Physics reach of CERN – INO baseline with Beta Beam

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work done in collaboration with

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Plan

- Beta beam
- India-based Neutrino Observatory (INO)
- Neutrino oscillations with matter effect
- Probing neutrino parameters with a long baseline experiment
- Results
- Performance of β beam at different baselines
- θ_{13}, δ degeneracy
- Conclusions

Beta Beam

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

- **Produced through the beta decay of radioactive ions circulating in a storage ring.**

Novelties of a Beta Beam

⇒ known energy spectrum, high intensity, low systematic errors

⇒ neutrino isotropically emitted in rest frame of spinless parent ion

⇒ Lorentz boost of the parent ions $\rightarrow$ strong collimation,

⇒ can be produced with existing CERN facilities. “High" γ option ($\gamma \geq$ 1500) accessible in the LHC era

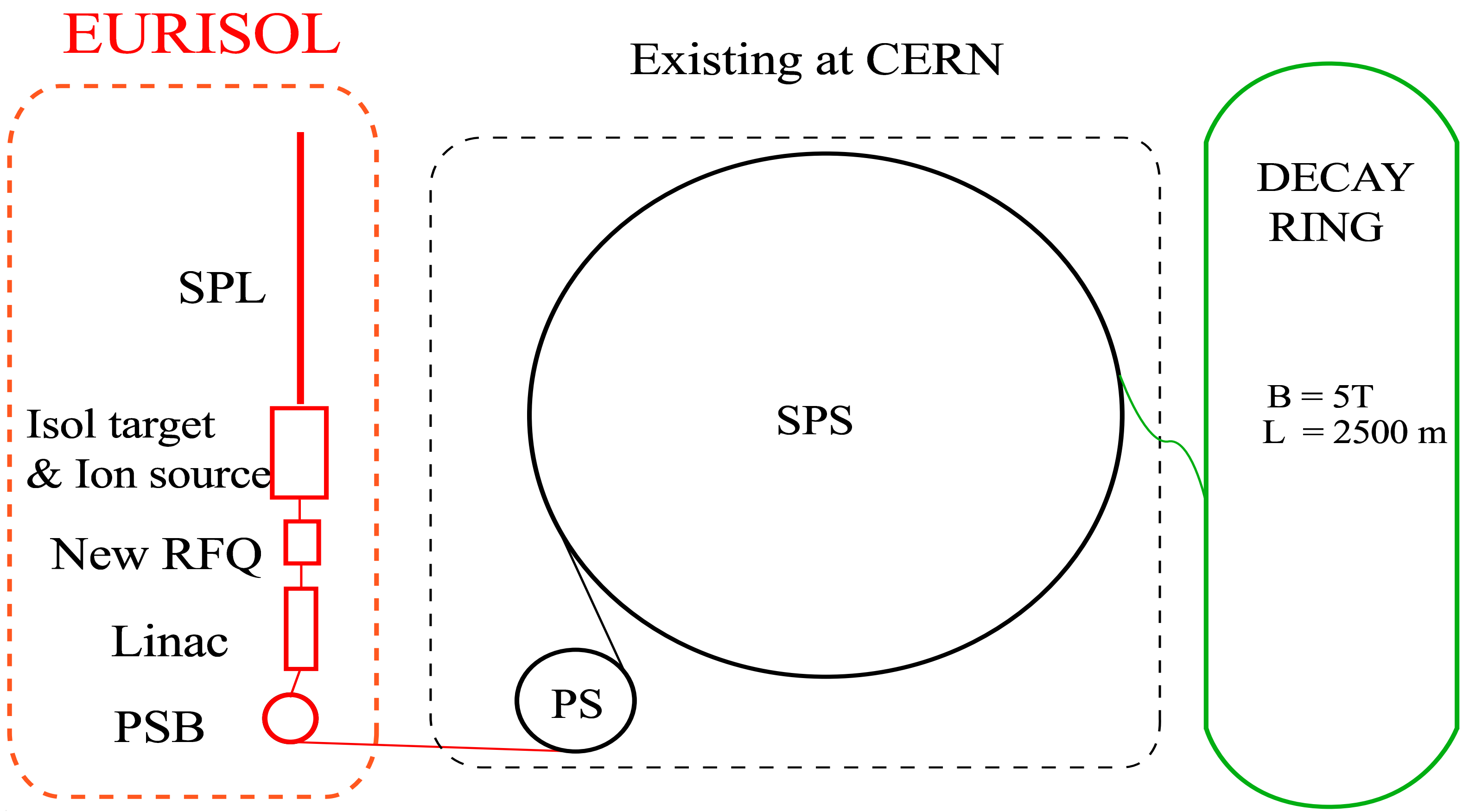

Figure 1: The beta beam complex based on CERN facilities in the low-γ configuration.

Beta Beam (contd.)

- The ν_e ($\bar{\nu}_e$) beams are produced via the β decay of accelerated and completely ionized ^{18}Ne (^{6}He) ions.
- $^{18}_{10}Ne \rightarrow {}^{18}_{9}F + e^{+} + \nu_e$.
- $^{6}_{2}He \rightarrow {}^{6}_{3}Li + e^{-} + \bar{\nu}_e$.

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- $^{6}_{2}He \rightarrow ^{6}_{3}Li + e^{-} + \bar{\nu}_e$.
- Both beams can run simultaneously in the storage ring which requires: $\gamma\,(Ne^{18}) = 1.67 \cdot \gamma\,(He^{6})$.
- Low-γ design, useful decays in case of anti-neutrinos can be 2.9×10^{18}/year and for neutrinos 1.1×10^{18}/year.
- The $\nu_e/\bar{\nu}_e$ flux is obtained from standard beta decay calculation.

