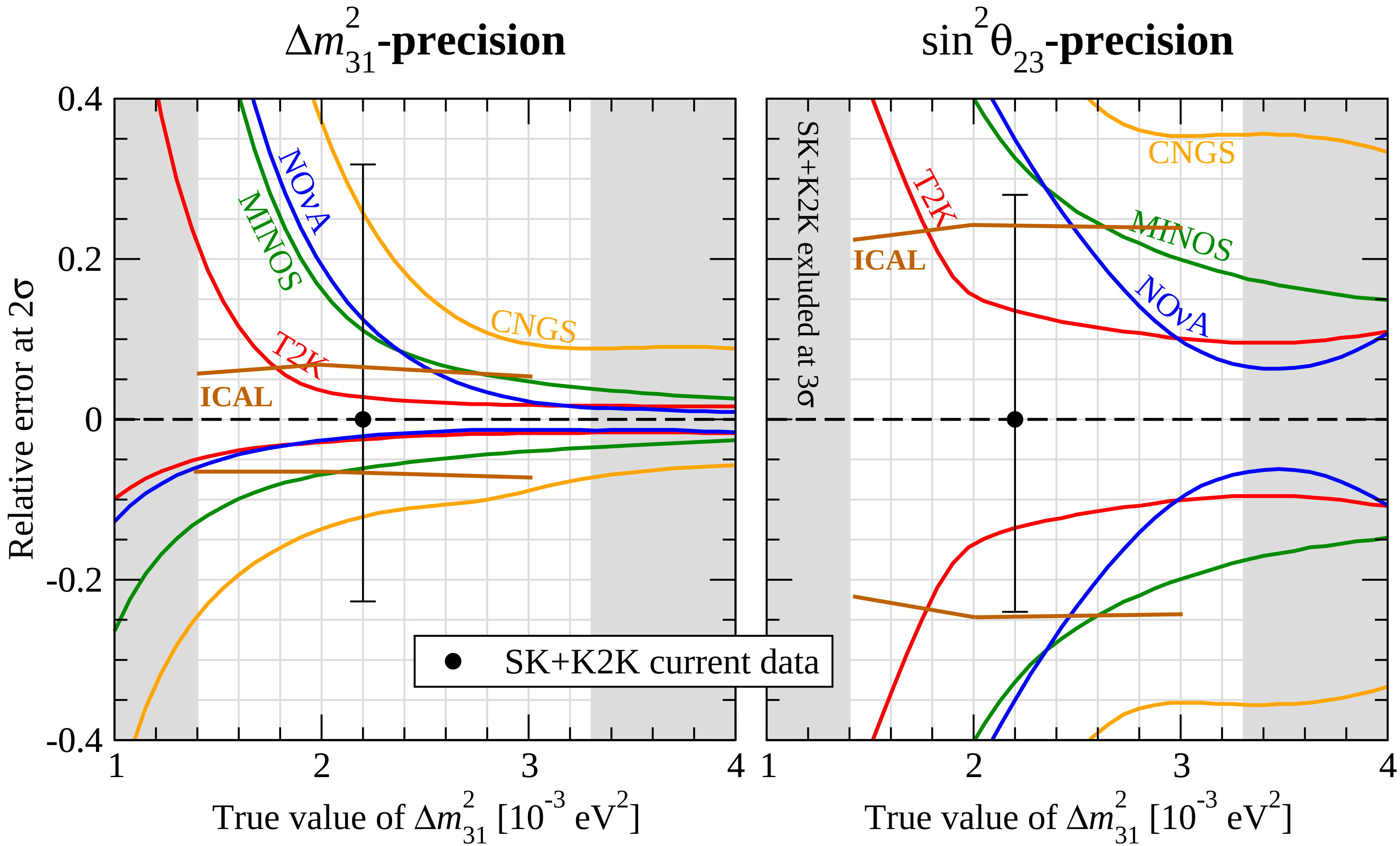
- Position of the dip $\Rightarrow \Delta m^2_{\rm atm}$
- Up/Down ratio at the dip $\Rightarrow \sin^2 2\theta_{23}$

Precision for $|\Delta_{31}|$ and $\sin^2\theta_{23}$

Experiment	Δ_{31}	$\sin^2\theta_{23}$
Current data	88%	79%
MINOS + CNGS	26%	78%
T2K (SK, 0.75 MW, 5 years)	12%	46%
NOνA (30 Kton, 0.6 MW, 5 years)	25%	86%
ICAL (50 Kton, atm ν, 5 years)	20%	60%

- Input values: $|\Delta_{31}| = 0.002$ eV^2 and $\theta_{23} = \pi/4$.
- Table adapted from P. Huber *et al.*, hep-ph/0412133, with the information of ICAL added.

