The novel aspects of a long baseline Beta Beam experiment with INO

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work done in collaboration with

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What is a BETA BEAM ?

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- It is 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.

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$\Rightarrow$ the neutrino is isotropically emitted in rest frame since the parent ion is spinless

$\Rightarrow$ it can be produced with the help of the existing CERN facilities and a “high" γ option ($\gamma \geq 1500$) would be accessible in the LHC era

- The $\underline{\nu_e\ (\ \bar{\nu}_e\ )}$ beams are produced via the β decay of accelerated and completely ionized $\underline{^{18}Ne\ (\ ^{6}He\ )}$ ions.
- $\underline{^{18}_{10}Ne} \rightarrow {}^{18}_{9}F + e^{+} + \underline{\nu_e}$.
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- Both beams can run simultaneously in the storage ring which requires: $\gamma\ (Ne^{18}) = 1.67 \cdot \gamma\ (He^{6})$.
- The number of injected ions in case of anti-neutrinos can be $\underline{2.9 \times 10^{18}\text{/year}}$ and for neutrinos $\underline{1.1 \times 10^{18}\text{/year}}$.
- The $\underline{\nu_e/\bar{\nu}_e}$ flux is obtained from standard beta decay calculation.

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⇒ two possible locations

(a) Singara (PUSHEP) in the Nilgiris ($L = 7177$ km)

(b) Rammam in the Darjeeling Himalayas ($L = 6937$ km)

⇒ a 32 Kiloton Iron detector

⇒ signal is the muon track ($\nu_e \rightarrow \nu_\mu$ channel)

