Neutrino mass hierarchy and θ_{13} with a magic baseline beta-beam experiment

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Phys. Lett. B629 (2005) 33-40 and Nucl. Phys. B (to appear) hep-ph/0610333

Plan

- Beta beam
- India-based Neutrino Observatory (INO)
- Neutrino oscillations with matter effect
- Probing neutrino parameters with a long baseline experiment
- Results
- Conclusions

Beta-beam

Beta Beam

- A pure, intense, collimated beam of ν_e or $\bar{\nu}_e$, essentially background free.

- ν_e and $\bar{\nu}_e$ beams possible at the same time

- Origin: beta decay of radioactive ions circulating in a storage ring. No contamination of other types of neutrinos.

Some positive features

$\Rightarrow$ known energy spectrum

$\Rightarrow$ high intensity, low systematic errors

$\Rightarrow$ High Lorentz boost of the parent ions $\Rightarrow$ better collimation and higher energy of beam

$\Rightarrow$ can be produced, for example, with existing CERN facilities or planned upgrades.

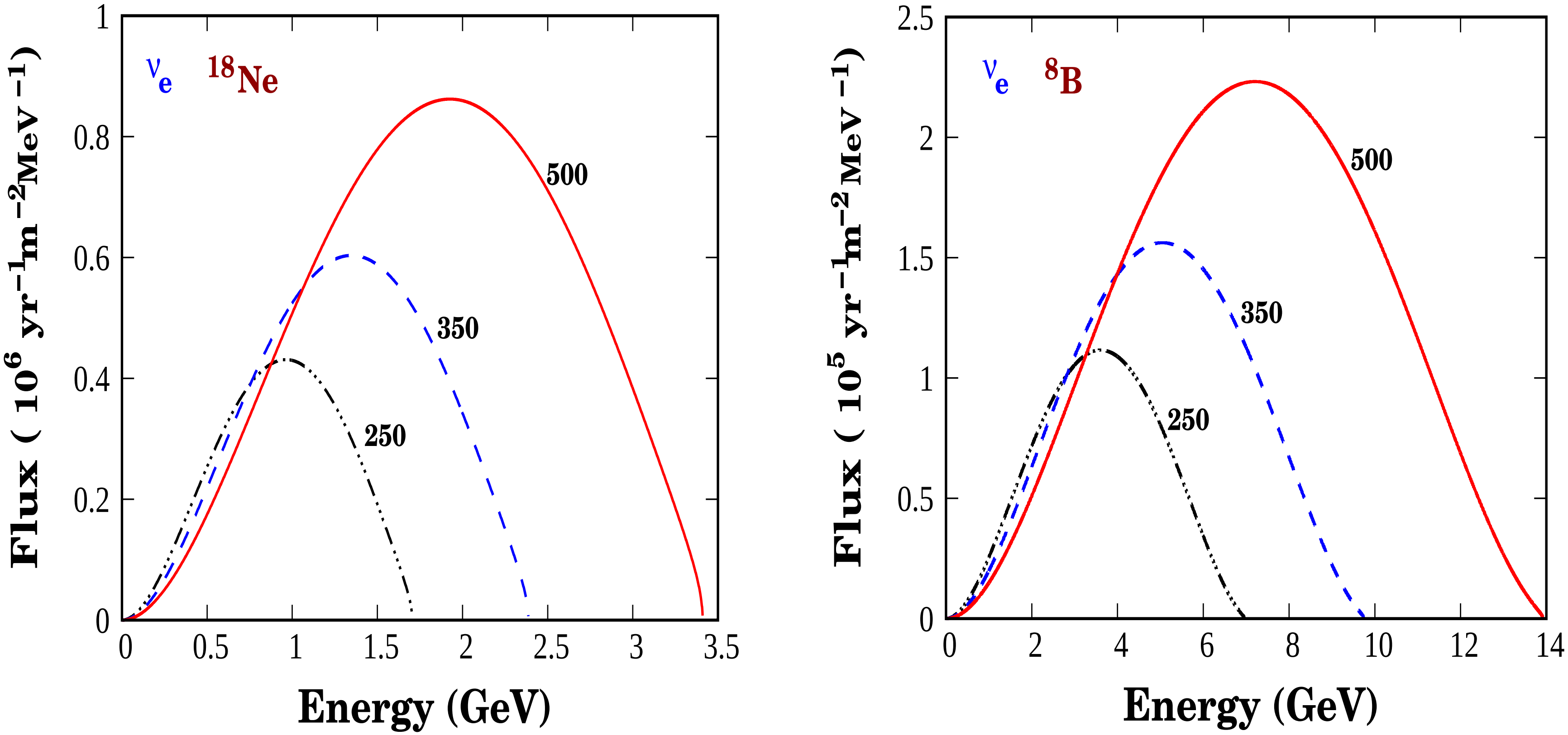
Beta Beam: Ion soures

Ion	τ (s)	E_0 (MeV)	f	Decay fraction	Beam
${}^{18}_{10}$Ne	2.41	3.41	393.5	92.1%	ν_e
${}^{6}_{2}$He	1.17	3.51	462.6	100%	$\bar{\nu}_e$
${}^{8}_{5}$B	1.11	13.92	501543.0	100%	ν_e
${}^{8}_{3}$Li	1.20	12.96	350500.5	100%	$\bar{\nu}_e$