The relative error on $|\Delta_{31}|$ and $\sin^2\theta_{23}$



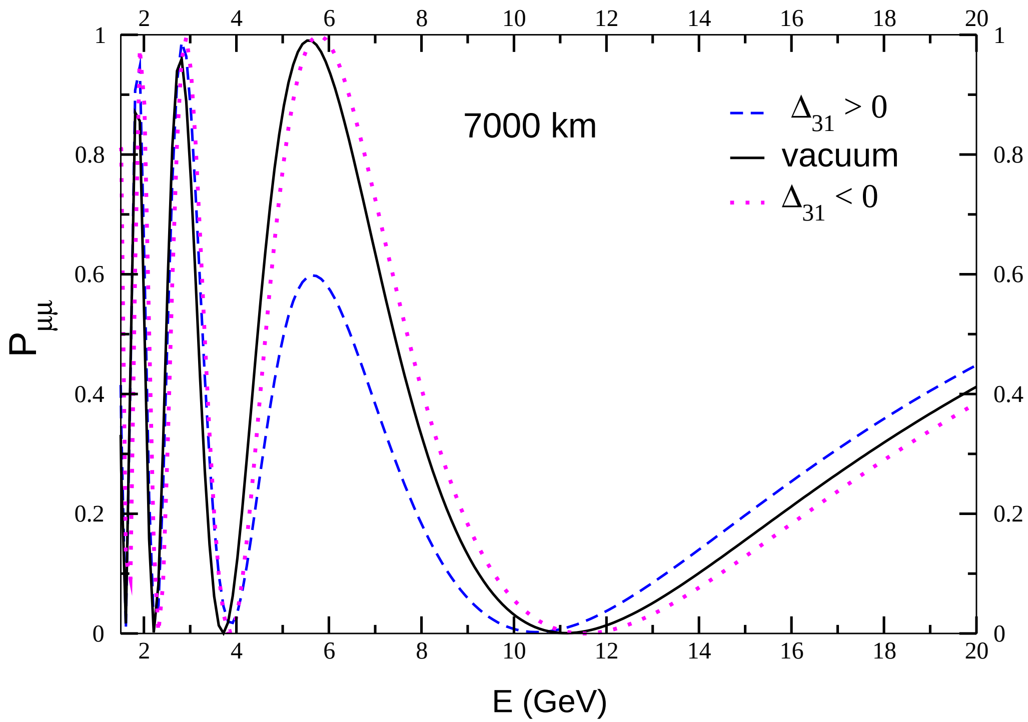
- Error as a function of the input value of $|\Delta_{31}|$ at 2 σ.

Mass hierarchy (normal/inverted)

- At resonance energies and long pathlengths, matter effects modify ν_μ survival probability significantly.

R. Gandhi *et al.*, PRL 94, 051801 (2005)

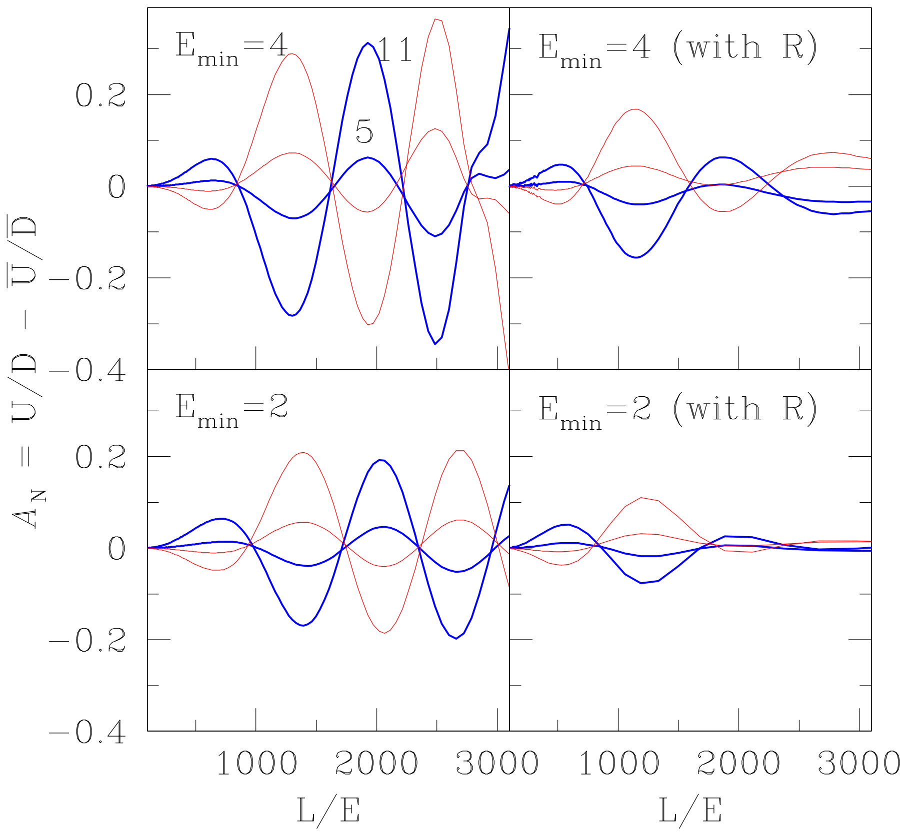
PRD 73, 053001 (2006)



- Situation reversed for antineutrinos

Up-down ratios for ν and $\bar{\nu}$

The difference in the up/down ratio for ν_μ and $\bar{\nu}_\mu$:
$\mathcal{A} \equiv U/D - \bar{U}/\bar{D}$ as a function of L/E
is very sensitive to the sign of Δ_{31}.