INO

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- $\Rightarrow$ a magnetized Iron calorimeter (ICAL) detector with excellent efficiency of charge identification ($\sim$ 95%) and good energy determination
- $\Rightarrow$ preferred location is Singara (PUSHEP) in the Nilgiris ($L = 7177$ km)
- $\Rightarrow$ a 50 Kiloton Iron detector
- $\Rightarrow$ signal is the muon track ($\nu_e \to \nu_\mu$ channel)
- $\Rightarrow$ energy threshold is around 800 MeV

ICAL

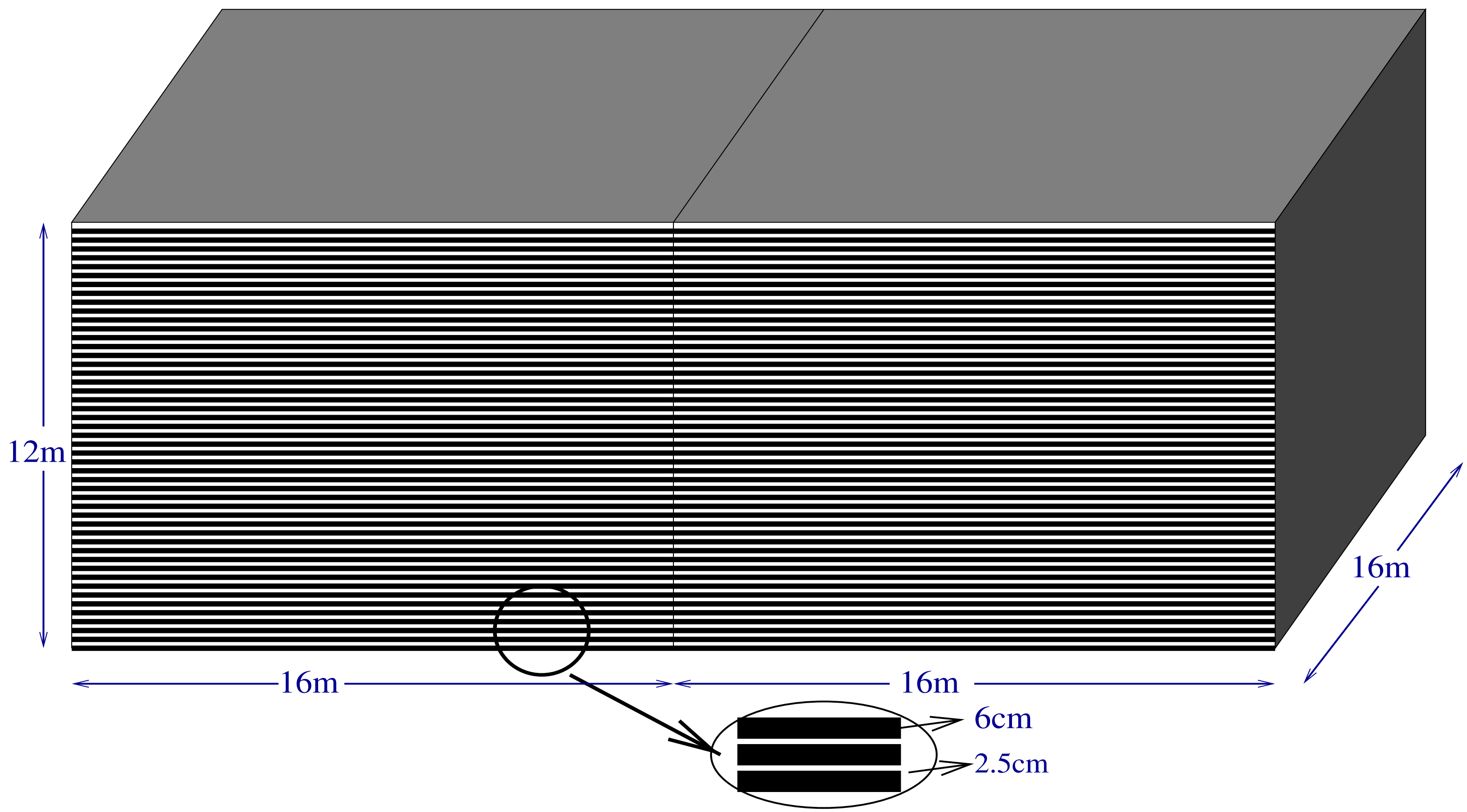

Figure 2: Schematic plan of the 32 kTon ICAL detector for INO.