Comparison of different source ions

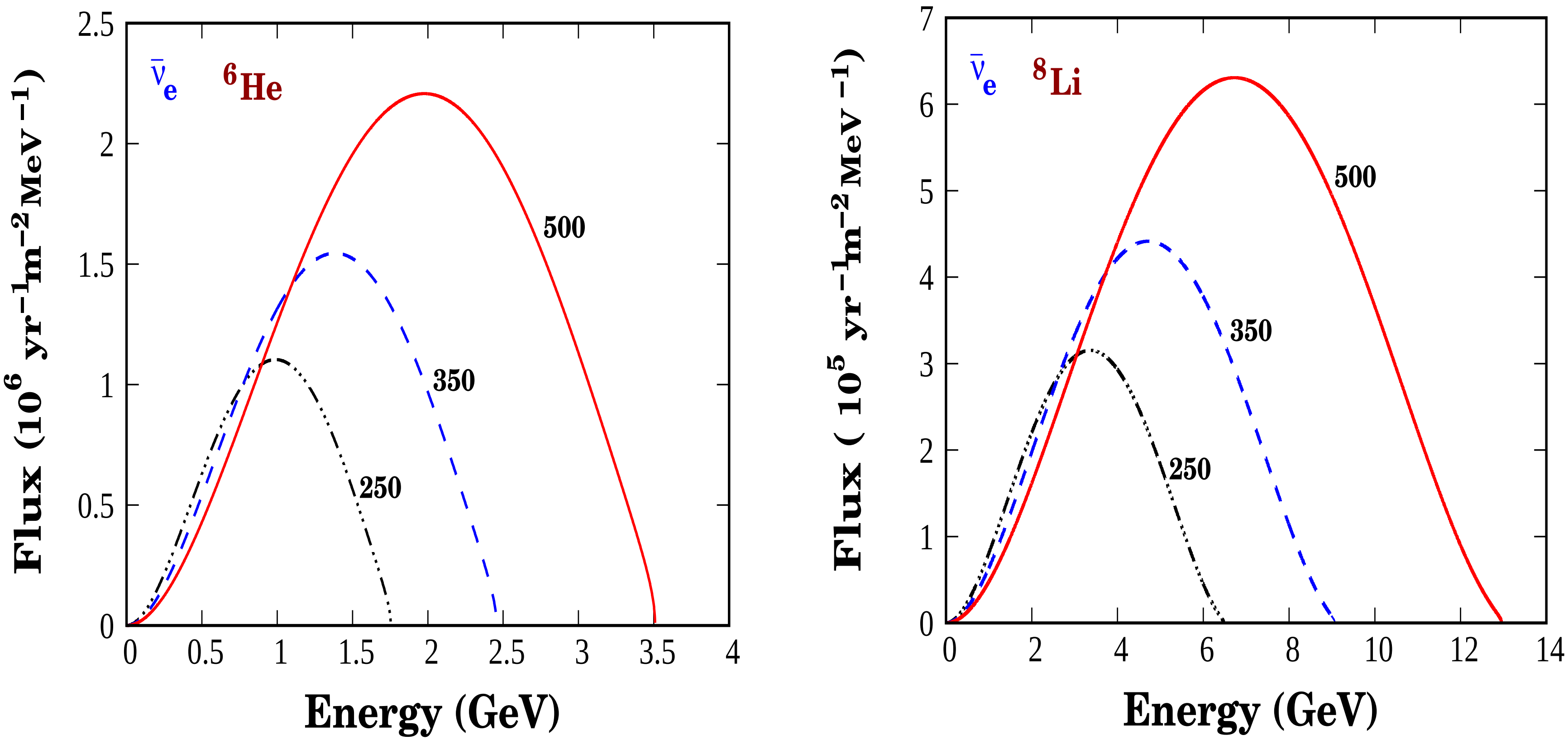
Larger end-point energy, E_0, is preferable

ν_e Spectrum



Boosted on-axis spectrum of neutrinos at the far detector assuming no oscillation.

$\bar{\nu}_e$ Spectrum



Boosted on-axis spectrum of anti-neutrinos at the far detector assuming no oscillation.

The India-based Neutrino Observatory (INO)

INO

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- $\Rightarrow$ Earlier experiments: KGF proton decay, atmospheric ν_μ detection
- $\Rightarrow$ ICAL: a magnetized Iron calorimeter with interleaved Glass RPC detectors
- $\Rightarrow$ good efficiency of charge identification ($\sim$ 95%)
- $\Rightarrow$ Excellent energy determination for $\mu^\pm$ with $E \geq$ 1 GeV
- $\Rightarrow$ $\nu_e \rightarrow \nu_\mu$ oscillation signal $\Rightarrow$ muon track

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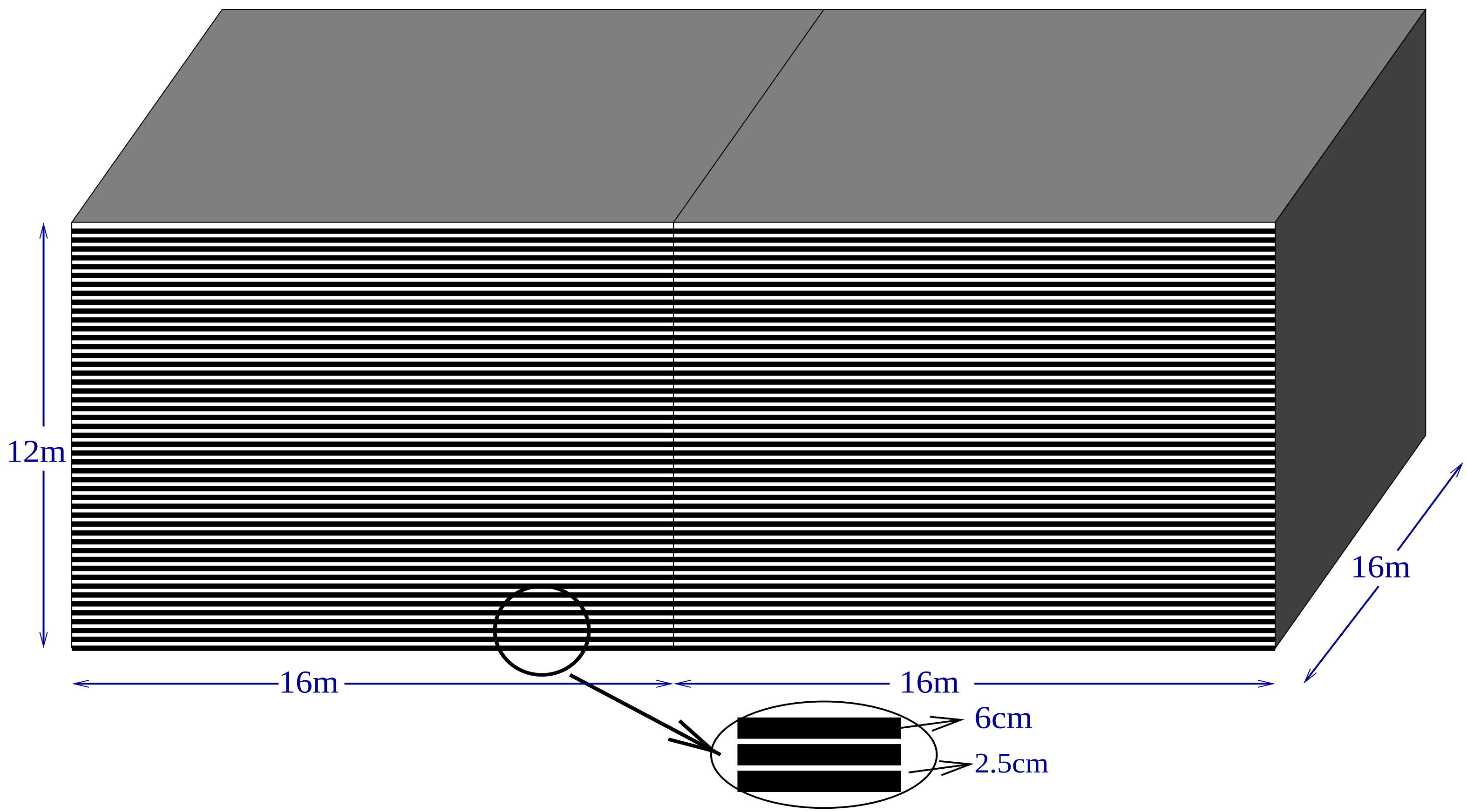

Schematic plan of the 50 kTon ICAL detector for INO.