R: energy/time resolution included

blue: normal hierarchy

red: inverted hierarchy

D. Indumathi and M.V.N. Murthy, PRD 71, 013001 (2005)
INO Project Report, May 2006

Higher $E_{\rm min} \Rightarrow$ more asymmetry but less events

$$\Delta\mathcal{A} \equiv \mathcal{A}_{\rm norm} - \mathcal{A}_{\rm inv}$$

Exposure (kt-years)	θ_{13}	$\Delta\mathcal{A}$	Signifi cance
480	7°	0.167 ± 0.230	$0.7\sigma, 51.6\%$
1120	7°	0.167 ± 0.151	$1.1\sigma, 72.9\%$
480	11°	0.415 ± 0.230	$1.8\sigma, 92.8\%$
1120	11°	0.415 ± 0.150	$2.8\sigma, 99.6\%$

480	7°	0.232 ± 0.220	$1.1\sigma, 72.9\%$
1120	7°	0.232 ± 0.144	$1.6\sigma, 89.0\%$
480	11°	0.565 ± 0.220	$2.6\sigma, 99.1\%$
1120	11°	0.565 ± 0.144	$3.9\sigma, 99.99\%$

- E and L resolutions of 15% (upper) and 10% (lower).
- Exposure time 480 kt-year $\longrightarrow$ 1120 kt-year
  has the same effect as resolution $15\% \longrightarrow 10\%$
- Importance of L and E resolution highlighted in
  S. Petcov and T. Schwetz, NPB 740, 1 (2006)

Octant ambiguity of θ_{23}

(Is θ_{23} greater or less than $\pi/4$?)

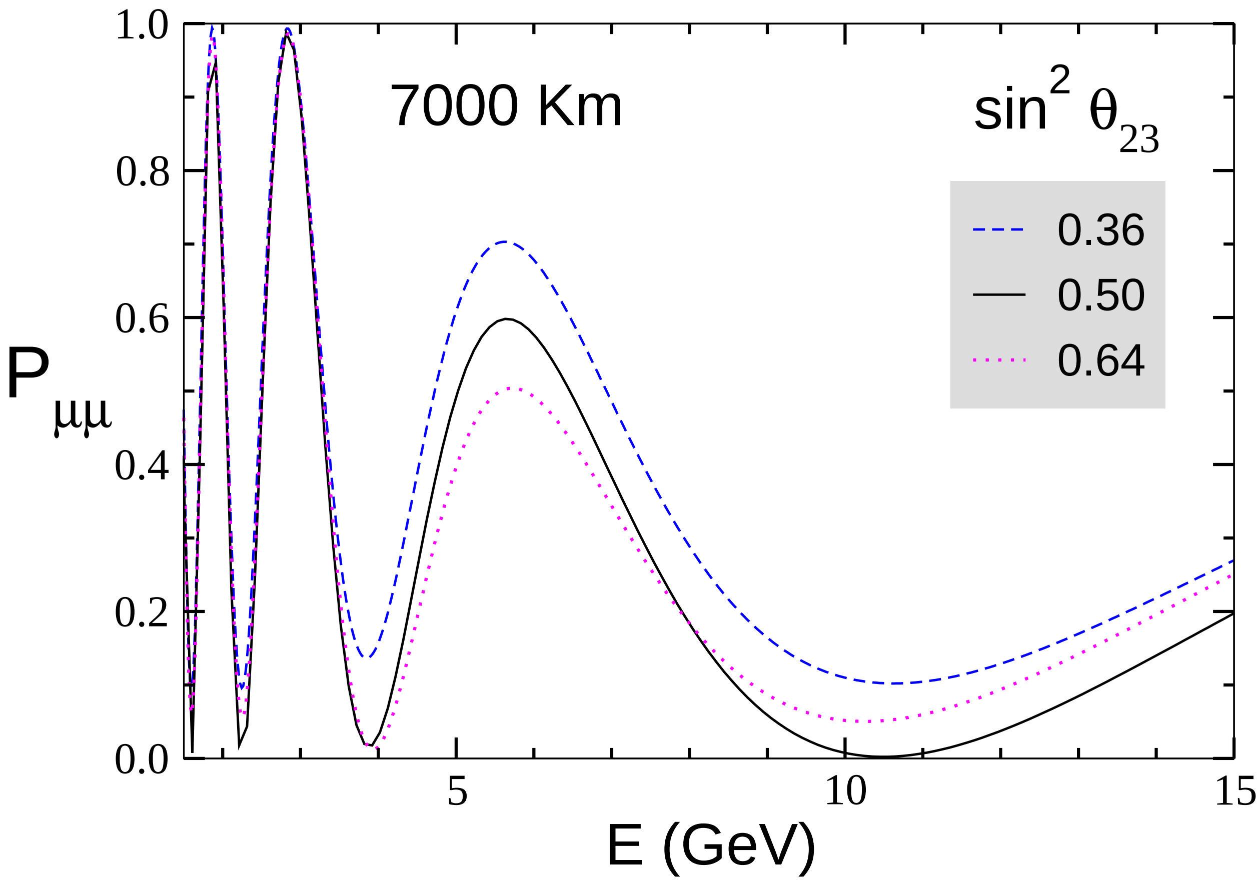
- One of the matter dependent terms in $P_{\mu\mu}$ goes as $\boxed{\sin^4\theta_{23}}$. By appropriate cuts on E and L this term can be isolated and to determine if θ_{23} is greater or less than $\pi/4$.

