Quantum Decoherence at ESSnuSB

Monojit Ghosh

Ruđer Bosković Institute, Zagreb, Croatia

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Based on: J. Aguilar *et al*. [ESSnuSB], JHEP **08** (2024), 063

Corr. Authors: MG, Alessio Giarnetti, Aman Gupta and Davide Meloni

Decoherence in Neutrino Oscillation

Neutrino Oscillation: a quantum mechanical interreference phenomenon due to the coherent superposition of different neutrino mass eigenstates.

Decoherence: Coherence in the interference pattern is lost

Two Types:

Kinematic Decoherence: Wave packet formalism - Separation of the wavepackets due to different velocities in the mass states

Dynamic Decoherence: Open quantum system formalism – Environment induced decoherence

We adopt the open quantum system formalism

Open Quantum System

Idea: neutrino as a subsystem interacting with the environment giving rise to decoherence

The evolution equation – Lindblad Master Equation

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

$$\mathcal{D} = D_{jk} \rho_k \lambda_j$$

H: Neutrino Oscillation Hamiltonian in matter
ρ = Density Matrix, $\mathcal{D}$ = Dissipator
λ = Gell-Mann Matrices

Oscillation probability -

$$P_{\alpha\beta} = \mathrm{Tr}\,[\rho_\alpha(0)\rho_\beta(x)]$$

Formalism

Many formalisms are studied. We adopted from:

Gomes, Forero, Guzzo, Holanda and Oliveira, Phys. Rev. D 100 (2019), 055023
De Romeri, Giunti, Stuttard and Ternes, JHEP 09 (2023), 097
Gomes, Gomes and Peres, JHEP 10 (2023), 035

$$D_{jk} = -\mathrm{diag}(\Gamma_{21}, \Gamma_{21}, 0, \Gamma_{31}, \Gamma_{31}, \Gamma_{32}, \Gamma_{32}, 0)$$

$$\Gamma_{31} = \Gamma_{21} + \Gamma_{32} - 2\sqrt{\Gamma_{21}\Gamma_{32}}$$

$\widetilde{U}$, $\widetilde{\Delta}$: PMNS Matrix and Mass square difference in matter

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

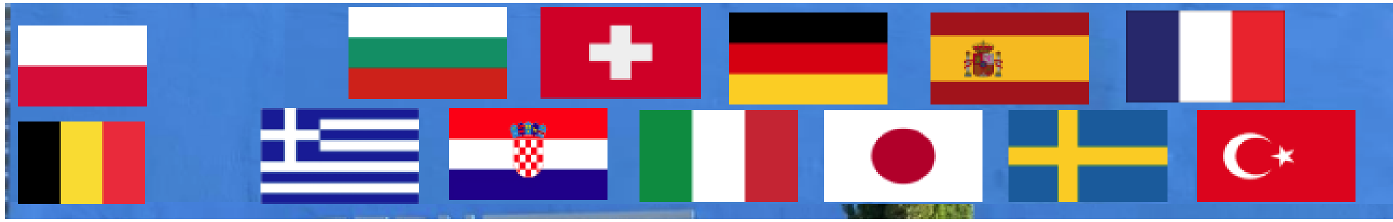
Only applicable if matter effect is small

D is conventionally defined in vacuum
Inclusion of matter effect requires rotation of D in matter basis → D becomes off-diagonal and the probability formula changes
This affects neutrinos at higher energies

The ESSnuSB Experiment

ESSnuSB - Horizon (2018 - 2022) – 3 M€
ESSnuSB+ -Horizon EU (2023 - 2026) - 3 M€

13 countries
23 Instititutes



Water Cerenkov Far Detector- 540 kt
5 MW Proton beam, 2 Gev proton energy

Main Goal: Precision measurement of the CP Violation phase with a long baseline setup

Other goals: Neutrino Cross-section measurements with the near detectors, Sterile neutrino searches with a short baseline setup, etc.