Three-flavour oscillations

Neutrino mixing

⇒ Atmospheric neutrinos 3σ :
$2.0 \times 10^{-3}\mathrm{eV}^2 < |\Delta_{32}| < 3.2 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2 2\theta_{23} > 0.9$

⇒ solar neutrinos 3σ : $0.25 < \sin^2\theta_{12} < 0.39$,
$7.2 \times 10^{-5}\mathrm{eV}^2 < \Delta_{12} < 9.2 \times 10^{-5}\mathrm{eV}^2$

⇒ current bound on CHOOZ mixing angle θ_{13} from the global oscillation analysis : $\sin^2 2\theta_{13} < 0.17$

⇒ two large mixing angles and the relative oscillation frequencies open the possibility to test CP violation in the neutrino sector, if θ_{13} and δ are not vanishingly small

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Neutrino mixing (contd.)

Unsolved issues

- ⇒ The sign of Δm^2_{31} is not known. Neutrino mass spectrum can be direct or inverted hierarchical
- ⇒ Only an upper limit on θ_{13}
- ⇒ The CP phase, δ, is unconstrained

Eightfold problem of parameter degeneracies:

- ⇒ the $(\theta_{13}, \delta_{CP})$ intrinsic degeneracy
- ⇒ the $(sgn(\Delta m^2_{31}), \delta_{CP})$ degeneracy
- ⇒ the $(\theta_{23}, \pi/2 - \theta_{23})$ degeneracy

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Magic baseline

Magic baseline

The appearance probability ($\nu_e \to \nu_\mu$) in matter, upto second order in the small parameters $\alpha \equiv \Delta m^2_{12}/\Delta m^2_{13}$ and $\sin 2\theta_{13}$,

$$
\begin{aligned}
P_{e\mu} &\simeq \sin^2 2\theta_{13}\, \sin^2\theta_{23} \frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} \\
&\pm \alpha \sin 2\theta_{13}\, \xi \sin\delta \sin(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha \sin 2\theta_{13}\, \xi \cos\delta \cos(\Delta) \frac{\sin(\hat{A}\Delta)}{\hat{A}} \frac{\sin[(1-\hat{A})\Delta]}{(1-\hat{A})} \\
&+ \alpha^2 \cos^2\theta_{23} \sin^2 2\theta_{12} \frac{\sin^2(\hat{A}\Delta)}{\hat{A}^2};
\end{aligned}
$$

where $\Delta \equiv \Delta m^2_{13} L/(4E)$, $\xi \equiv \cos\theta_{13}\, \sin 2\theta_{12}\, \sin 2\theta_{23}$,
and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{13}$.

Magic Baseline (contd.)

If one chooses: $\sin(\hat{A}\Delta) = 0$

- The δ dependence disappears from $P(\nu_e \rightarrow \nu_\mu)$.
- A clean measurement of the hierarchy and θ_{13} is possible without any correlation with δ.

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The fi rst non-trivial solution: $\sqrt{2} G_F n_e L = 2\pi$ (indep of E)

- Isoscalar medium of constant density ρ : $L_{\rm magic}[\rm km] \approx 32726/\rho[\rm gm/cm^3]$.
- The averaged density for the CERN-INO path is $\rho \simeq$ 4.25 gm/cc $\Rightarrow L_{\rm magic} \simeq$ 7690 km.

CERN – INO long baseline

- The longer baseline captures a matter-induced contribution to the neutrino parameters, essential for probing the sign of Δm^2_{23}.
- The CERN-INO baseline, 7152 km, close to the ‘magic’ value, ensures essentially no dependence of the fi nal results on δ.
- This permits a clean measurement of θ_{13} avoiding the degeneracy issues which plague other baselines.

Resonance in matter effect

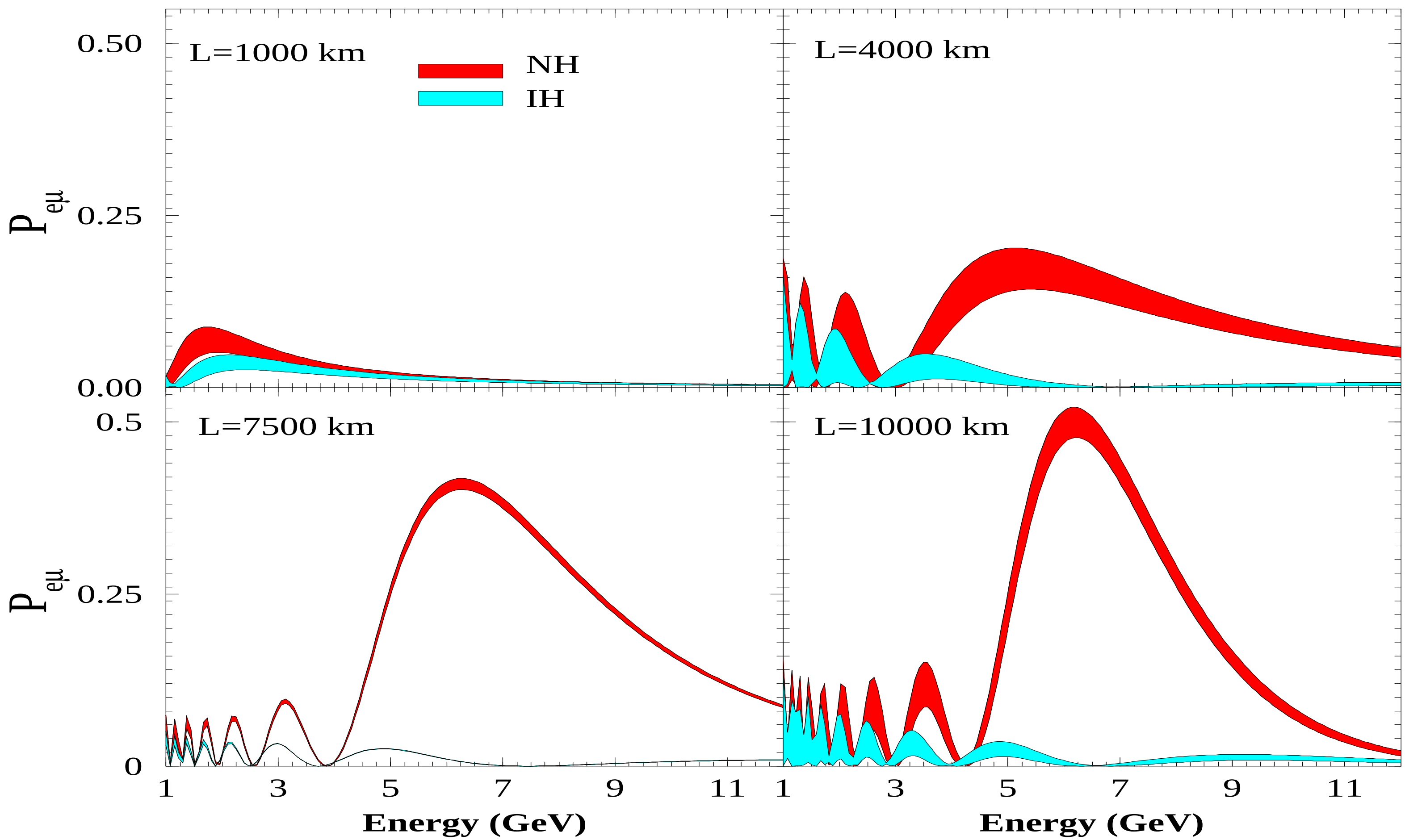
- The very long CERN-INO baseline provides an excellent avenue to pin-down matter-induced contributions