⇒ energy threshold is around 800 MeV

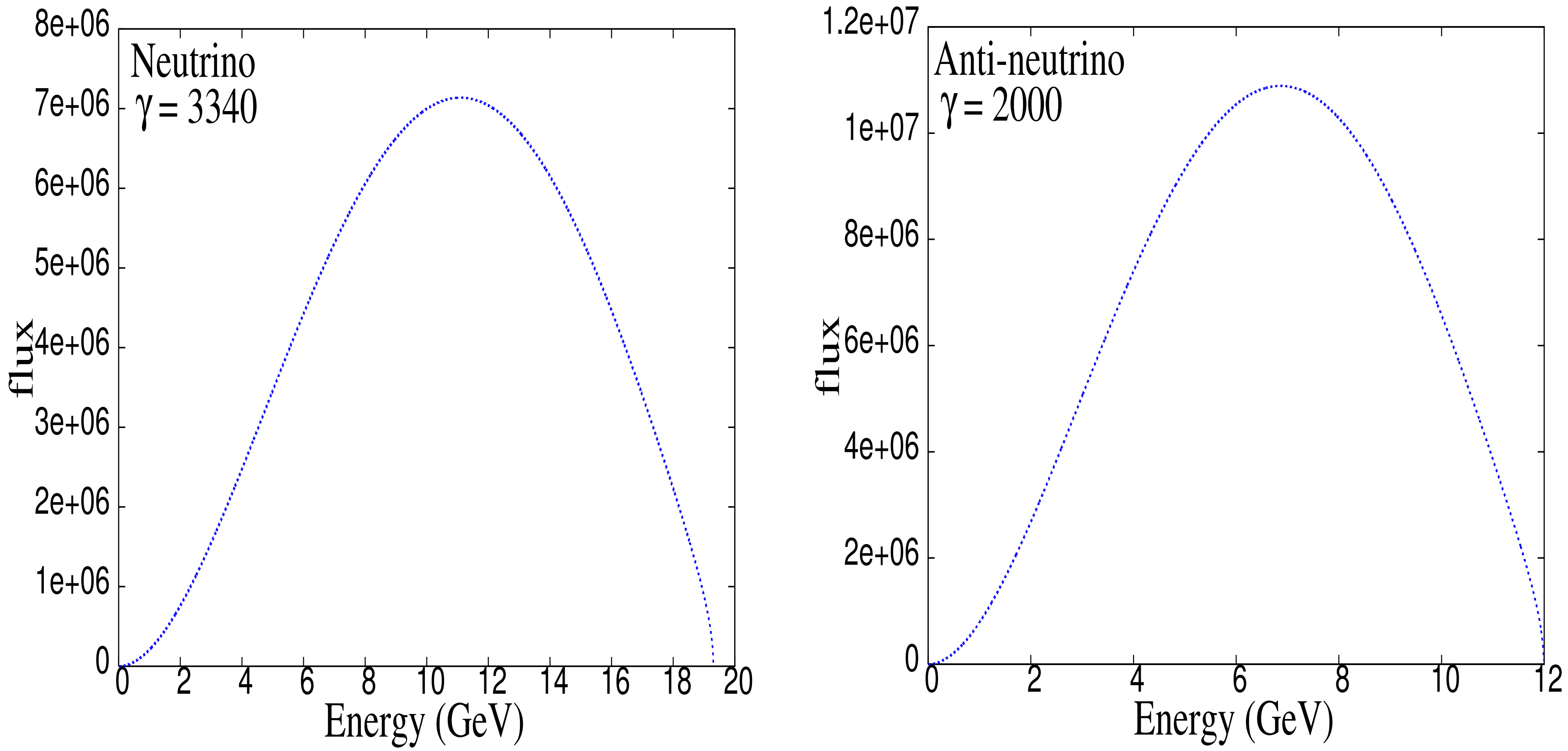

Figure 1: Boosted spectrum of neutrinos and anti-neutrinos at the far detector assuming no oscillation. The flux is given in units of $\text{yr}^{-1}\text{m}^{-2}\text{MeV}^{-1}$.

Neutrino oscillation and present status

$\Rightarrow$ neutrino oscillations are governed by the two mass squared differences and three mixing angles

$\Rightarrow$ 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, $\theta_{23} \simeq 45.0^{\circ}{}^{+10.55^{\circ}}_{-9.33^{\circ}}$

$\Rightarrow$ solar neutrinos tell us : $\Delta m^2_{12} \simeq 7.9 \times 10^{-5}$ eV^2, $\theta_{12} \simeq 33.21^{\circ}$ (our convention : $\Delta m^2_{ij} = m^2_j - m^2_i$)

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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

Unsolved issues $\longrightarrow$

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Our goal $\longrightarrow$

$\Rightarrow$ to address the question of neutrino mass hierarchy

$\Rightarrow$ to determine the mixing angle θ_{13} precisely

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 $\sin 2\theta_{13}$,

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

where $\Delta \equiv \Delta m^2_{13} L/(4E)$, $\xi \equiv \cos\theta_{13}\ \sin 2\theta_{12}\ \sin 2\theta_{23}$,

and $\hat{A} \equiv \pm(2\sqrt{2} G_F n_e E)/\Delta m^2_{13}$.

<u>**If one chooses:**</u> $\sin(\hat{A}\Delta) = 0$

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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.

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- 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.
- Here all the plots are obtained by numerically solving the full 3-flavour neutrino propagation equation.