Eur. Phys. J. ST \textbf{231} (2022) no.21, 3779-39554

Talk by Joakim Cederkall on 4th Sept

Probability and Flux

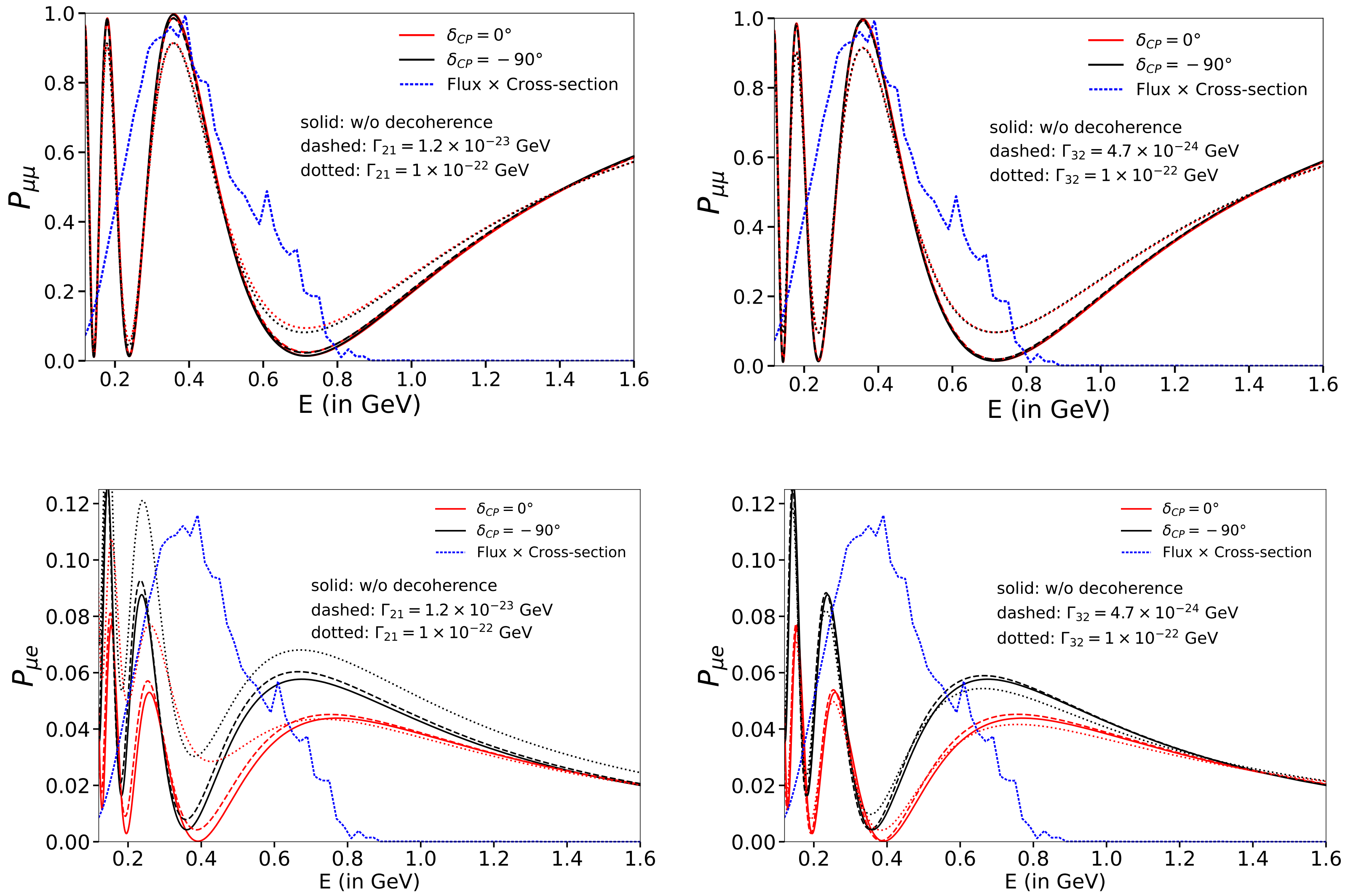
Benchmark: 90% bound from DUNE

Γ_{21} = 1.2 x 10^{-23} GeV
Γ_{32} = 4.7 x 10^{-24} GeV

Gomes, Forero, Guzzo, Holanda and Oliveira, Phys. Rev. D 100 (2019), 055023