- In particular, a resonance occurs at

$$E_{res} \equiv \frac{|\Delta m^2_{31}| \cos 2\theta_{13}}{2\sqrt{2} G_F n_e},$$

- For $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ eV^2, $\sin^2 2\theta_{13} = 0.1$ and the PREM profi le $\rho_{av} = 4.13$ gm/cc, it is $E_{res} \simeq 6.1$ GeV.

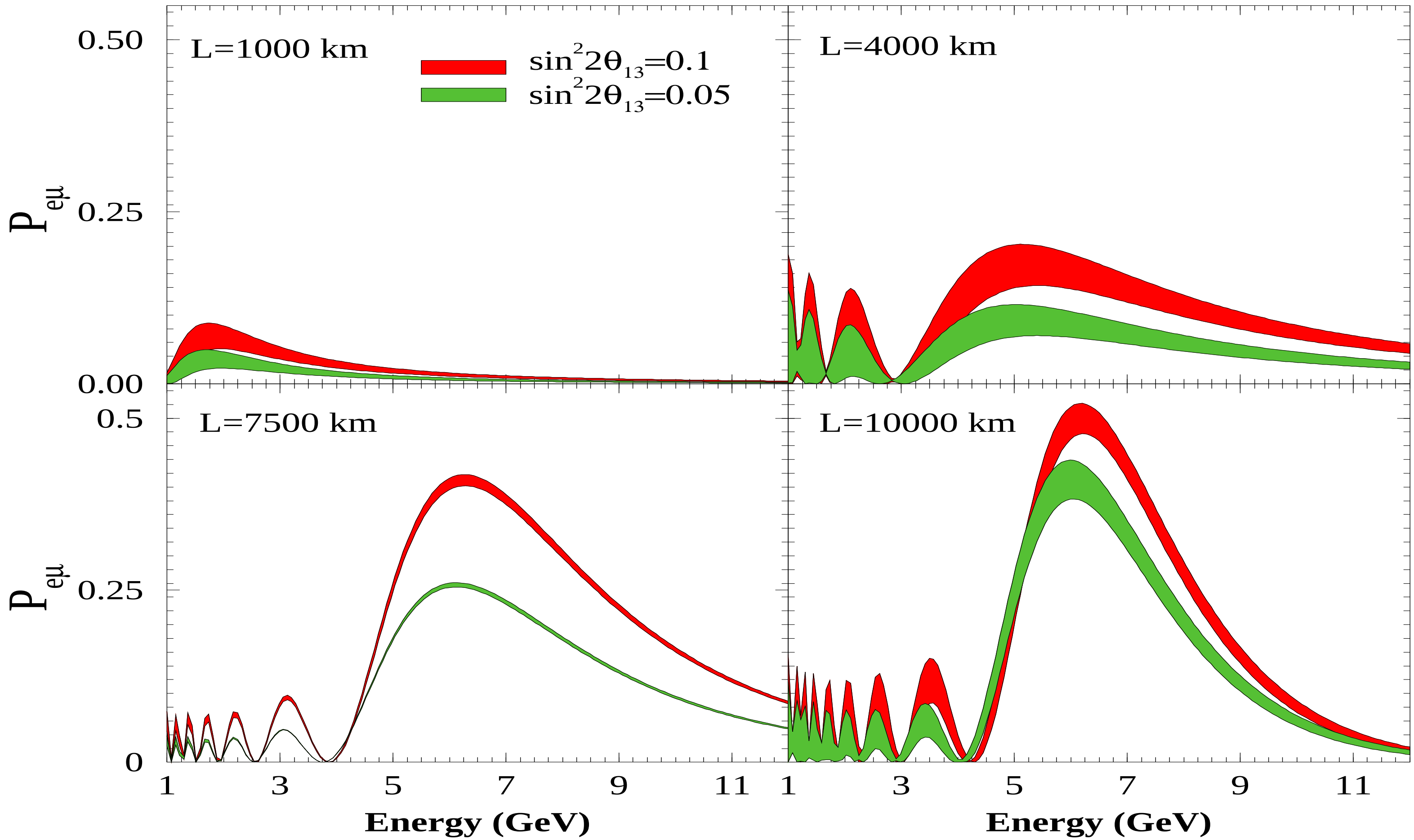
Transition Probability $P_{e\mu}$



Transition probability for different baselines.

Normal vs. Inverted hierarchy.

Transition Probability $P_{e\mu}$



Transition probability for different baselines.