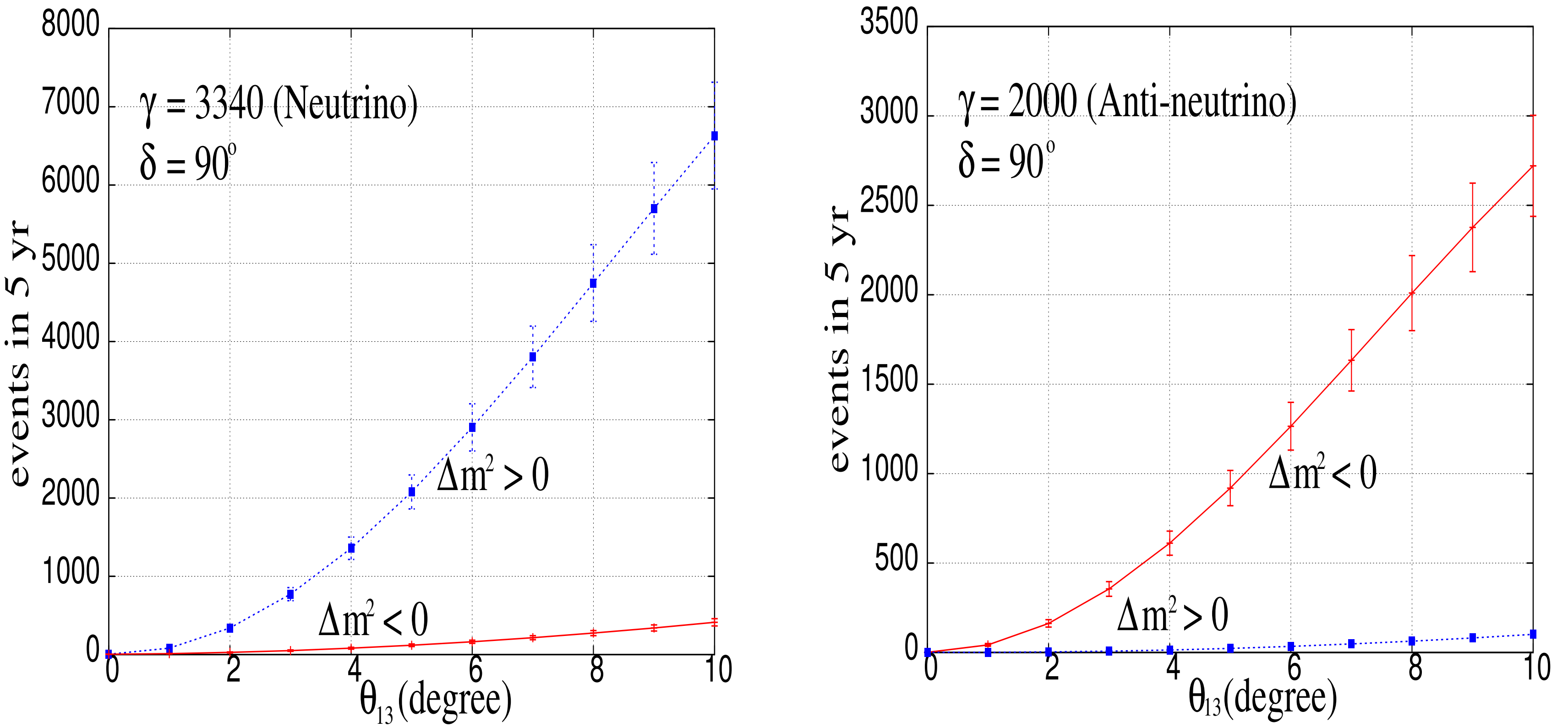

Figure 2: The number of events as a function of θ_{13} for neutrinos (antineutrinos) is shown in the left (right) panel for a 5-year run. The solid (broken) curves correspond to $\Delta m^2_{23} < 0$ ($\Delta m^2_{23} > 0$).

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

$\Rightarrow$ the mass hierarchy can be probed at the 4.4 (4.8)σ level with a neutrino (anti-neutrino) beam for values of θ_{13} as low as $\sim 1^\circ$, sensitivity increases 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 3.5 - 5.3σ (4.6 - 5.1σ) for neutrinos (anti-neutrinos)

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- $\Rightarrow$ we have considered all type of events and deep-inelastic events dominate
- $\Rightarrow$ 2$\%$ systematic error, 10$\%$ fluctuation in the cross section
- $\Rightarrow$ the statistical error has been added to the above in quadrature and nuclear effects are neglected