ν_e Spectrum

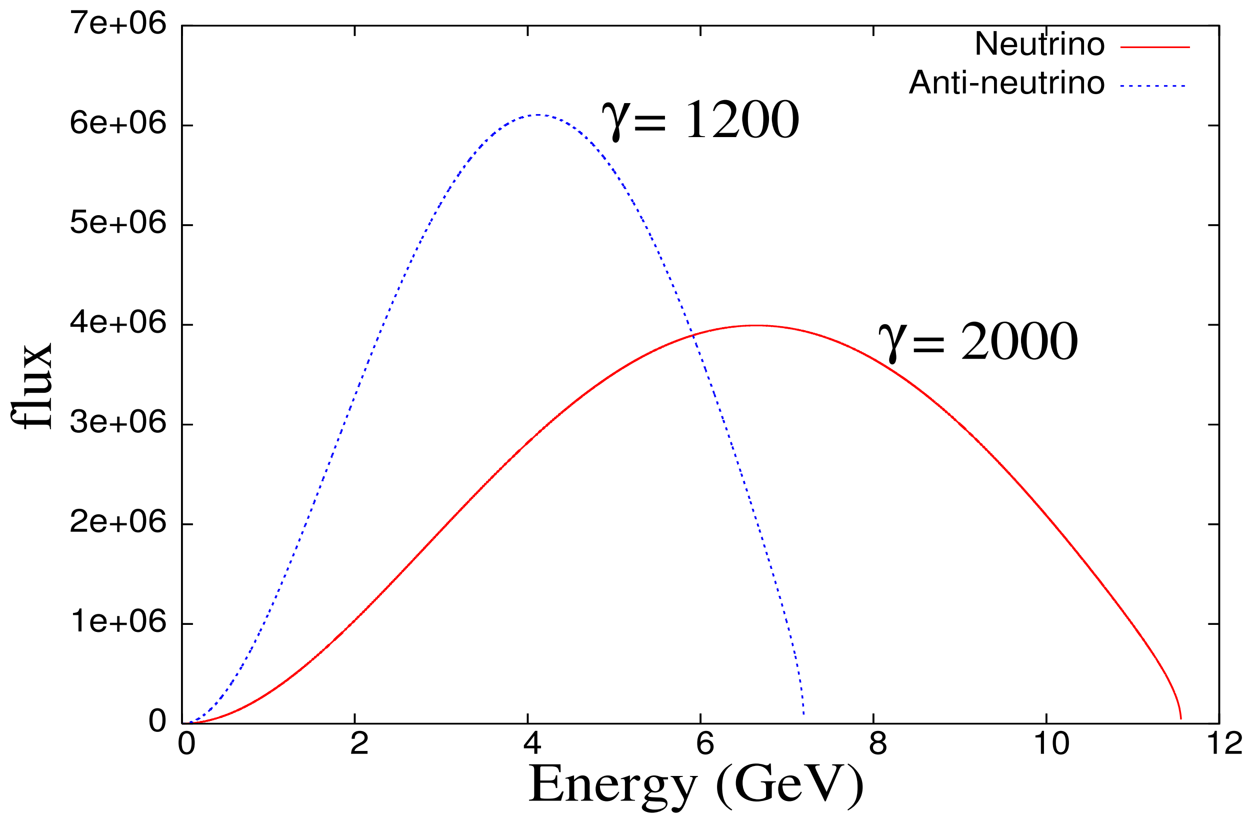

Figure 3: Boosted spectrum of neutrinos and anti-neutrinos at the far detector assuming no oscillation. The flux is given in units of yr^{-1}m^{-2}MeV^{-1}.

Three-flavour oscillations

⇒ Neutrino parameters: neutrino mass eigenvalues and the PMNS mixing matrix

⇒ neutrino flavour states $|\nu_\alpha\rangle$ ($\alpha = e, \mu, \tau$) are linear superpositions of the mass eigenstates $|\nu_i\rangle$ (i = 1, 2, 3) with masses m_i

$$|\nu_\alpha\rangle = \sum_i U_{\alpha i}|\nu_i\rangle$$

⇒ $U \equiv 3 \times 3$ unitary matrix (PMNS) parametrized as:

$$U = V_{23} W_{13} V_{12}$$

Three-flavour oscillations (contd.)

where

$$V_{12} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}, W_{13} = \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix},$$

$$V_{23} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix}.$$

$\Rightarrow$ $c_{12} = \cos\theta_{12}$, $s_{12} = \sin\theta_{12}$ etc.

$\Rightarrow$ δ denotes the CP-violating (Dirac) phase

(Majorana phases ignored)

Three-flavour oscillations (contd.)

The probability that an initial ν_f of energy E gets converted to a ν_g after traveling a distance L in vacuum

$$
\begin{aligned}
P(\nu_f \to \nu_g) = \delta_{fg} \quad & - \quad 4 \sum_{j>i} \mathrm{Re}(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \sin^2(1.27 \Delta m^2_{ij} \frac{L}{E}) \\
& \pm \quad 2 \sum_{j>i} \mathrm{Im}(U^*_{fi} U_{gi} U_{fj} U^*_{gj}) \sin(2.54 \Delta m^2_{ij} \frac{L}{E})
\end{aligned}
$$

L is expressed in km, E in GeV and Δm^2 in eV^2.

The – (+) refers to neutrinos (anti-neutrinos).

Matter effects

Probabilites in matter

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⇒ the 3-flavour neutrino evolution equation in matter :

$$i\frac{d}{dt}\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} =$$

$$\left[\frac{1}{2E}U\begin{pmatrix}m_1^2 & 0 & 0\\ 0 & m_2^2 & 0\\ 0 & 0 & m_3^2\end{pmatrix}U^\dagger + \begin{pmatrix}V_{CC} & 0 & 0\\ 0 & 0 & 0\\ 0 & 0 & 0\end{pmatrix}\right]\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix}$$

- $V_{CC} = \sqrt{2}G_F n_e$ (matter-induced potential)
- n_e is the electron number density

Neutrino mixing

$\Rightarrow$ atmospheric neutrinos reveal the best-fit values with 3σ error : $|\Delta m^2_{23}| \simeq 2.12^{+1.09}_{-0.81} \times 10^{-3}$ eV^2, $\theta_{23} \simeq 45.0^\circ{}^{+10.55^\circ}_{-9.33^\circ}$

$\Rightarrow$ the same for solar neutrinos : $\Delta m^2_{12} \simeq 7.9^{+1.0}_{-0.8} \times 10^{-5}$ eV^2, $\theta_{12} \simeq 33.21^\circ{}^{+4.85^\circ}_{-4.55^\circ}$

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⇒ current bound on CHOOZ mixing angle θ_{13} from the global oscillation analysis : $\sin^2\theta_{13} < 0.05$ (3σ)