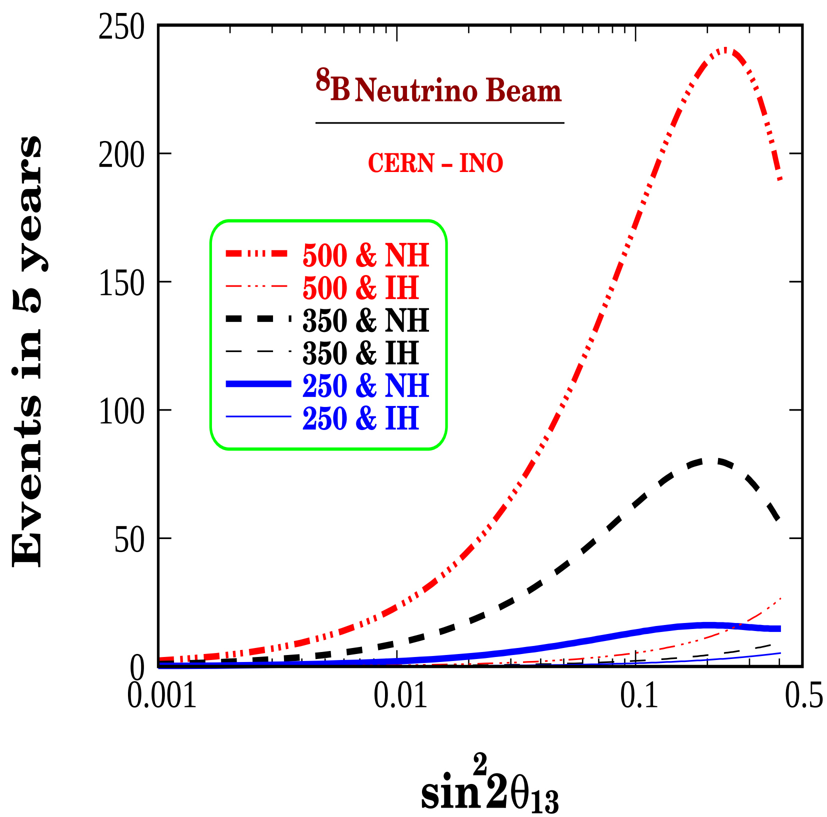
θ_{13} variation.

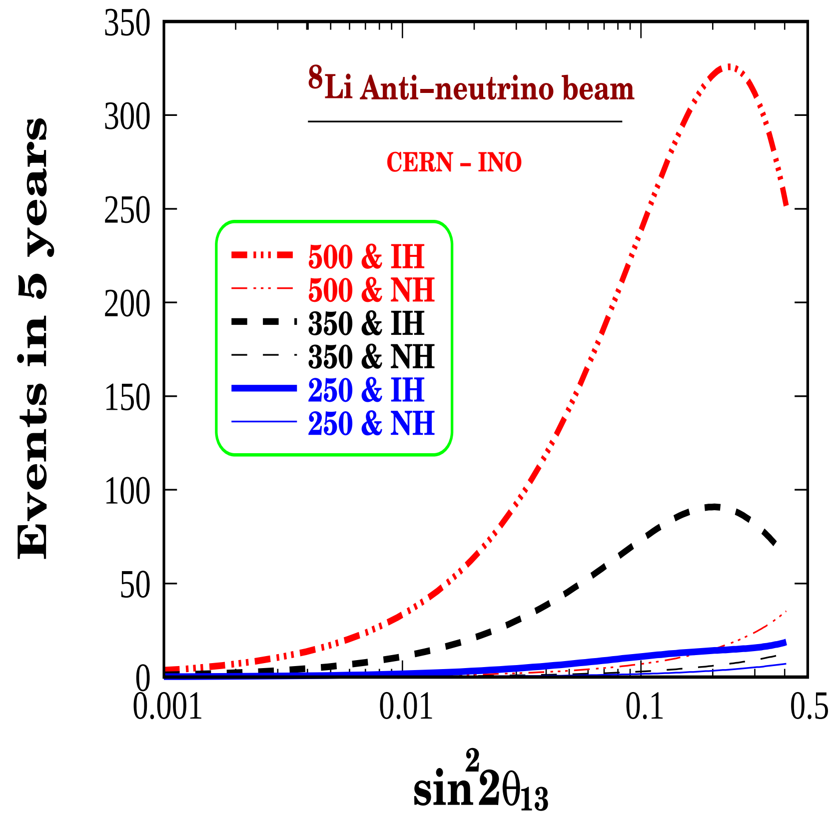
Results

Detector assumptions

Total Mass	50 kton
Energy threshold	1.5 GeV
Detection Effi ciency (ϵ)	60%
Charge Identifi cation Effi ciency (f_D)	95%