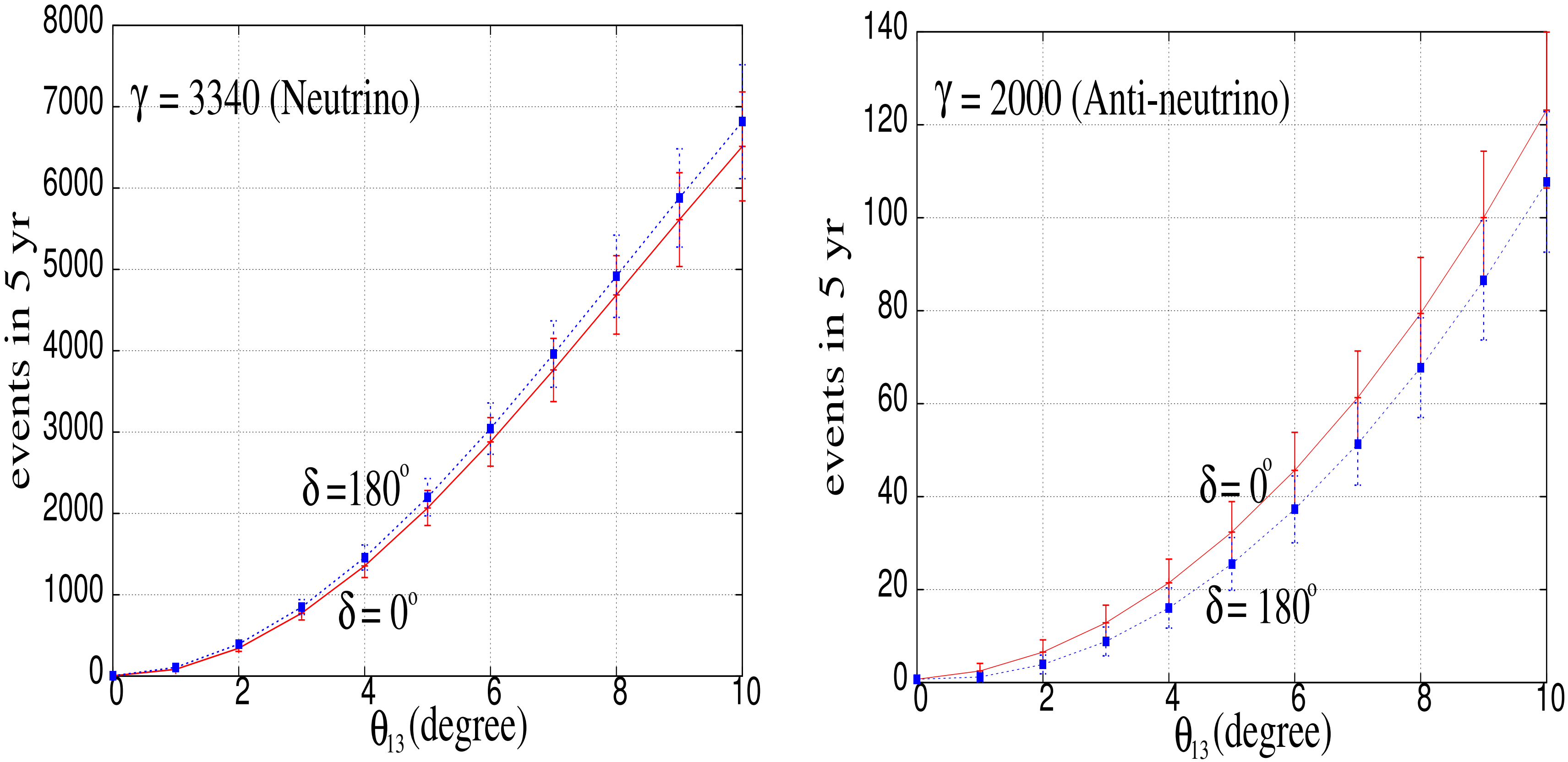

Figure 3: Variation of the number of events with θ_{13} for ν (left) and $\bar{\nu}$ (right) for a 5-year run. Here, Δm^2_{23} is chosen positive.

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

$\Rightarrow$ θ_{13} can be probed down to 1°

$\Rightarrow$ the estimated 3σ errors on θ_{13} measured to be $1^\circ (5^\circ)$ are $\underline{{}^{+0.6^\circ}_{-0.5^\circ}}$ $\underline{({}^{+2.2^\circ}_{-1.4^\circ})}$ with $\delta = 0^\circ$ and $\Delta m^2_{23} > 0$ for neutrinos

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$\Rightarrow$ the 1σ error of Δm^2_{23} translates to uncertainties of $\sim \pm 1^\circ$ at $\theta_{13} = 5^\circ$ and less than $\pm\frac{1}{4}^\circ$ at $\theta_{13} = 1^\circ$ for a neutrino beam with $\delta = 90^\circ$ and $\Delta m^2_{23} > 0$

$\Rightarrow$ here we present the results using the CERN to Rammam (L = 6937 km) baseline and the results vary by less than 5% if the baseline for the alternate PUSHEP site (L = 7177 km) is used

Conclusions

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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.
- 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.