  S. Choubey and P. Roy, PRD 73, 013006 (2006)

  D. Indumathi *et al.*, hep-ph/0603032

- At present $|D \equiv 0.5 - \sin^2\theta_{23}|$ is constrained to be about 0.16 at 3σ. If $\sin^2\theta_{13} = 0.02$ then 1000 kt-year exposure can:
  - measure a non-zero value for $|D| > 0.09$ at 3σ.
  - Determine the sign of D for $|D| > 0.1$ at 3σ

$P_{\mu\mu}$ as a function of θ_{23}



- For intermediate E, even the sign of D discernible

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D. Choudhury and A. Datta, hep-ph/0606100

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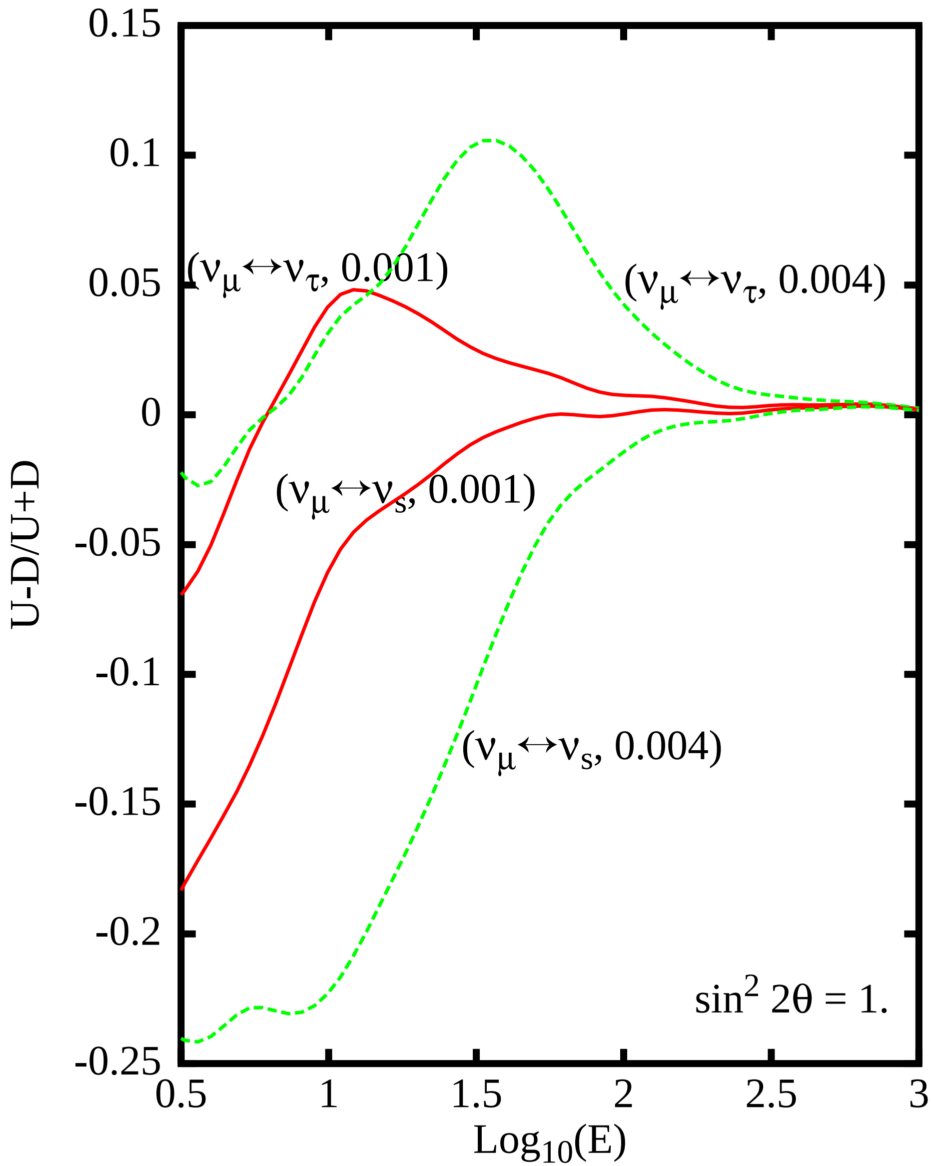
  D. Choudhury and A. Datta, hep-ph/0606100
- MINOS is also capable of doing this