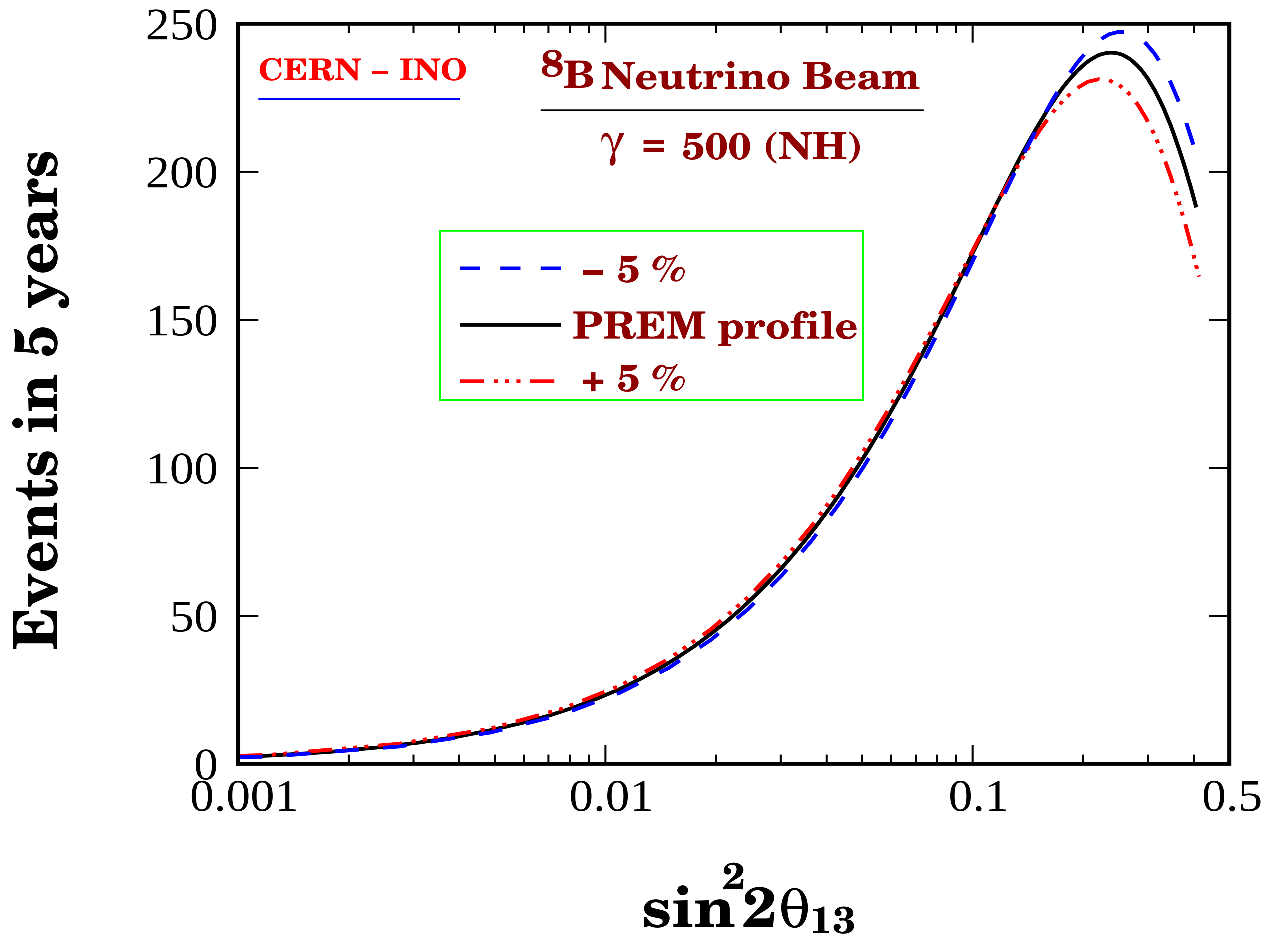
No. of events





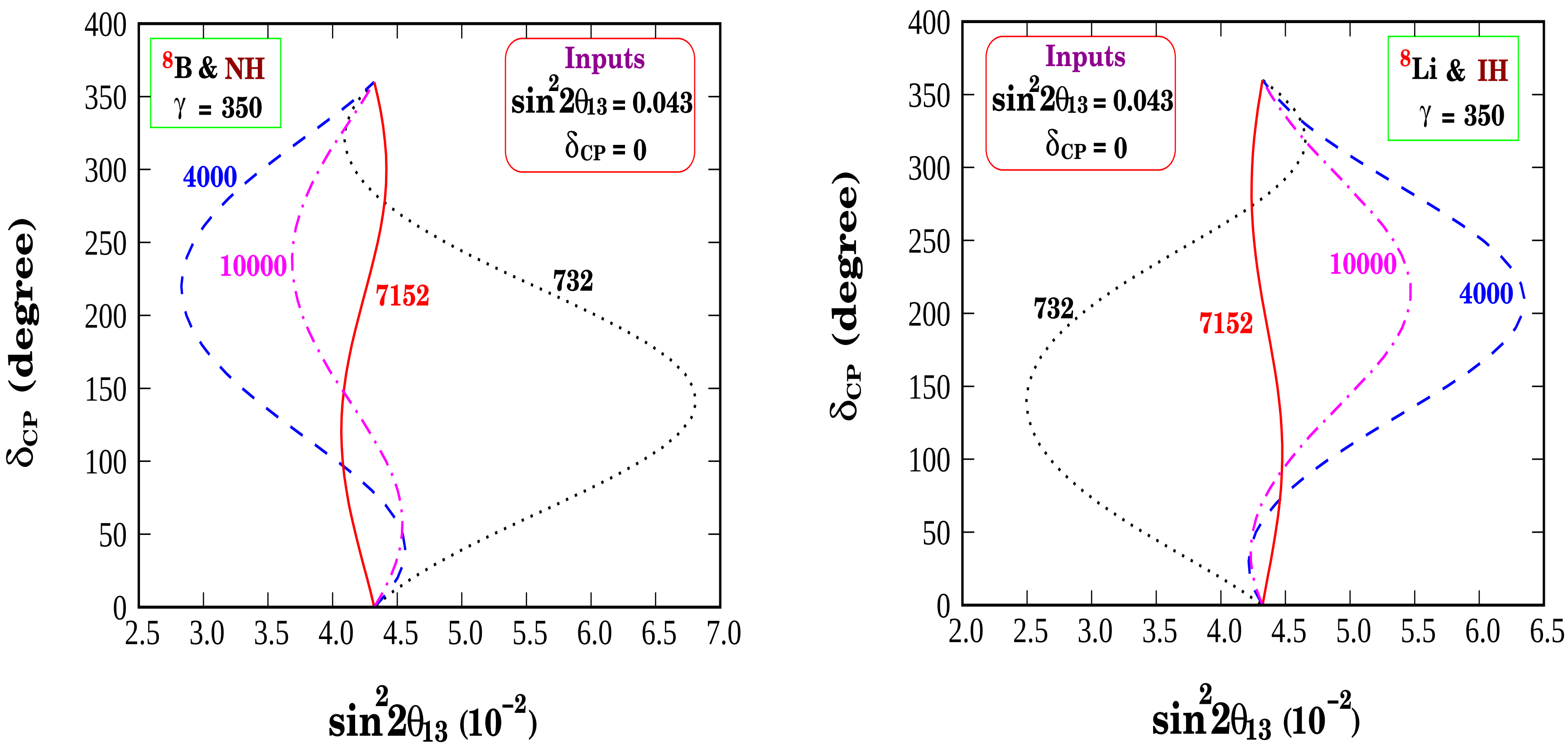
Event rates.

No. of events (contd.)



Sensitivity to matter profi le

Degeneracy



Iso-event curves: dependence on δ_{CP}.