⇒ 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

HIERARCHY

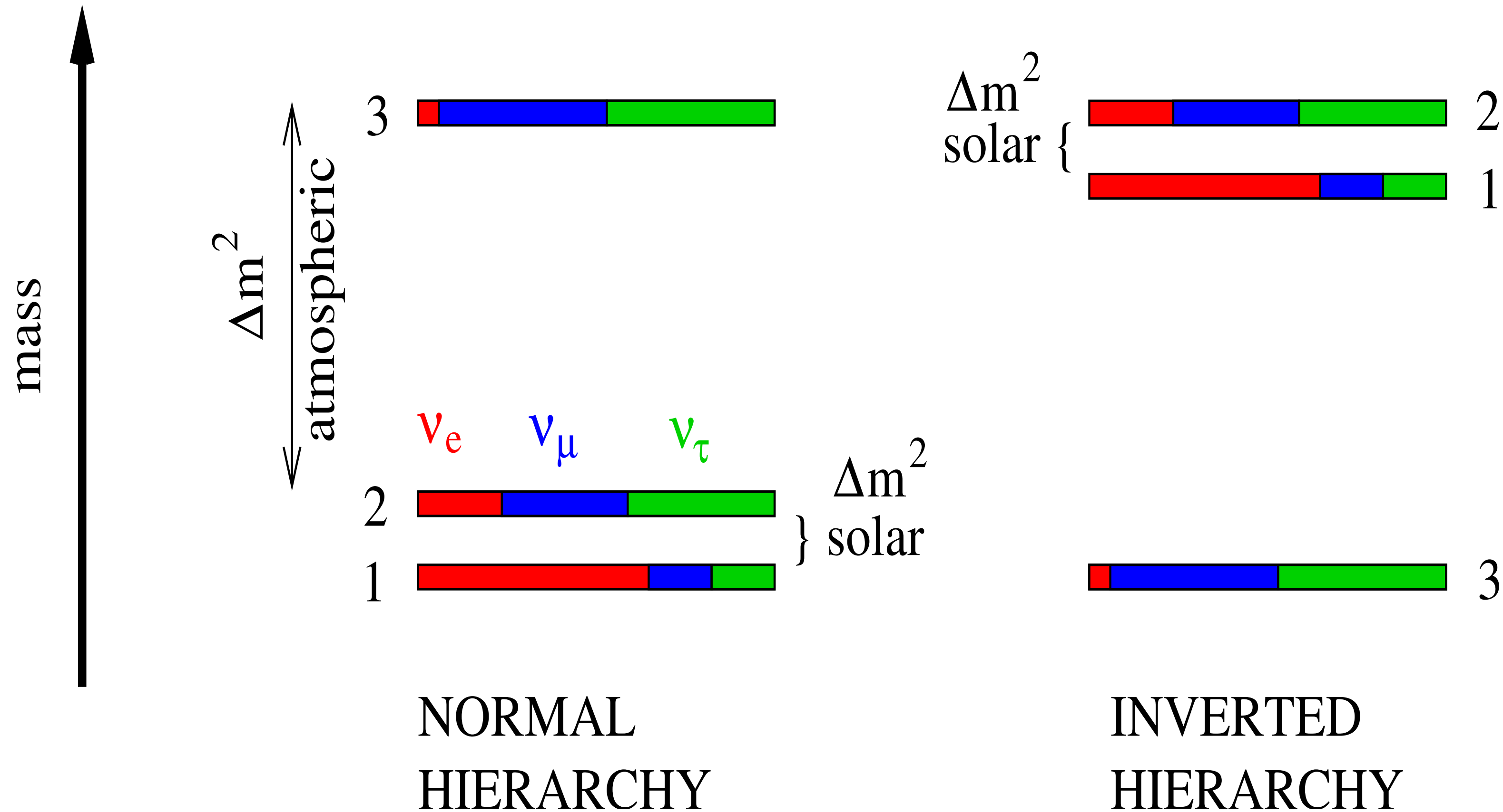

Figure 4: Schematic view of the hierarchy.

Neutrino mixing (contd.)

Unsolved issues

⇒ The sign of Δm^2_{23} 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

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Our goal $\longrightarrow$

⇒ to address the question of neutrino mass hierarchy

⇒ to determine the mixing angle θ_{13} precisely

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

Magic Baseline (contd.)

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The first non-trivial solution: $\sqrt{2} G_F n_e L = 2\pi$

- For an approximately 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 turns out to be ρ = 4.15 gm/cc for which $L_{\rm magic}$ = 7886 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}.

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- 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, close to the ‘magic’ value, ensures essentially no dependence of the final results on δ.
- This permits a clean measurement of θ_{13} avoiding the degeneracy issues which plague other baselines.

Interaction Cross sections

⇒ in case of low energy the quasi-elastic events dominate and the cross-section grows rapidly for $E_\nu \leq 1$ GeV

Interaction Cross sections

$\Rightarrow$ in case of low energy the quasi-elastic events dominate and the cross-section grows rapidly for $E_\nu \leq$ 1 GeV

$\Rightarrow$ in the highest-energy case for $E_\nu \geq$ a few GeV, samples are mostly deep-inelastic scattering and the growth is linear in the neutrino energy

$\Rightarrow$ for the medium-energy case, there is a sizeable contribution from both types of events, as well as resonant channels which is dominated by the Δ (1232) resonance

Cross sections (contd.)

- We have considered all type of events. Deep-inelastic events dominate.

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- There is also 10% contribution of quasi-elastic and single-pion production events each.
- Atmospheric neutrino and other backgrounds will be eliminated by the directionality cut imposed in event selection.
- Here all the plots are obtained by numerically solving the full 3-flavour neutrino propagation equation.

