ID #40;
arXiv:2404.17559
amann16.iitr@gmail.com

Investigating Quantum Decoherence in ν-Oscillation at ESSnuSB Experiment

Author: Aman Gupta [1,2]; Presenter: Monojit Ghosh [3] on behalf of the ESSnuSB collaboration
[1]Saha Institute of Nuclear Physics,Kolkata, India, [2]HBNI,Mumbai, India,[3]Ruđer Bošković Institute,Zagreb, Croatia

Introduction

- Neutrino oscillation is a quantum mechanical phenomenon that arises due to the *coherent superposition of neutrino mass states.* However, if neutrino as a quantum system is coupled to an environment, the coherence between two or more propagating states may be lost leading to the suppression of flavour oscillations.
- Such type of **environmentally induced** quantum decoherence (QD) in neutrino states might emerge *from quantum gravity effects or space-time "foam" which acts as dissipative sources and can modify the ν-oscillation probability in various ways [1].*

QD: Formalism

The time evolution of neutrinos in an open quantum system is given by

$$\boxed{\frac{\partial\rho(t)}{\partial t} = -i[H,\rho(t)] + \mathcal{D}[\rho(t)]}, \tag{1}$$

where H is the neutrino Hamiltonian which can be written as

$$H = \frac{1}{2E}\left[U\begin{pmatrix}0 & 0 & 0\\ 0 & \Delta m^2_{21} & 0\\ 0 & 0 & \Delta m^2_{31}\end{pmatrix}U^\dagger\right. \\ \left. + V_{CC}\begin{pmatrix}1&0&0\\0&0&0\\0&0&0\end{pmatrix}\right]. \tag{2}$$

The effect of decoherence is given by the dissipator matrix D which on imposing relevant physical conditions can be parametrized as

$$\boxed{D = -\mathrm{diag}(\Gamma_{21},\Gamma_{21},0,\Gamma_{31},\Gamma_{31},\Gamma_{32},\Gamma_{32},0)}. \tag{3}$$

The solution to the Eq.1 is given by

$$\boxed{\rho^\alpha_{ij}(x) = \tilde{U}^*_{\alpha i}\tilde{U}_{\alpha j}e^{-(\Gamma_{ij}+i\tilde{\Delta}_{ij})x}} \tag{4}$$

and the oscillation probabilities in the presence of decoherence read as

$$\boxed{P(\nu_\alpha\to\nu_\beta) = \mathrm{Tr}\left[\rho^\alpha(0)\rho^\beta(x)\right]} \tag{5}$$

Here, $\tilde{U}$ is the modified PMNS matrix in matter and $\tilde{\Delta}_{ij} = \frac{\Delta\tilde{m}^2_{ij}L}{4E}$, with $\Delta\tilde{m}^2_{ij}$ being the mass squared differences in matter.

- *L = 360 km, Water Cherenkov detector of fiducial volume 538 kt and 5 years run-time of neutrino + 5 years of antineutrino [2].*

Oscillation Probability including Decoherence

$$\boxed{P(\nu_\alpha\to\nu_\beta) = \delta_{\alpha\beta} - 2\sum_{i>j}\mathrm{Re}\left[\tilde{U}^*_{\alpha i}\tilde{U}_{\beta i}\tilde{U}_{\beta j}\tilde{U}^*_{\beta j}\right]\left[1-\cos\left(2\tilde{\Delta}_{ij}\right)\ e^{-\Gamma_{ij}L}\right] + 2\sum_{i>j}\mathrm{Im}\left[\tilde{U}^*_{\alpha k}\tilde{U}_{\beta k}\tilde{U}_{\beta j}\tilde{U}^*_{\beta j}\right]\ \sin\left(2\tilde{\Delta}_{ij}\right)e^{-\Gamma_{ij}L}},$$

QD induces terms similar to damping phenomena of the form $\mathrm{e}^{-\Gamma_{ij}L}$ in the oscillation probability.