The χ^2 function

Assume Poissonian distribution and defi ne

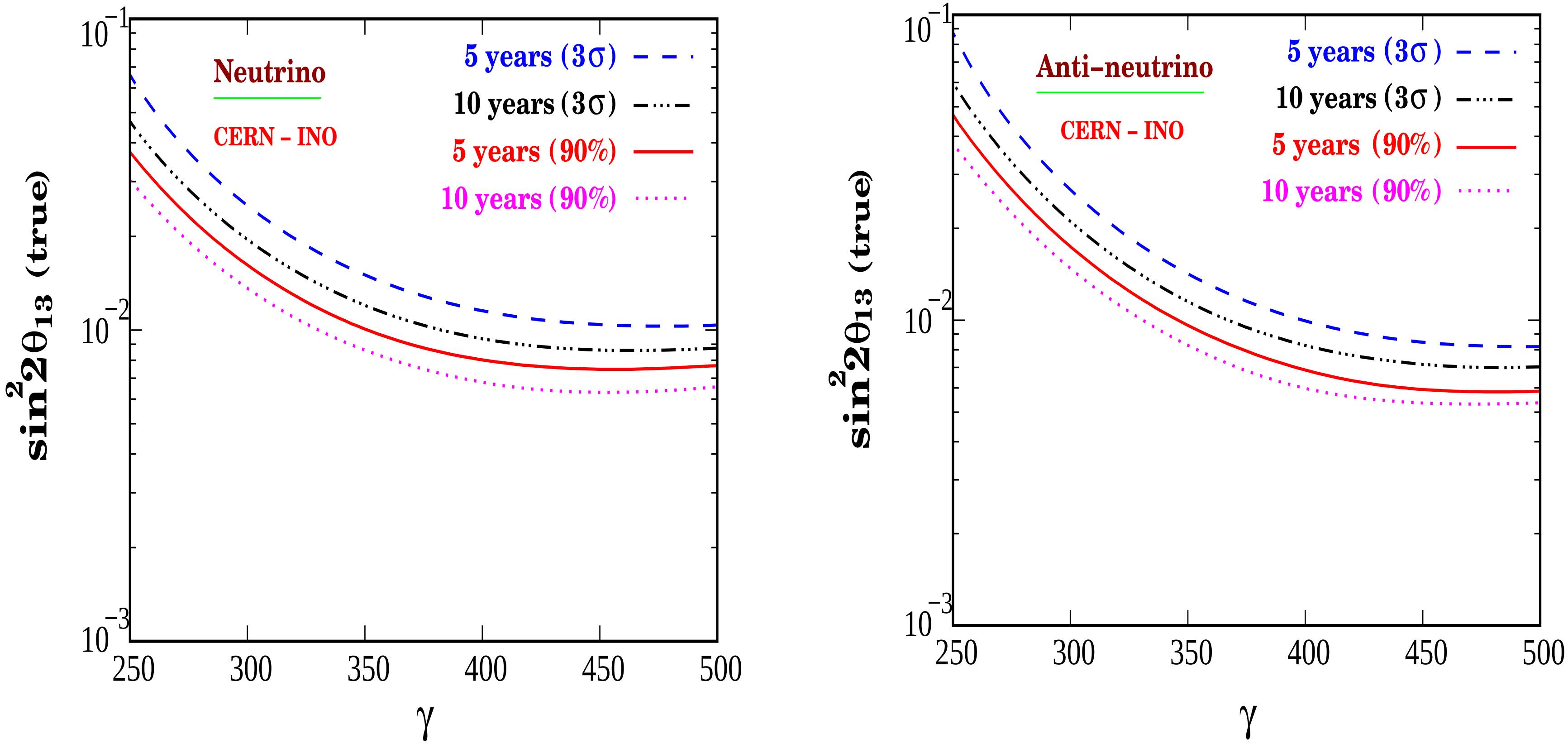
$$\chi^2(\{\omega\}) = \min_{\xi_k} \left[2 \left(\tilde{N}^{th} - N^{ex} - N^{ex} \ln \frac{\tilde{N}^{th}}{N^{ex}} \right) + \sum_k \xi_k^2 \right] .$$

$\{\omega\}$: oscillation parameters, $\{\xi_k\}$: “pulls”, where k: runs over systematic uncertainties

$$\tilde{N}^{th}(\{\omega\}, \{\xi_k\}) = N^{th}(\{\omega\}) \left[1 + \sum_{k=1}^{K} \pi^k \xi_k \right] + \mathcal{O}(\xi_k^2) ,$$

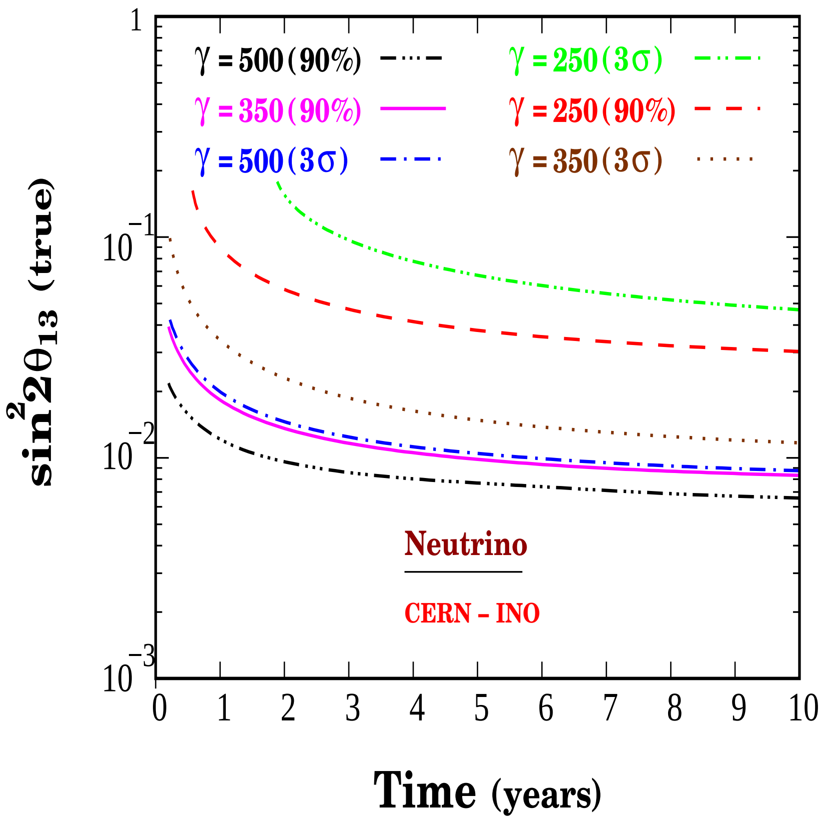
Minimise χ^2 by varying over $\{\omega\}$ and fi nally marginalise over Δm^2_{31}, $\sin^2 2\theta_{23}$ by minimising $\chi^2_{total} = \chi^2 + \chi^2_{prior}$