Δm^2_{23} determination

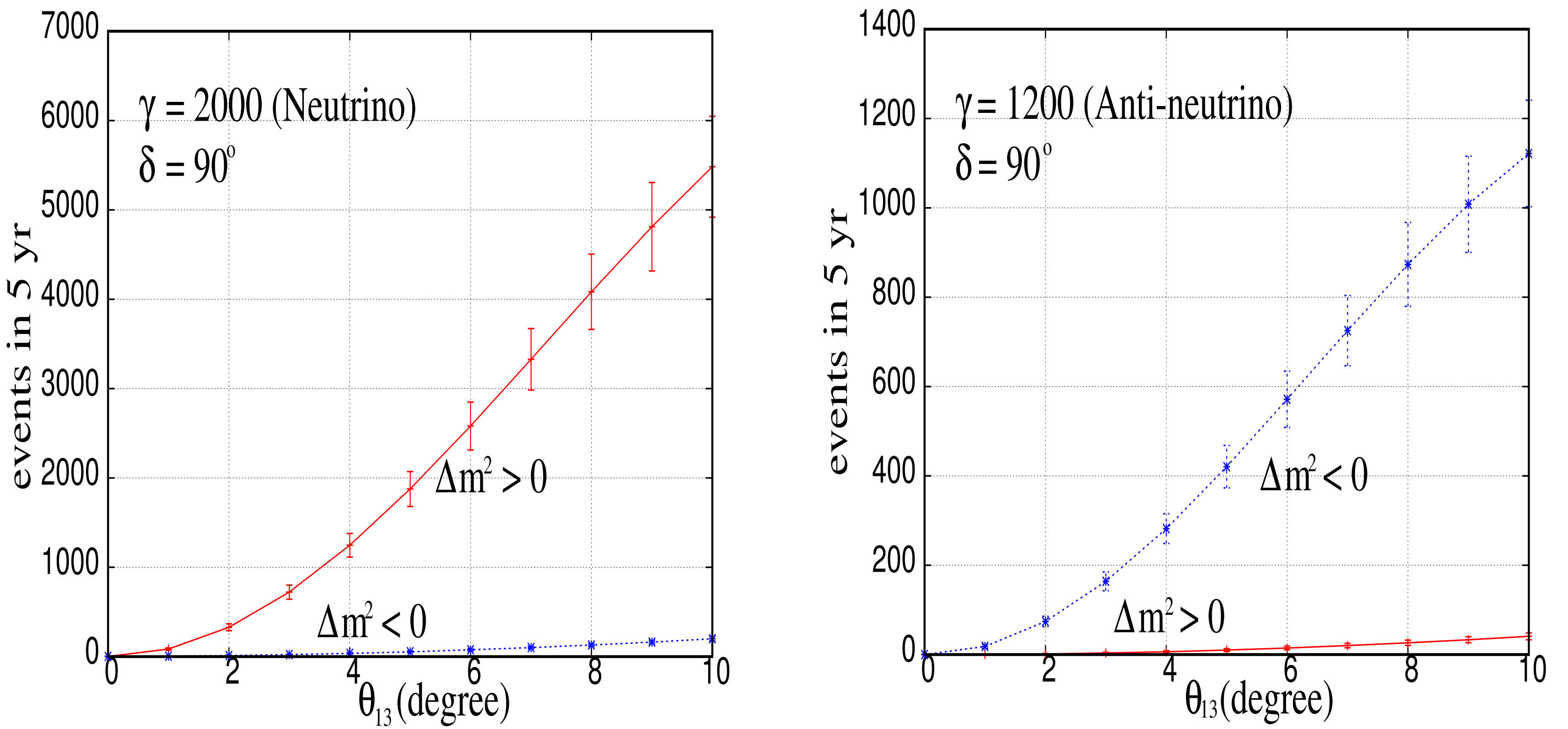

Figure 5: The number of events as a function of θ_{13} for neutrinos (antineutrinos) is shown in the left (right) panel for a 5-year run. The blue (red) curves correspond to $\Delta m^2_{23} < 0$ ($\Delta m^2_{23} > 0$).

Δm^2_{23} determination (contd.)

Determination of the sign(Δm^2_{23}) $\longrightarrow$

$\Rightarrow$ the mass hierarchy can be probed at the 5.3 (3.4)σ level with a neutrino (anti-neutrino) beam for values of $\sin^2\theta_{13}$ as low as 0.0003

$\Rightarrow$ the sensitivity increases dramatically with θ_{13}

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$\Rightarrow$ the sensitivity increases dramatically with θ_{13}

$\Rightarrow$ for Δm^2_{23} within the present 1σ interval [1.85 - 2.48] $\times 10^{-3}$ eV^2, this significance varies within 4.8 - 5.7σ (3.6 - 3.0σ) for neutrinos (anti-neutrinos)

Δm^2_{23} determination (contd.)

$\sin^2 2\theta_{13}$	ν_e-beam (3σ)	$\bar{\nu}_e$-beam (3σ)
0.01	2.82 years	3.16 years
0.03	1.07 years	1.15 years
0.08	178 days	197 days

Table 1: measurement of hierarchy with only one type of beam at a time

Δm^2_{23} determination (contd.)

Error estimation $\longrightarrow$

$\Rightarrow$ we have considered an uncertainty of 2% in the knowledge of the number of ions in the storage ring

$\Rightarrow$ we have assumed a 10% fluctuation in the cross section, σ

Δm^2_{23} determination (contd.)

Error estimation $\longrightarrow$

- $\Rightarrow$ we have considered an uncertainty of 2$\%$ in the knowledge of the number of ions in the storage ring
- $\Rightarrow$ we have assumed a 10$\%$ fluctuation in the cross section, σ
- $\Rightarrow$ the statistical error has been added to the above in quadrature
- $\Rightarrow$ we have neglected nuclear effects