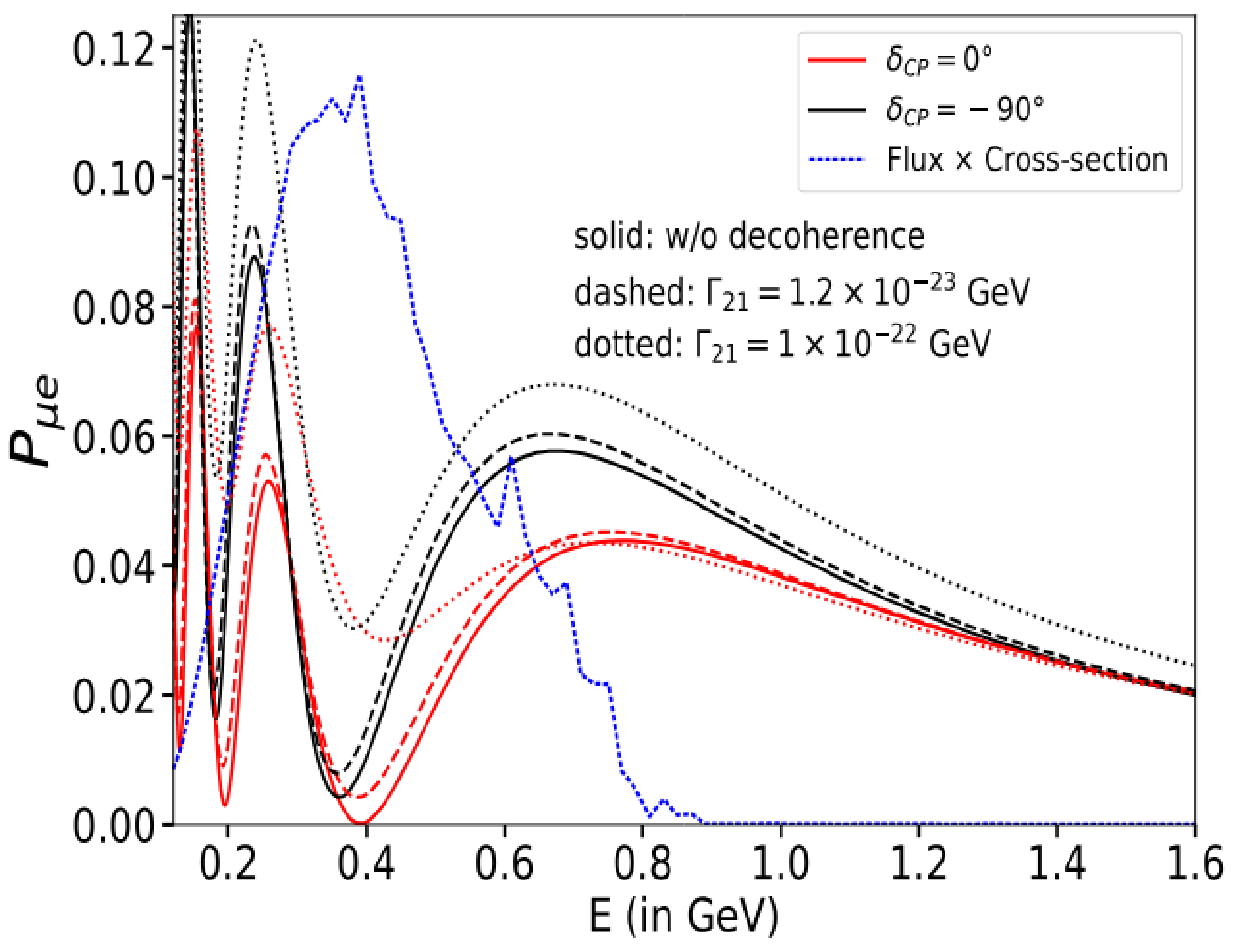


Fig.: Effect of Γ_{21} and Γ_{32} on the appearance probability for the ESSnuSB.

- The $\mathrm{P}_{\mu e}$ probability is mostly affected by Γ_{21} in comparison to Γ_{32}.
- The effect of Γ_{21} is significant when δ_{CP} is $-90°$.

Important Analytical Formulae

For maximal CPV, the relevant contributing terms for Γ_{21} and Γ_{32} are

$$|P^{\mathrm{CP-odd}}_{\mu e}| \propto |2\alpha\Delta_{31}(\Gamma_{21}L - 2\sin^2\Delta_{31}) - \Gamma_{21}L\sin2\Delta_{31}|\,.$$

$$|P^{\mathrm{CP-odd}}_{\mu e}| \propto |\Gamma_{32}L\cos2\Delta_{31} + 2\sin^2\Delta_{31}|\,.$$

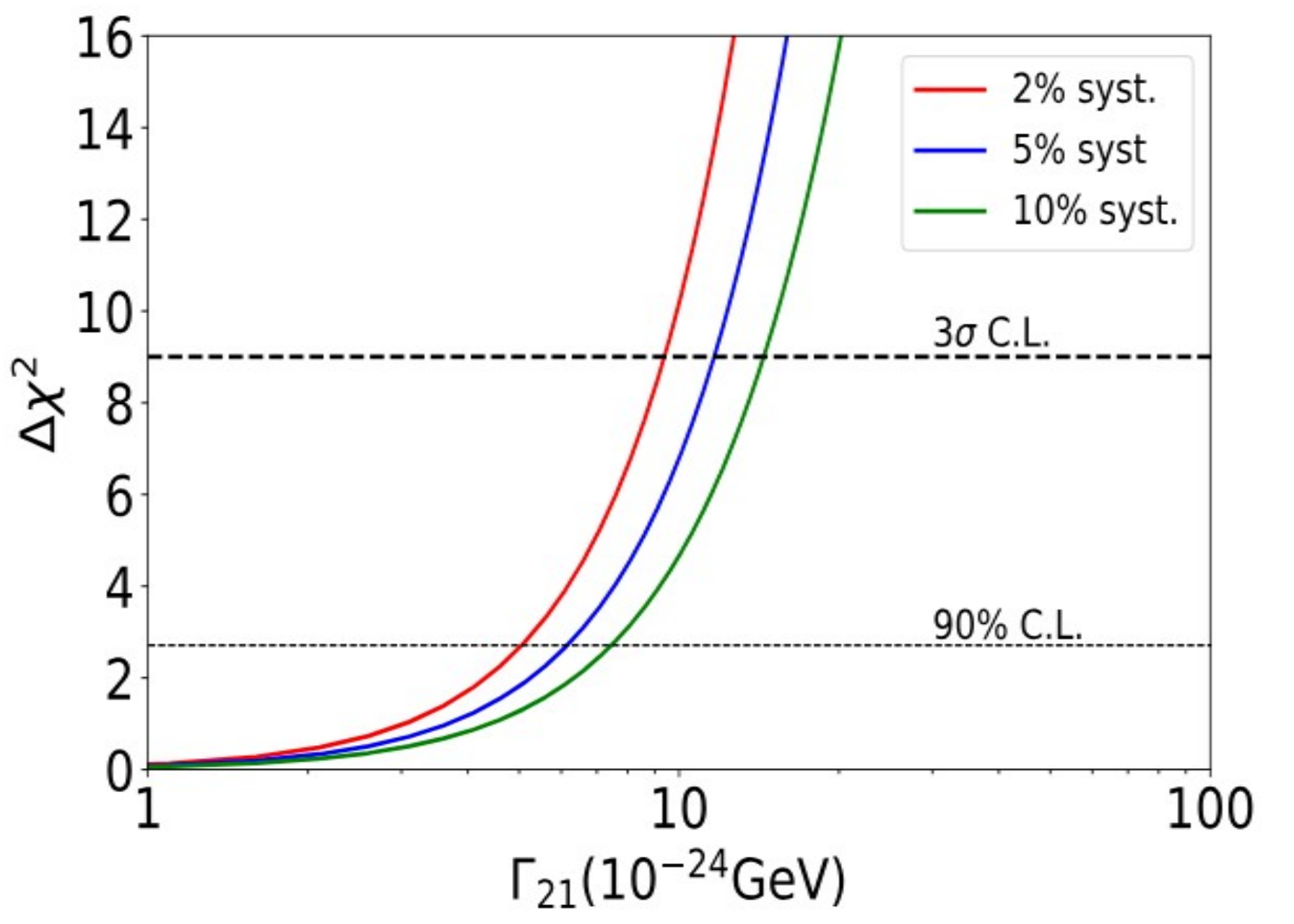
For $\delta_{CP} = 0, 180°$, expression for CPV precision is given by:

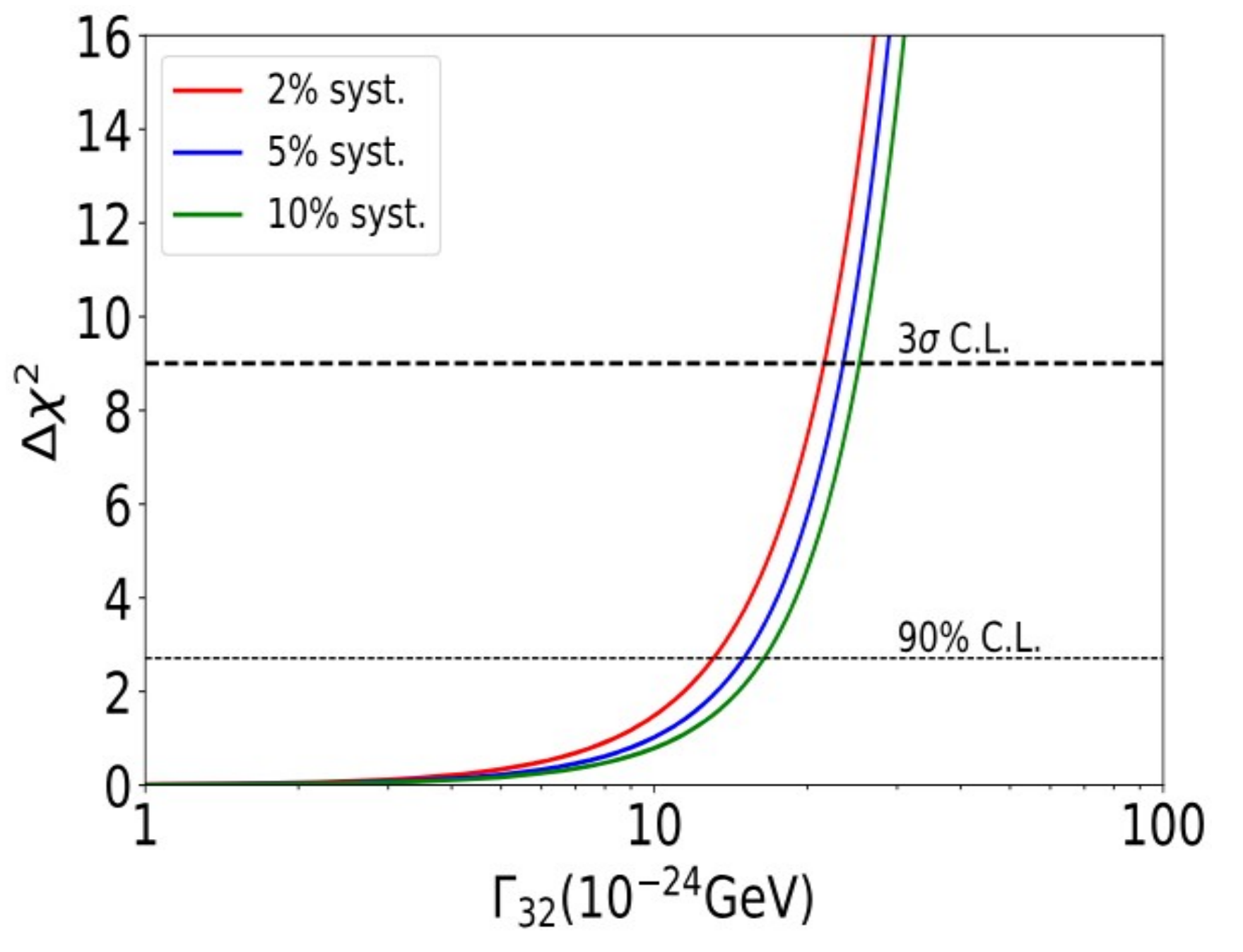
$$\Delta\delta_{\mathrm{CP}} \propto \frac{1}{|2\alpha\Delta_{31}(\Gamma_{21}L - 2\sin^2\Delta_{31}) - \Gamma_{21}L\sin2\Delta_{31}|};\frac{1}{|\alpha\Delta_{31}\Gamma_{32}L\cos2\Delta_{31} + 2\alpha\Delta_{31}\sin^2\Delta_{31}|}.$$