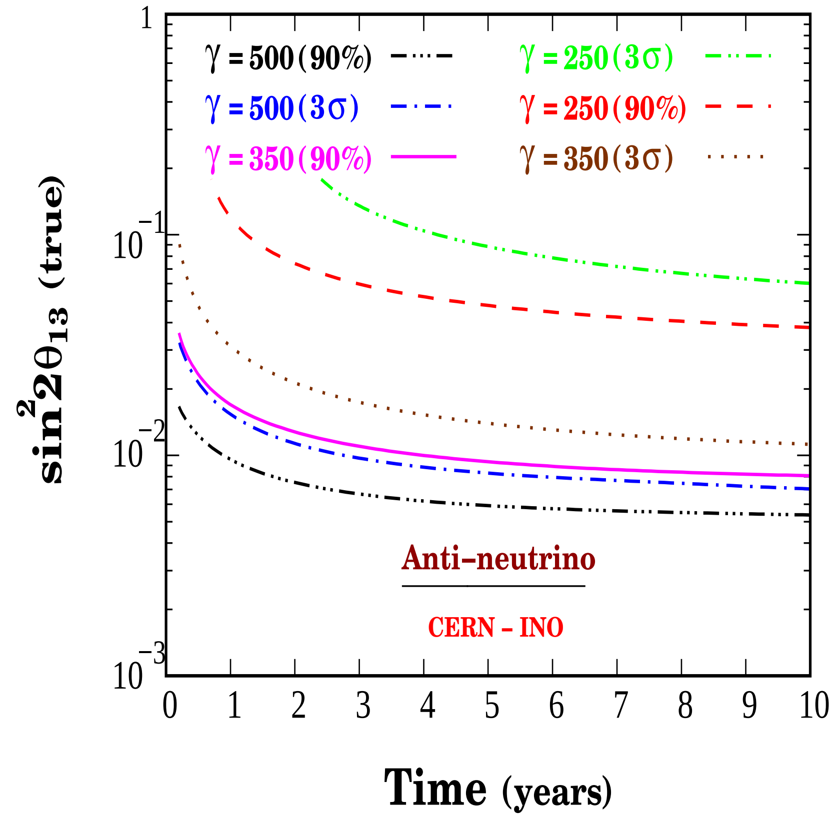
Neutrino mass ordering



The minimum value of $\sin^2 2\theta_{13}$ as a function of the boost γ at which the wrong hierarchy can be disfavored at the 90% and 3σ C.L. For ν_e ($\bar{\nu_e}$) true hierarchy is assumed normal (inverted)

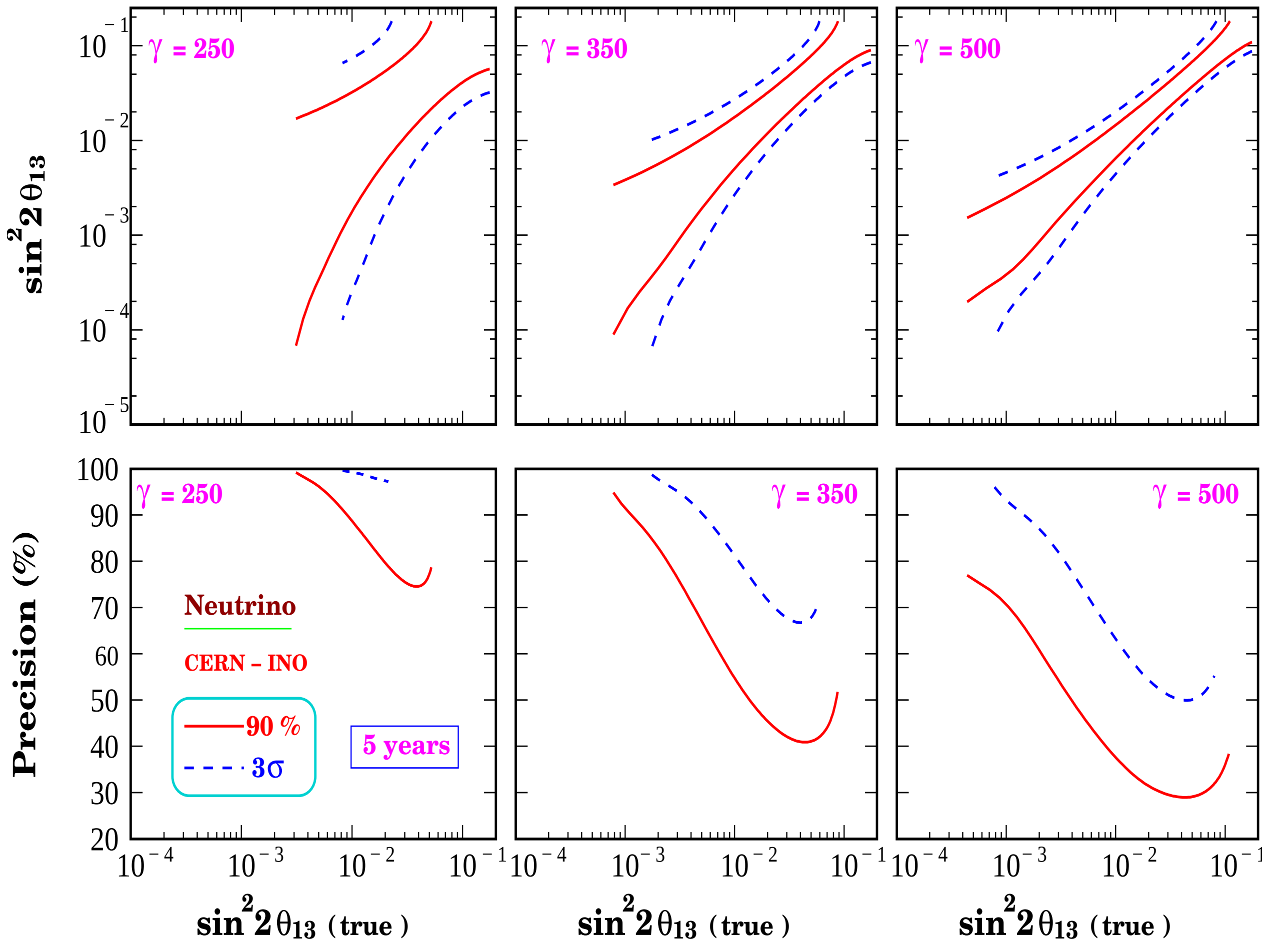
θ_{13} sensitivity





$\sin^2 2\theta_{13}$ limit below which experiment is insensitive

θ_{13} measurement



$\sin^2 2\theta$ measurement. 5 years, neutrino channel, normal hierarchy.
"measured" $\sin^2 2\theta_{13}$ (upper), corresponding precision (lower)

Conclusions

- Beta-beam source at CERN and magnetised iron calorimeter at INO: Good for exploring θ_{13} and sign(Δm^2_{23})
- The baseline is close to the “magic” value and hence avoids degeneracy problems
- Large distance captures signifi cant matter effect
- Neutrino energy for boost $\gamma \simeq 500$ gives resonant enhancement
- Results are very encouraging

Thank you!