θ_{13} measurement

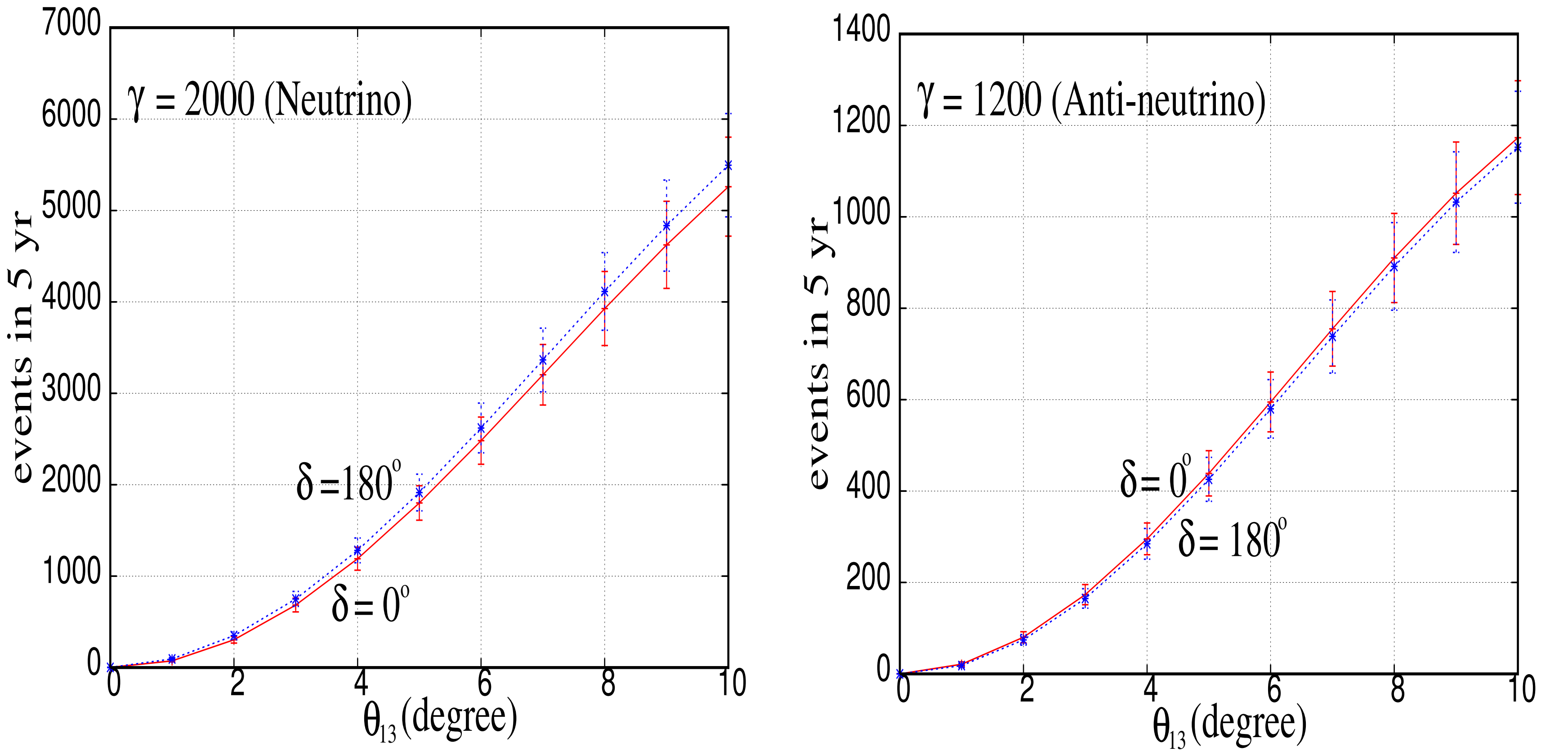

Figure 6: Variation of the number of events with θ_{13} for ν (left) and $\bar{\nu}$ (right) for a 5-year run. Here, Δm^2_{23} is chosen $+$ $(-)$ for ν $(\bar{\nu})$.

θ_{13} measurement (contd.)

Precision measurement of θ_{13} $\longrightarrow$

$\Rightarrow$ $\sin^2 2\theta_{13}$ can be probed down to 0.001

$\Rightarrow$ the estimated 3σ errors on θ_{13} measured to be $1^\circ(5^\circ)$ are $^{+0.6^\circ}_{-0.5^\circ}$ ($^{+2.3^\circ}_{-1.5^\circ}$) with $\delta = 0^\circ$ and $\Delta m^2_{23} > 0$ for neutrinos

θ_{13} measurement (contd.)

Precision measurement of $\theta_{13} \longrightarrow$

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$\Rightarrow$ for $\bar{\nu}$ with $\Delta m^2_{23} < 0$ the fluctuations are ${}^{+0.9^\circ}_{-0.8^\circ}$ $({}^{+2.7^\circ}_{-1.7^\circ})$ around $1^\circ (5^\circ)$ at 3σ level

$\Rightarrow$ the 1σ error of Δm^2_{23} translates to uncertainties of ${}^{+0.5^\circ}_{-0.4^\circ}$ $({}^{+0.7^\circ}_{-0.2^\circ})$ at $\theta_{13} = 5^\circ$ for a ν $(\bar{\nu})$ beam with normal (inverted) hierarchy