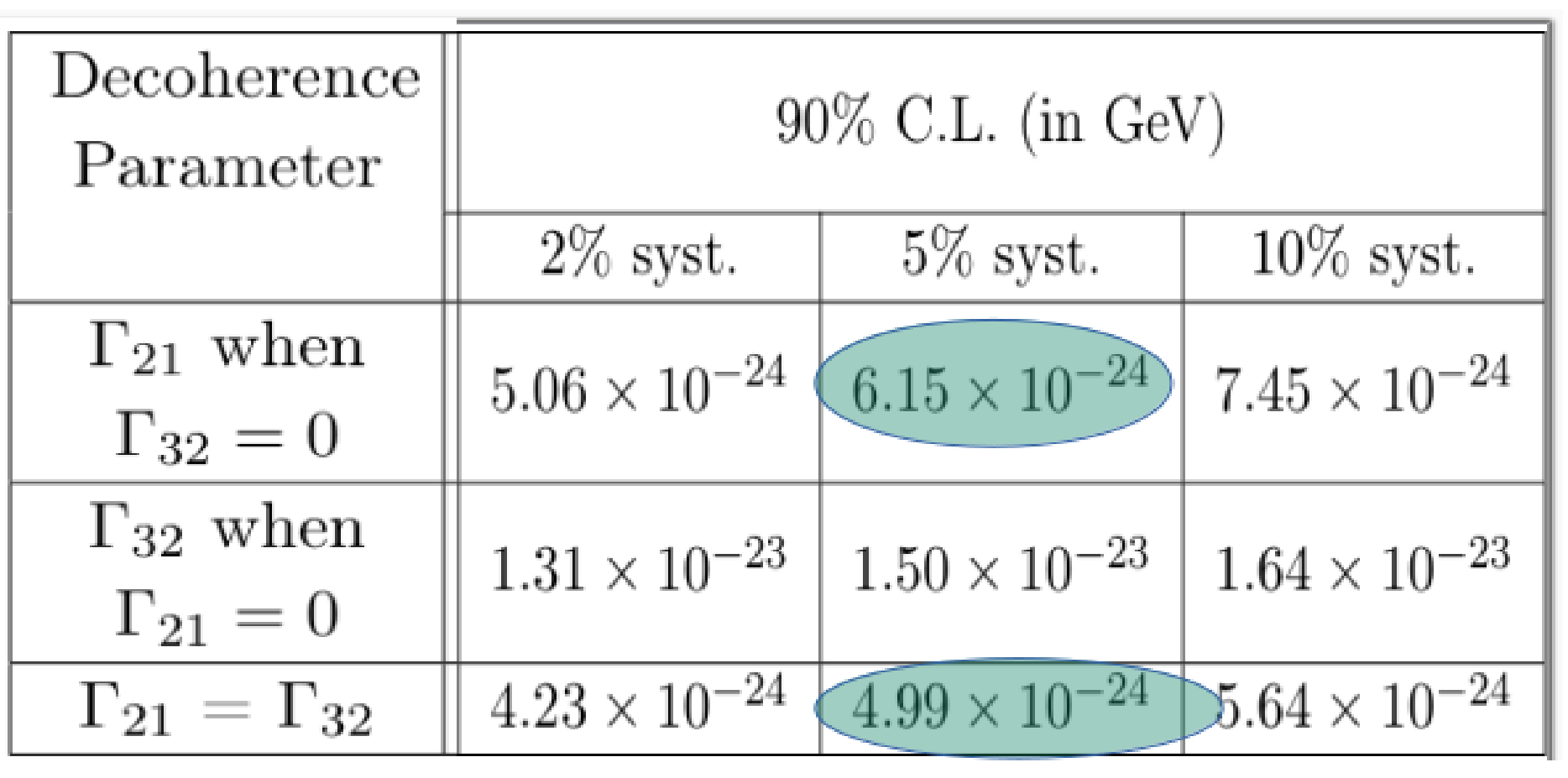
On the other hand, for maximal CP violation, we obtain

$$\Delta\delta_{\mathrm{CP}} \propto \frac{1}{|\Gamma_{21}L(\cos2\Delta_{31} + \cos2\theta_{12}) + 2\alpha\Delta_{31}\sin2\Delta_{31}|};\frac{1}{|\alpha\Delta_{31}(1-\Gamma_{32}L)\sin\Delta_{31}|}.$$