Up-down asymmetry for muonless events



Asymmetry vs. E for different Δ_{31} values for $\nu_\mu \longrightarrow \nu_\tau$ and $\nu_\mu \longrightarrow \nu_s$

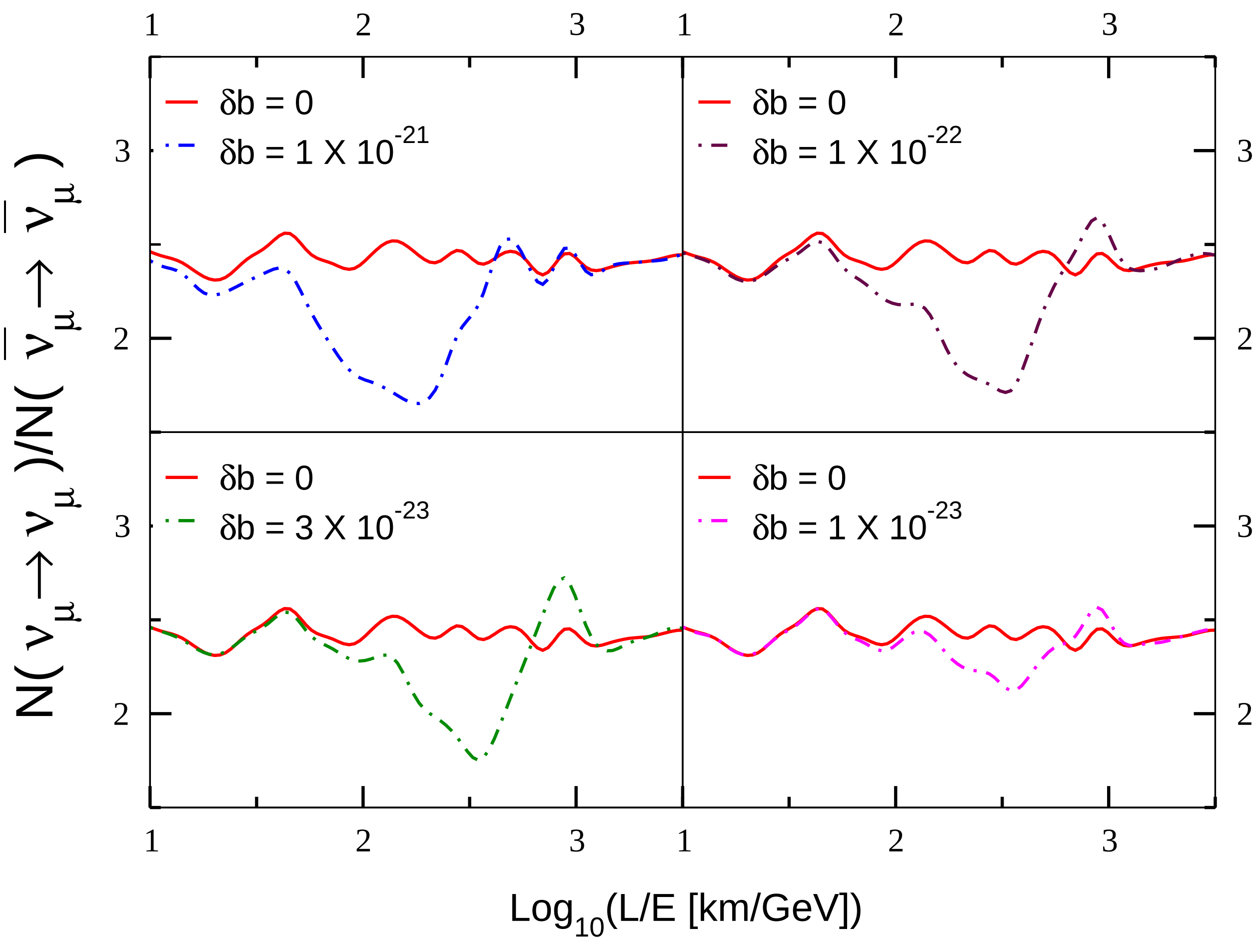
CPT violation

- Charge determination $\Rightarrow$
  both $P_{\mu\mu}$ and $P_{\bar{\mu}\bar{\mu}}$ measurable independently.
- Possibility of searching for CPT violation.
- CPT violation Parametrized as: $\mathcal{L}_{\rm CPT} = \bar{\nu}_L^{\alpha} b^{\mu}_{\alpha\beta} \gamma_\mu \nu_L^{\beta}$