boost .vs. hierarchy

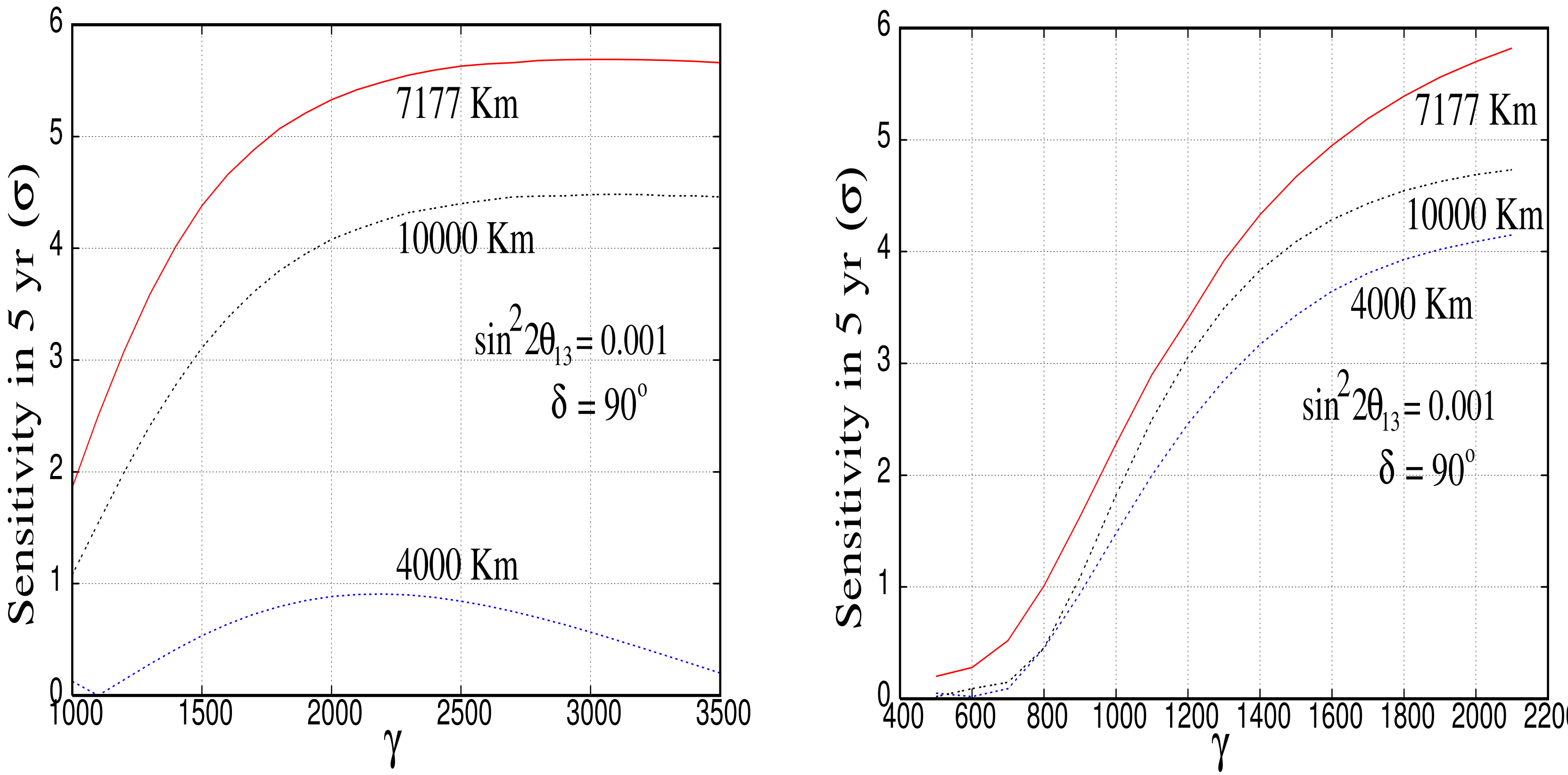

Figure 7: The sensitivity in the hierarchy measurement as a function of γ for neutrinos (anti-neutrinos) is shown in the left (right) panel.