Bounds on Γ_{21} and Γ_{32}





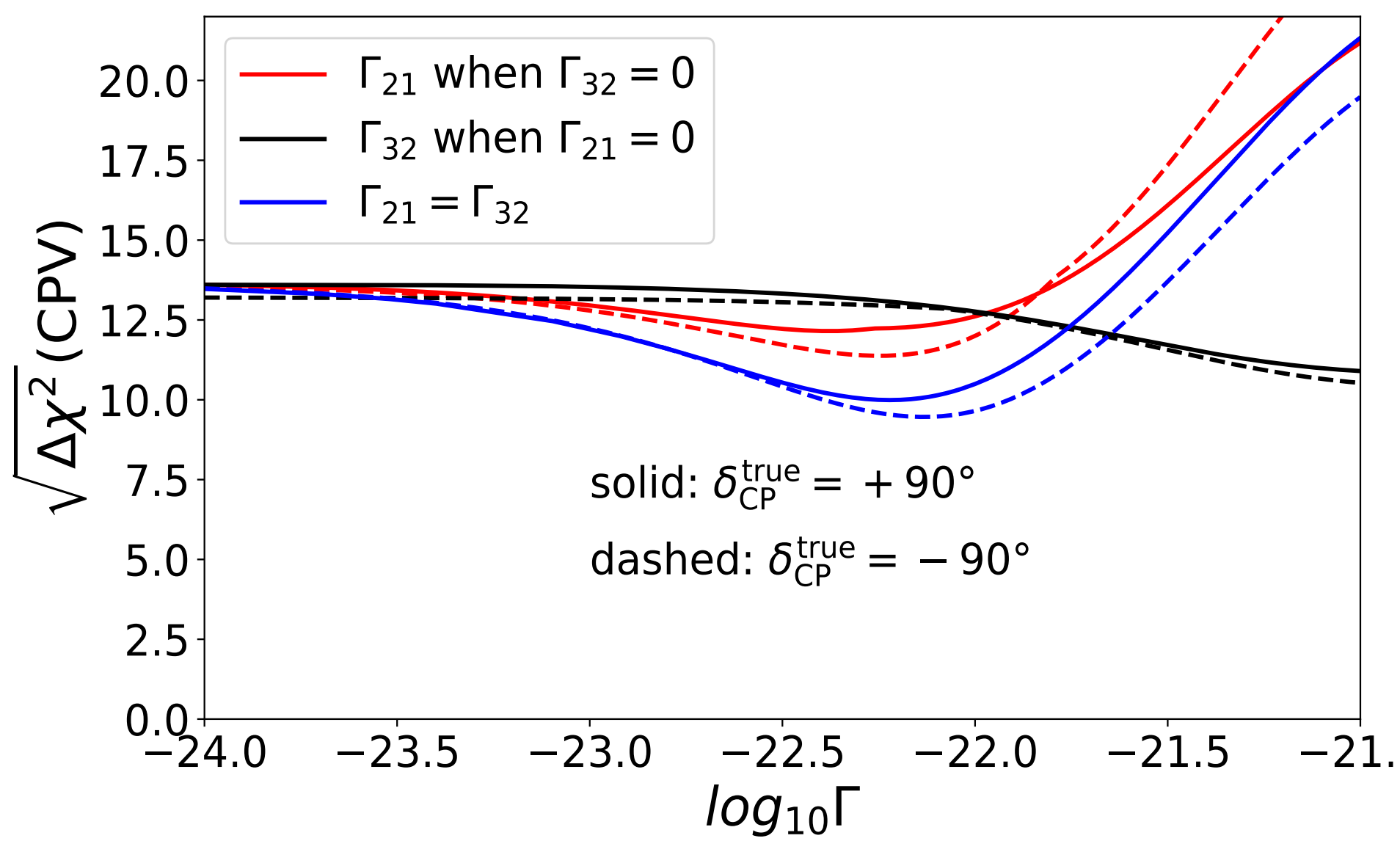


Decoherence Parameter	90% C.L. (in GeV)		
	2% syst.	5% syst.	10% syst.
Γ_{21} when $\Gamma_{32} = 0$	5.06×10^{-24}	6.15×10^{-24}	7.45×10^{-24}
Γ_{32} when $\Gamma_{21} = 0$	1.31×10^{-23}	1.50×10^{-23}	1.64×10^{-23}
$\Gamma_{21} = \Gamma_{32}$	4.23×10^{-24}	4.99×10^{-24}	5.64×10^{-24}

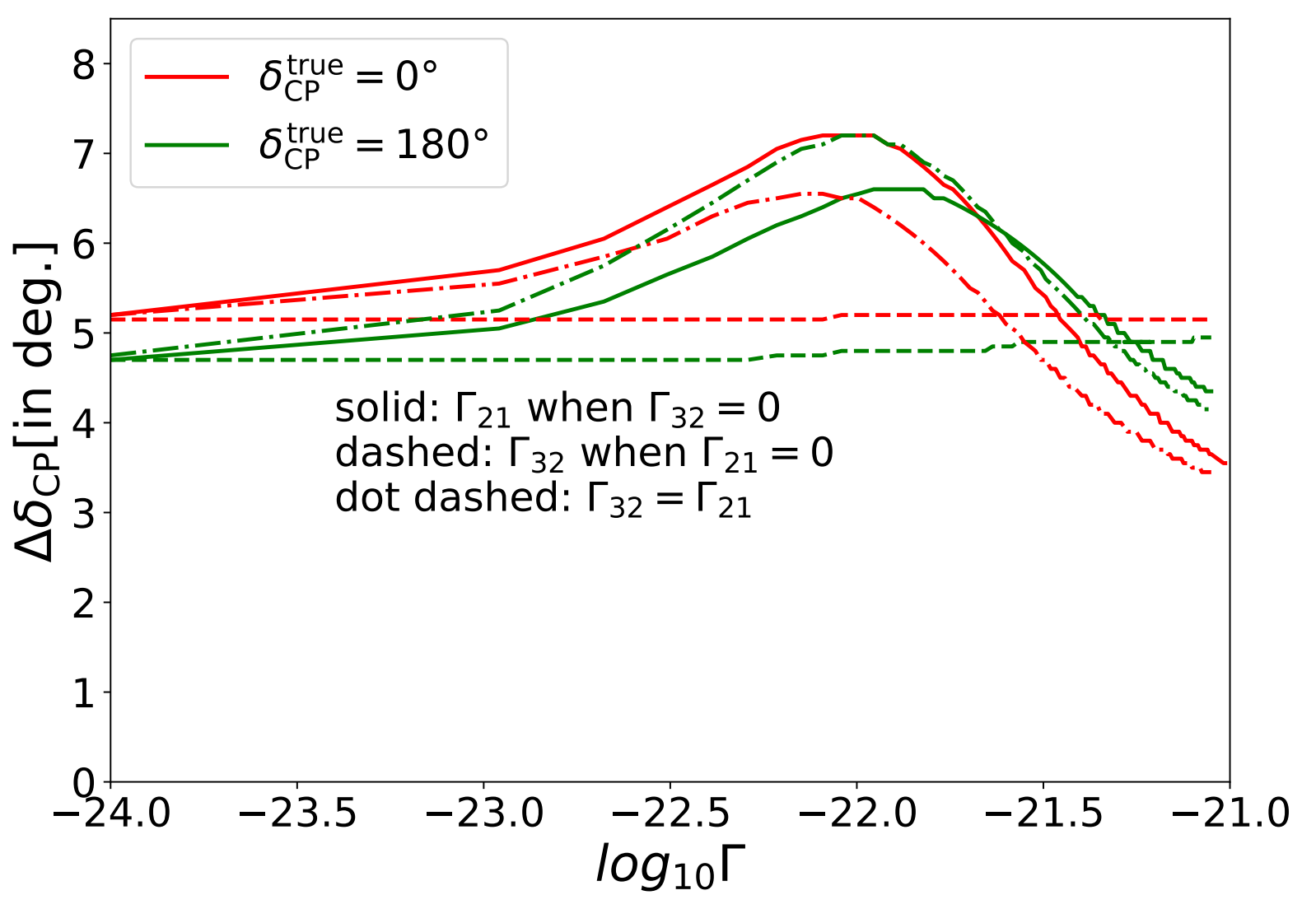
Other experimental bounds at 90% C.L. are [3, 4]