  V. Barger *et al.*, PRL 85, 5055 (2000)
- Energy operator becomes $H = m^2/2E + b^0$
- Measurable CPT violating parameter: δb, the difference in the eigenvalues of the b^0 matrix

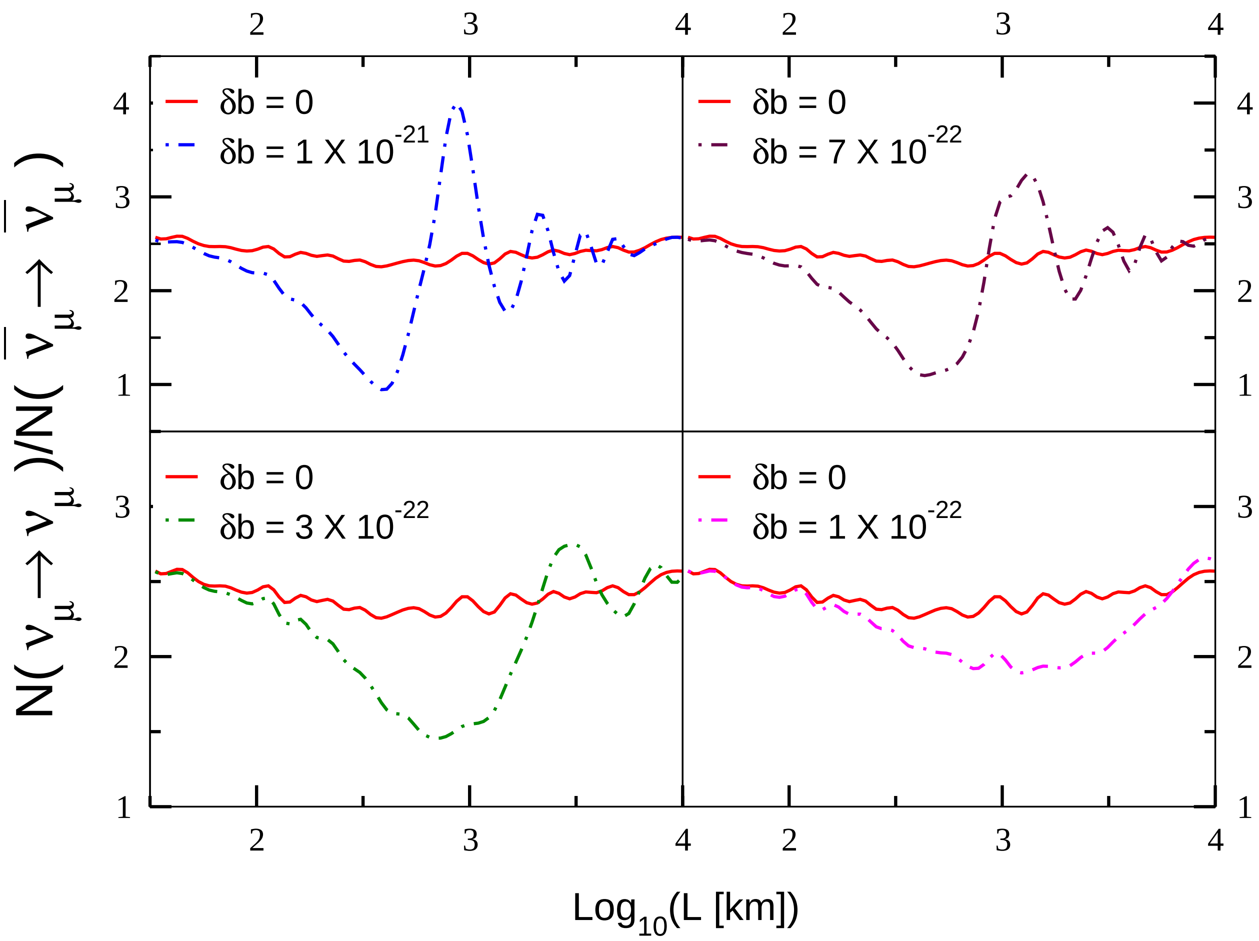
  A. Datta *et al*, Phys. Lett. B 597, 356 (2004).