boost .vs. precision in θ_{13}

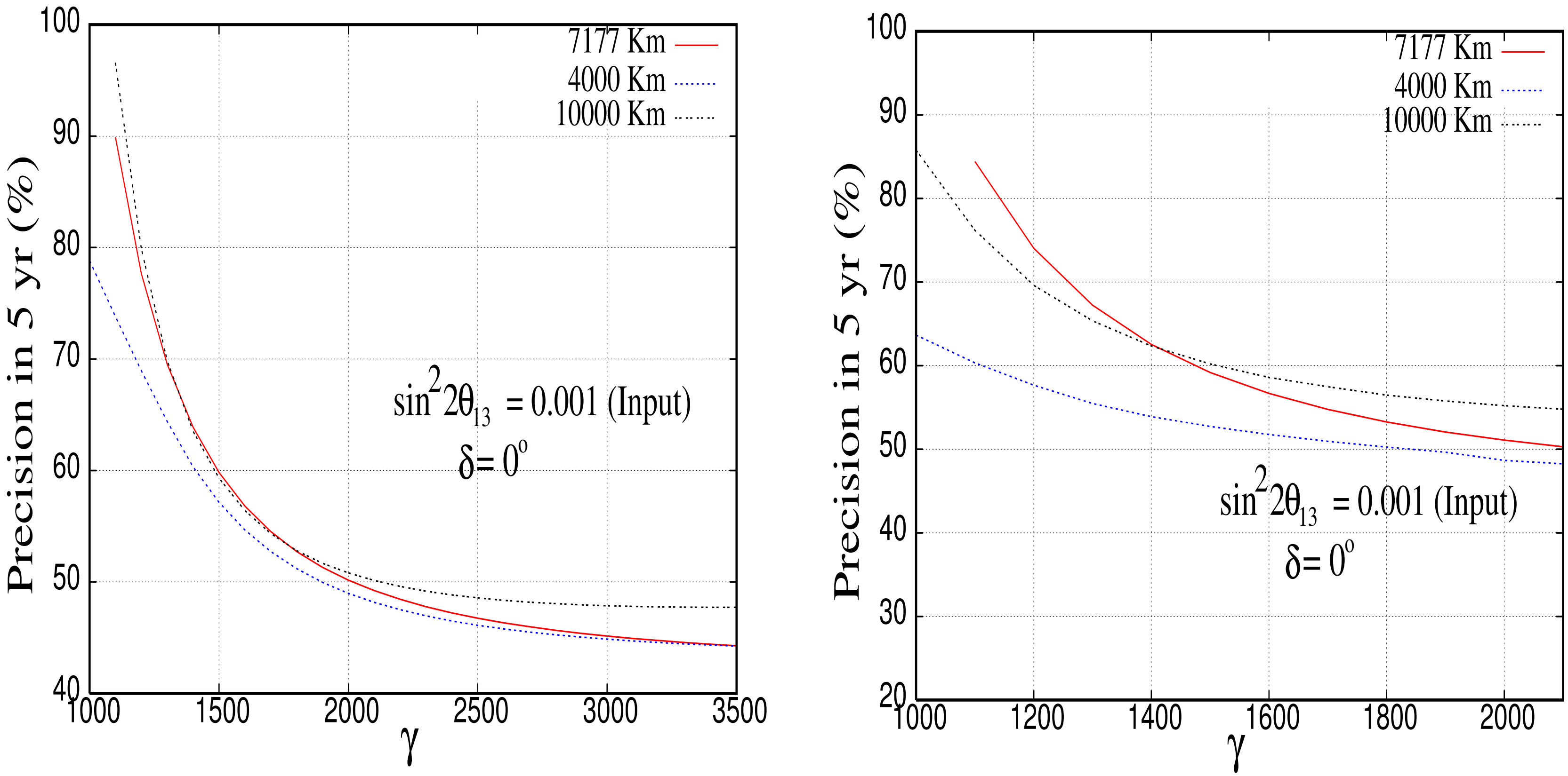

Figure 8: Variation of precision in the measurement of θ_{13} with γ at 3σ level for ν with $\Delta m^2_{23} > 0$ (left) and $\bar{\nu}$ with $\Delta m^2_{23} < 0$ (right).

θ_{13}, δ degeneracy

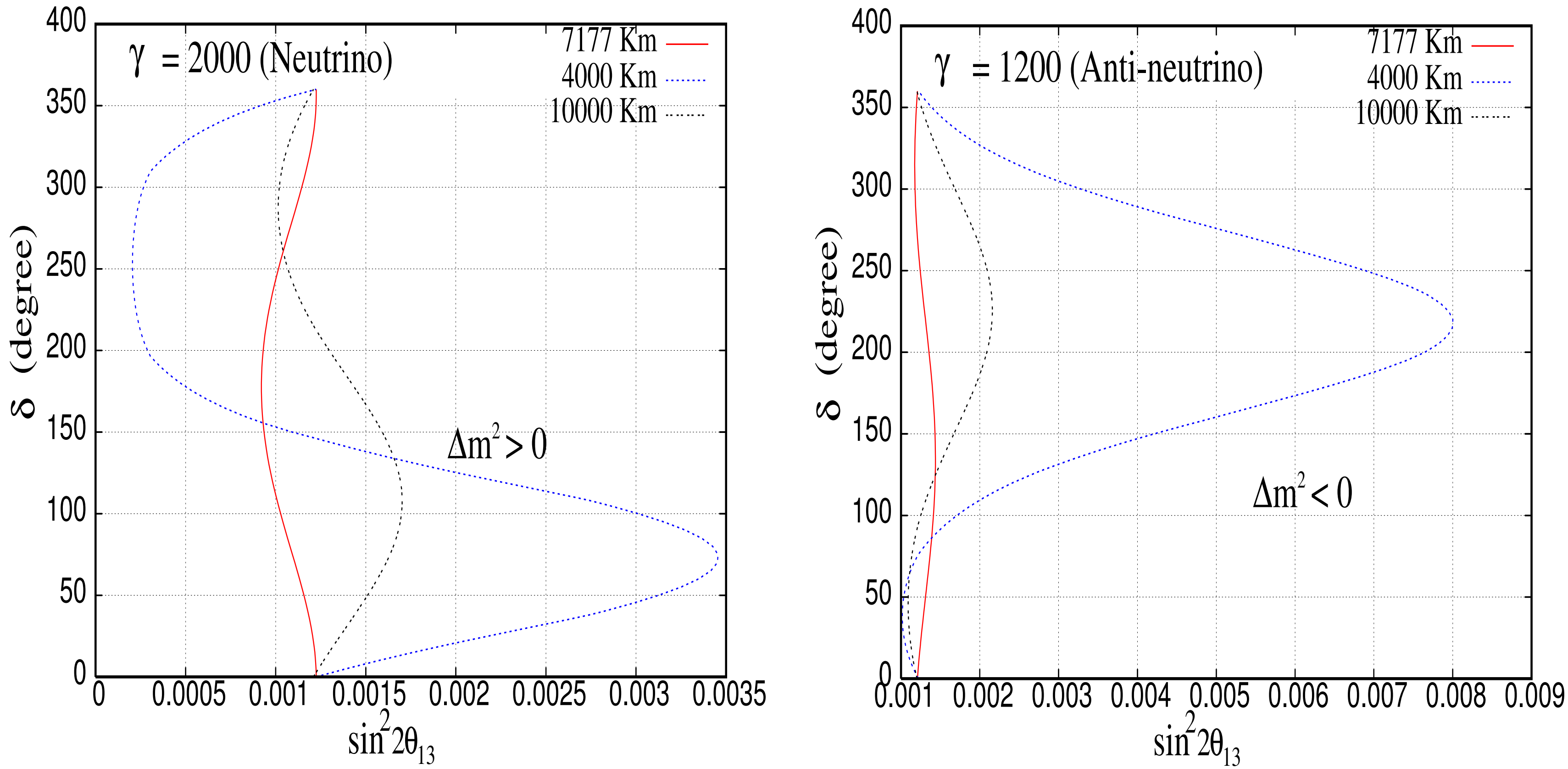

Figure 9: Showing the degeneracy between θ_{13} and δ with $\sin^2 2\theta_{13} = 0.001$ and $\delta = 0^\circ$ as input values.

Some comments

- In principle, the long baseline beta beam experiment can narrow down the permitted range of Δm^2_{23}.
- However, it is very likely that this improvement will be achieved in the meanwhile by other experiments.

Conclusions

- We have discussed the prospects of obtaining information on the mixing angle θ_{13} and the sign of Δm^2_{23} using the proposed ICAL detector at INO with a high γ beta beam source at CERN.

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- We have discussed the prospects of obtaining information on the mixing angle θ_{13} and the sign of Δm^2_{23} using the proposed ICAL detector at INO with a high γ beta beam source at CERN.
- The performance of the CERN - INO baseline is quite significant in comparison with other baselines avoiding the issue of degeneracy.
- It appears that such a combination of a high intensity $\nu_e, \bar{\nu}_e$ source and a magnetized iron detector is well-suited for this purpose.