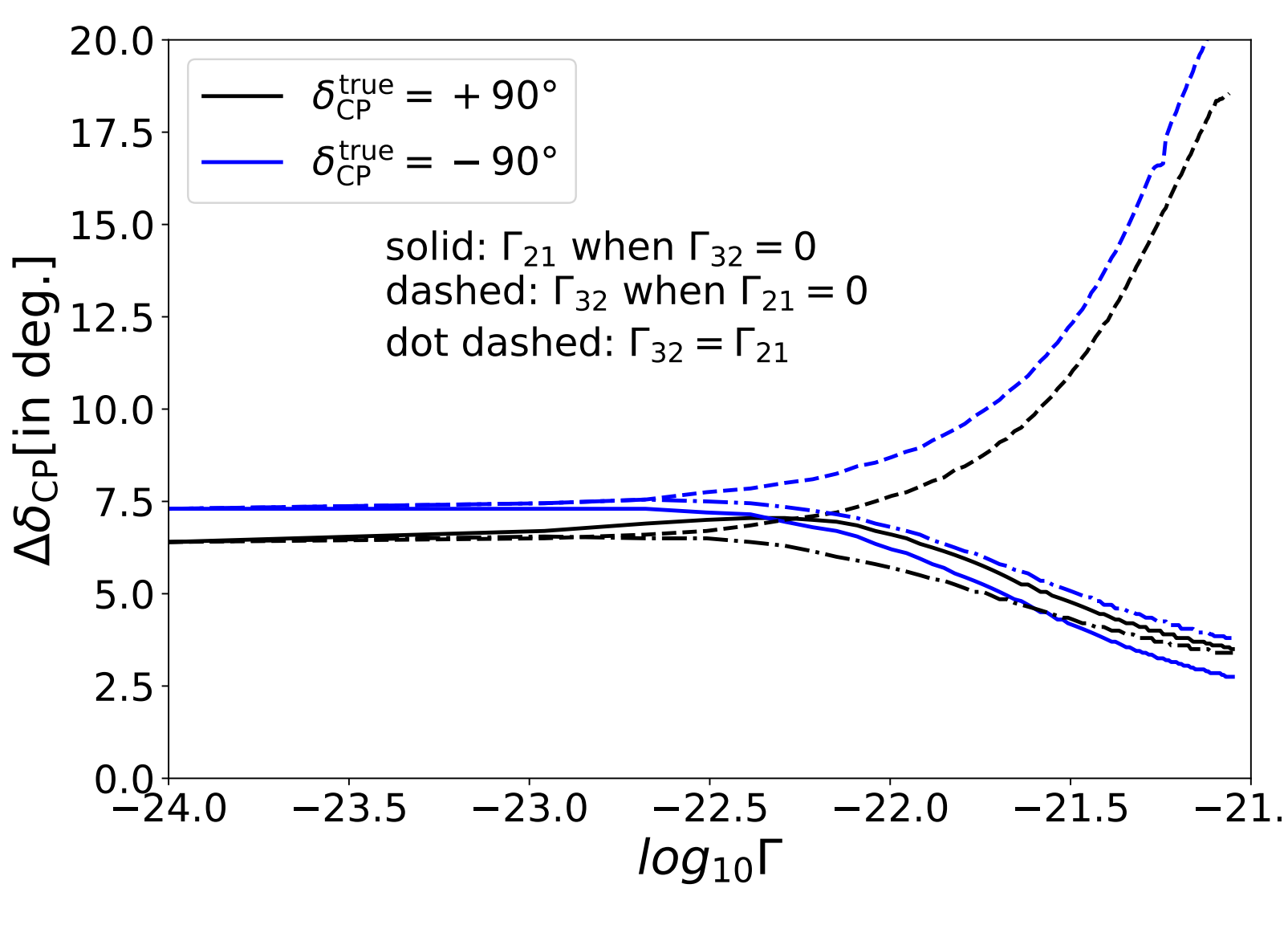
$$\Gamma_{32} = \Gamma_{21} < \mathbf{9.4\times10^{-24}}\ \mathrm{GeV}\quad[\mathrm{MINOS/MIN}$$
$$\Gamma_{21} < \mathbf{1.2\times10^{-23}}\ \mathrm{GeV}\quad[\mathrm{DUNE}],$$
$$\Gamma_{32} < 4.7\times10^{-24}\ \mathrm{GeV}\quad[\mathrm{DUNE}]\,.$$