Sensitivity to CPT violation



- L/E distribution can detect $\delta b \gtrsim 10^{-23}$ GeV
- To be compared to $\Delta m^2/2E \sim 10^{-21}$ GeV

Determination of δb



- For $\delta b > 10^{-22}$ GeV, distribution in L is sensitive to the value of δb

Concluding Remarks

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- We welcome more International participation

That's all, folks !

http://www.imsc.res.in/∼ino

Extra slides

$P_{\mu\mu}$ in vacuum and matter

Muon neutrino survival probability in vacuum:

$$
\begin{aligned}
P_{\mu\mu}(vac) \;&=\; 1 - \sin^2 2\theta_{23} \cos^2 \theta_{13} \sin^2 (1.27 \Delta_{31} L/E) \\
&\quad - \sin^4 \theta_{23} \sin^2 2\theta_{13} \sin^2 (1.27 \Delta_{31} L/E)
\end{aligned}
$$

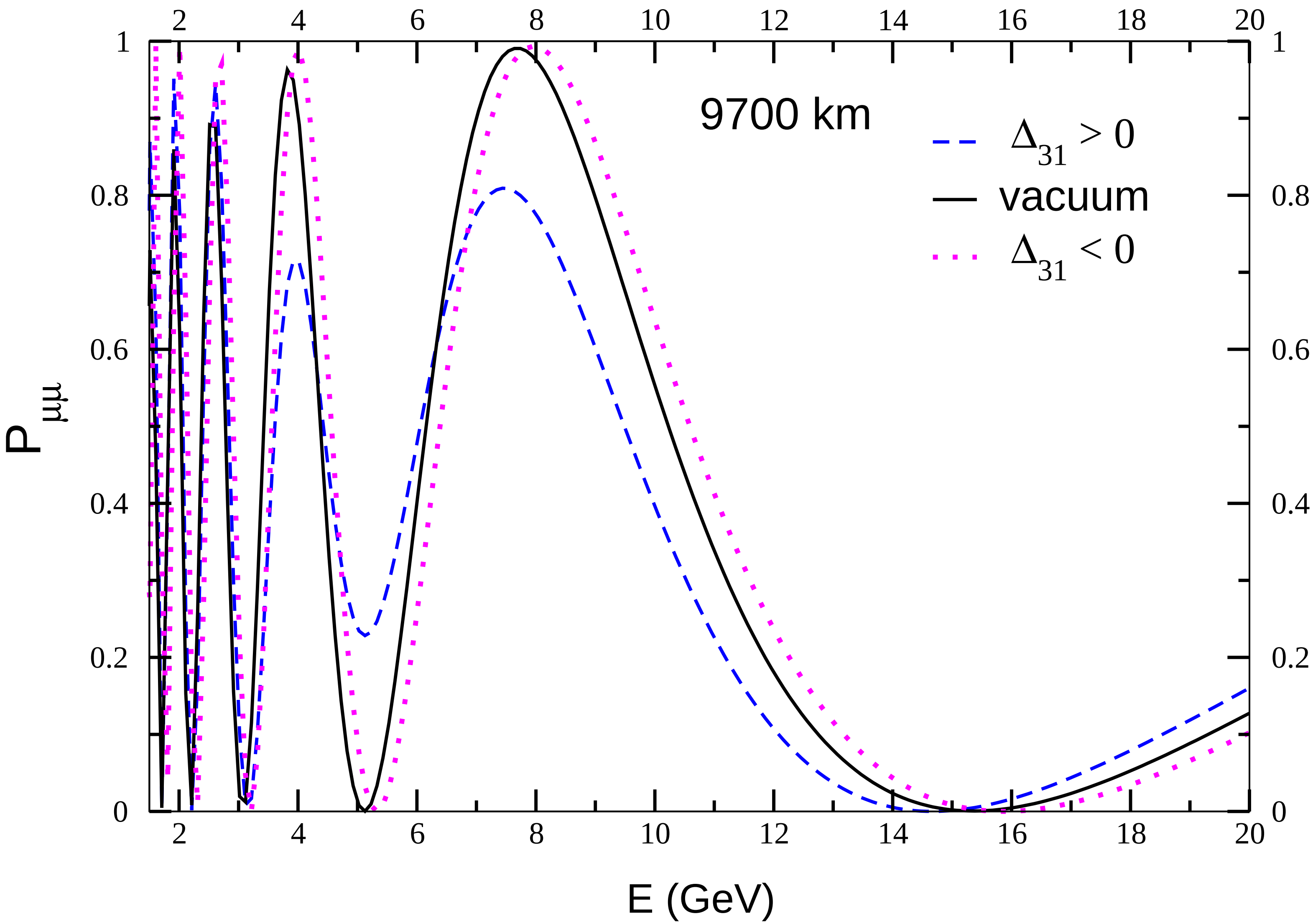
Muon neutrino survival probability in matter:

$$
\begin{aligned}
P_{\mu\mu}(mat) \;&=\; 1 - \sin^2 2\theta_{23} \cos^2 \theta^m_{13} \sin^2 [1.27(\Delta_{31} + A + \Delta^m_{31}) L/2E \\
&\quad - \sin^2 2\theta_{23} \sin^2 \theta^m_{13} \sin^2 [1.27(\Delta_{31} + A - \Delta^m_{31}) L/2E] \\
&\quad - \sin^4 \theta_{23} \sin^2 2\theta^m_{13} \sin^2 (1.27 \Delta^m_{31} L/E)
\end{aligned}
$$