CPV Sensitivity & Precision

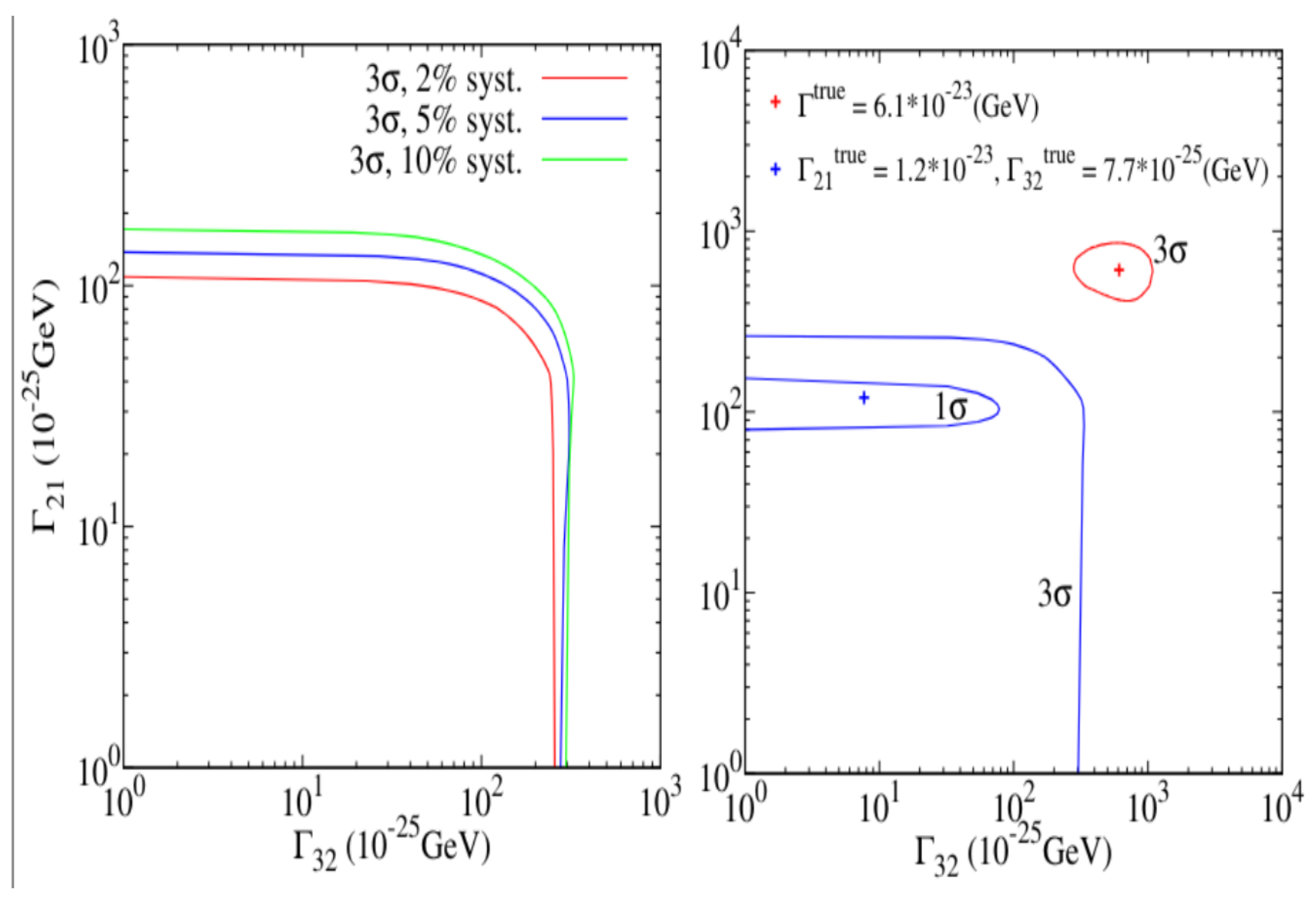


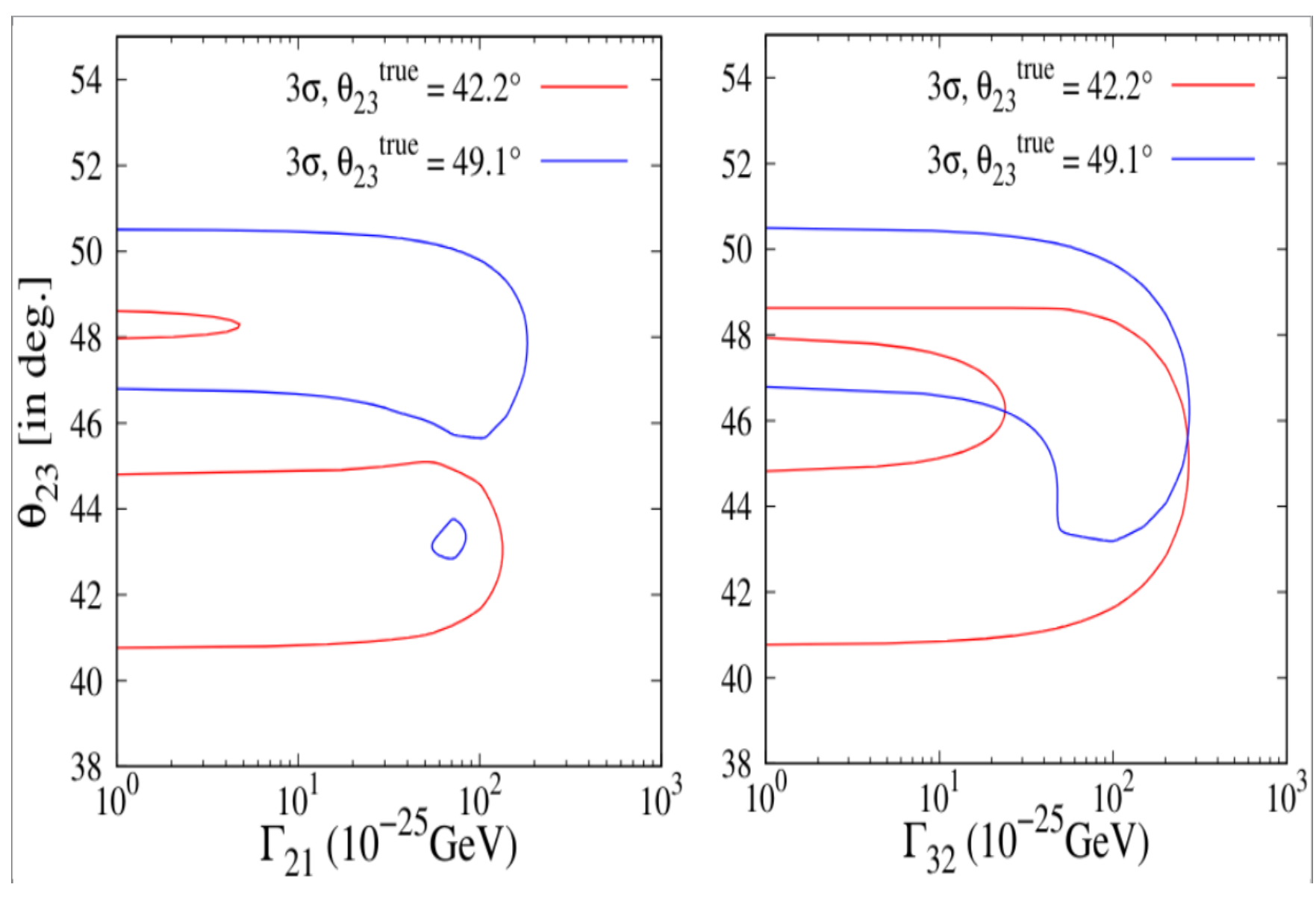
For small Γ_{21}, the sensitivity first slightly decreases and when the decoherence term becomes dominant, the relevant probability increases along with Γ_{21}, improving the sensitivity.