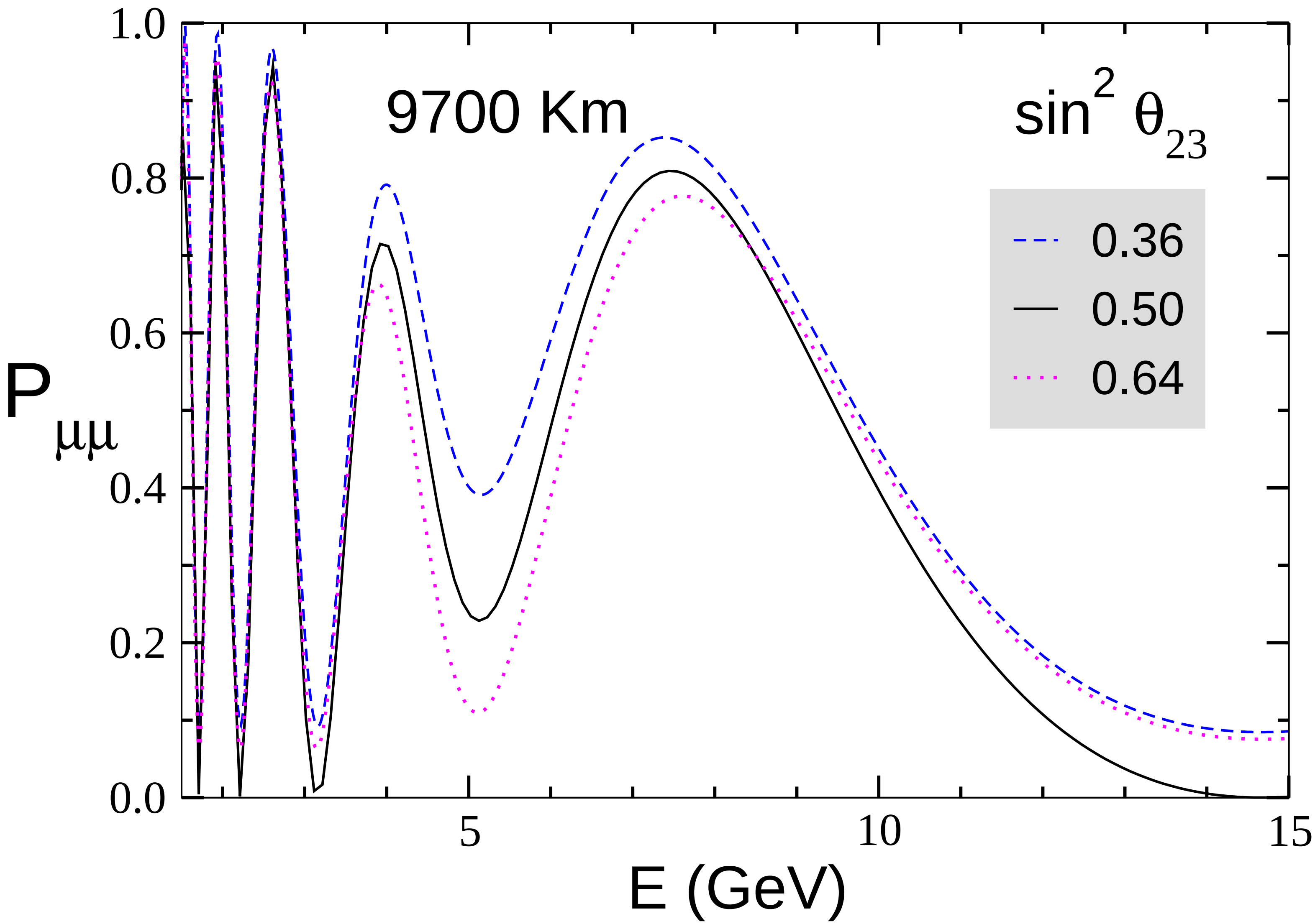
$$A = 2\sqrt{2} G_F N_e E$$

$\boxed{\Leftarrow}$

$P_{\mu\mu}$ for both hierarchies, $L = 9700$ km



$P_{\mu\mu}$ vs. θ_{23} for $L = 9700$ km



CPT violation: a comment

- If we parametrize CPT violation as
  $\Delta = \Delta_{\rm GUT} + \Delta_{\rm CPT}$ and $\overline{\Delta} = \Delta_{\rm GUT} - \Delta_{\rm CPT}$,
  INO is sensitive to $\Delta_{\rm CPT}/\Delta_{\rm GUT} \sim 1\%$