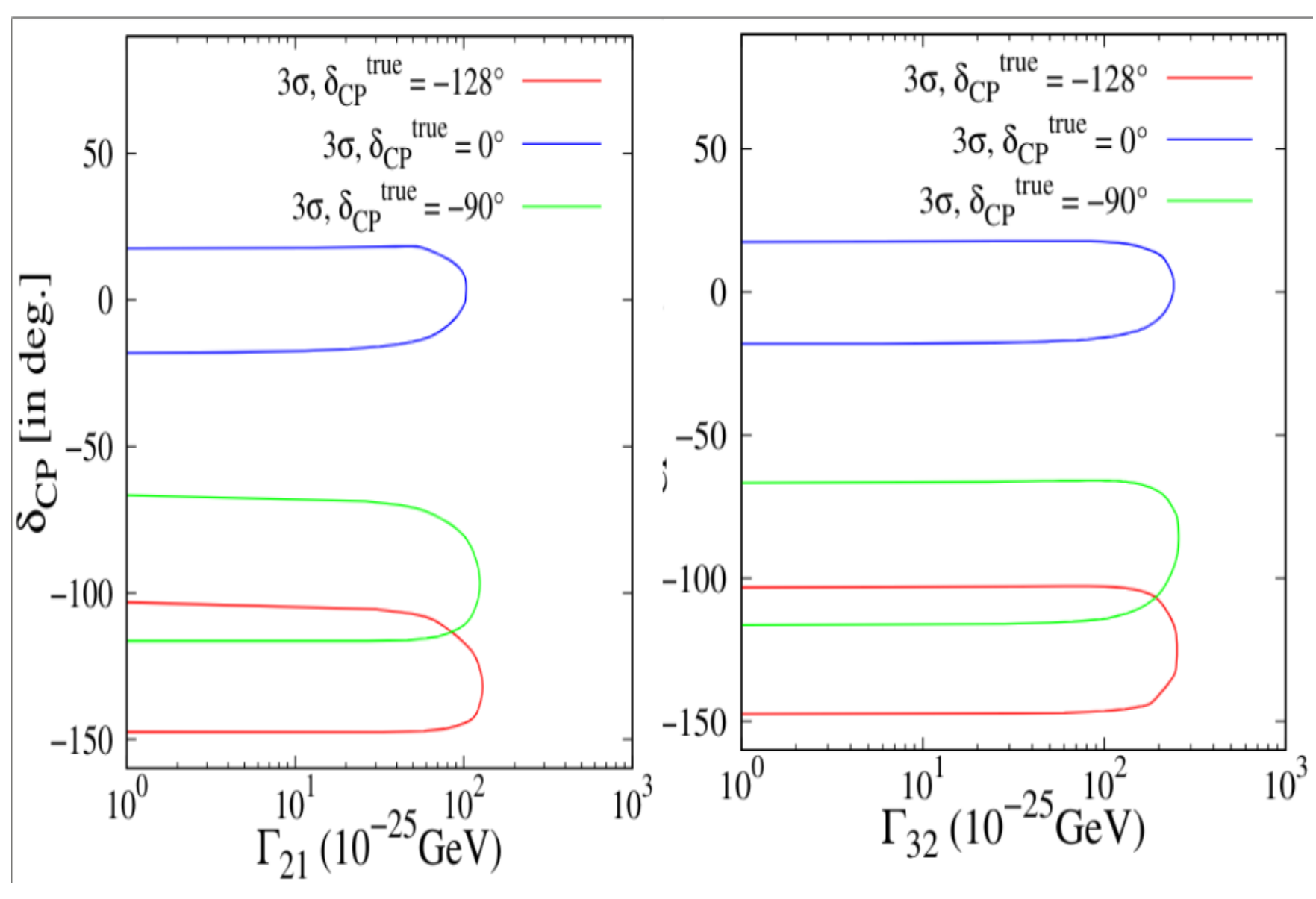




Correlations







Key Takeaways

- *For the first time*, we explore the sensitivity of **ESSnuSB** to constrain Γ_{21} and Γ_{32} [5].
- We find that, *the bounds on Γ_{21} are better than MINOS/MINOS+ and DUNE, while constraint on Γ_{32} is competitive.*
- *ESSnuSB measurement of δ_{CP} remains robust for Γ_{ij} in the range $[10^{-24}, 10^{-21}]$ GeV.*
- *For the case of maximal CP violation, an uncertainty below $10°$ can be maintained for $\Gamma_{ij} \gtrsim 10^{-22}$ GeV.*
- *Interesting correlations have been observed among θ_{23} and Γ*

References

[1] E. Lisi, A. Marrone, and D. Montanino. Probing possible decoherence effects in atmospheric neutrino oscillations. *Phys. Rev. Lett.*, 85:1166–1169, 2000.

[2] A. Alekou et al. The European Spallation Source neutrino super-beam conceptual design report. *Eur. Phys. J. ST*, 231(21):3779–3955, 2022.

[3] Valentina De Romeri, Carlo Giunti, Thomas Stuttard, and Christoph A. Ternes. Neutrino oscillation bounds on quantum decoherence. *JHEP*, 09:097, 2023.

[4] G. Balieiro Gomes, D. V. Forero, M. M. Guzzo, P. C. De Holanda, and R. L. N. Oliveira. Quantum Decoherence Effects in Neutrino Oscillations at DUNE. *Phys. Rev. D*, 100(5):055023, 2019.

[5] J. Aguilar et al. Decoherence in Neutrino Oscillation at the ESSnuSB Experiment. 4 2024.