$$P_{\mu e} \sim \Gamma_{21}$$

$$P_{\mu\mu} \sim \Gamma_{21} \text{ and } \Gamma_{32}$$



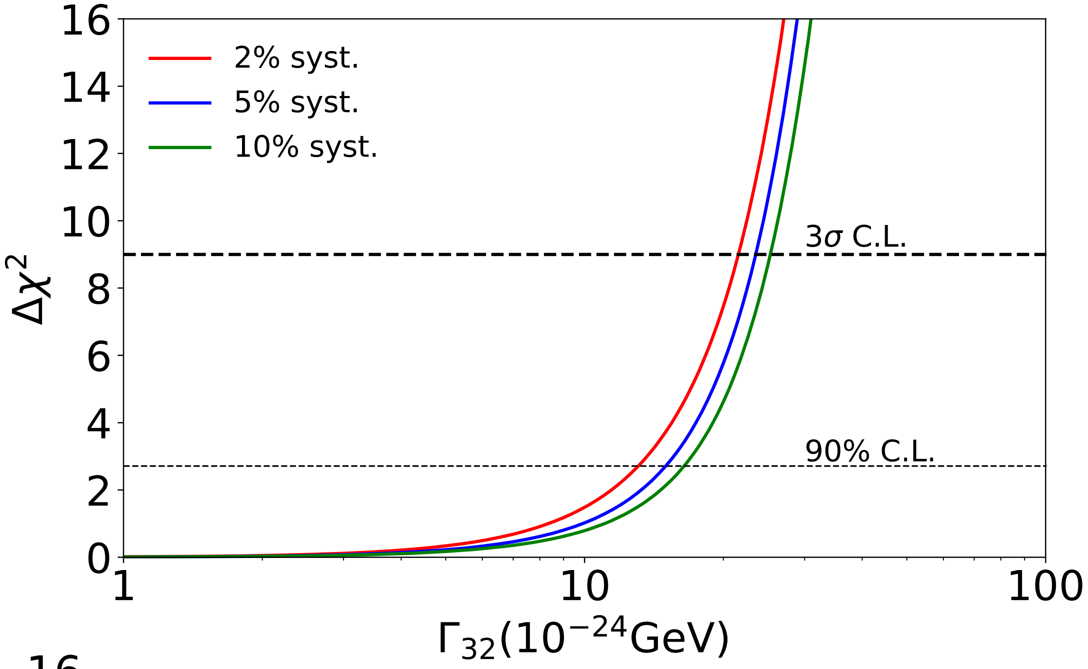
Bounds on Γ_{21} and Γ_{32}

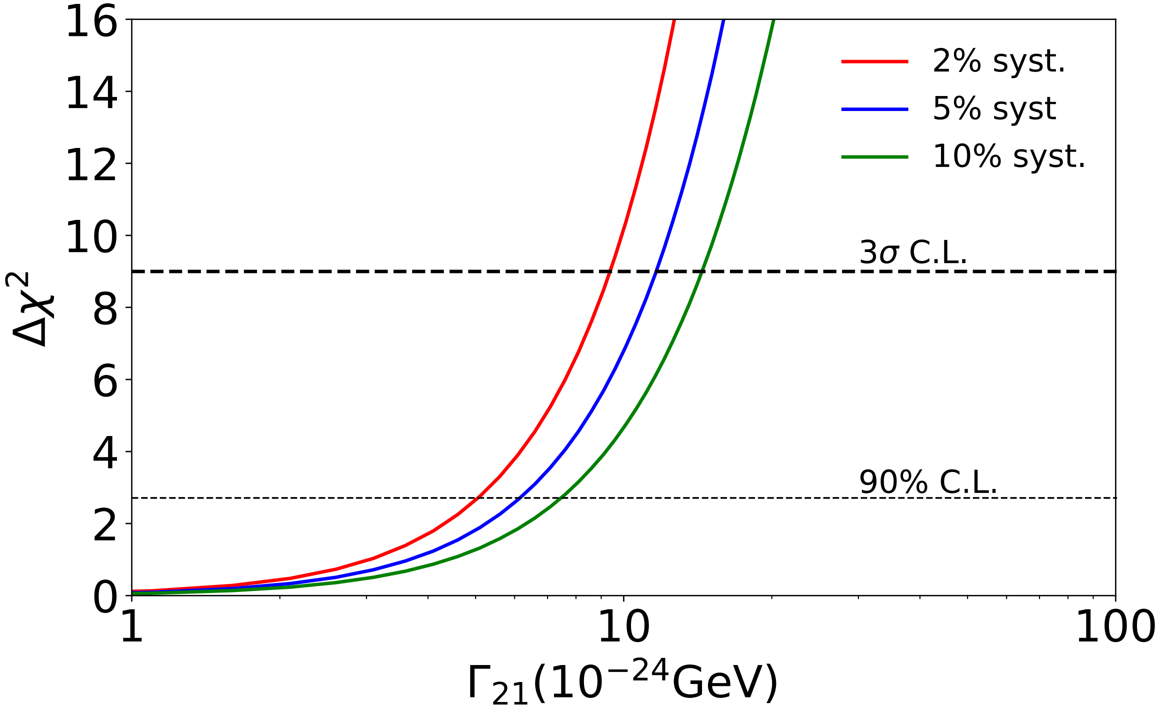
$$\Gamma_{32} = \Gamma_{21} < 9.4 \times 10^{-24}\ \text{GeV} \quad [\text{MINOS/MINOS+}, (90\%\ \text{C.L.})],$$

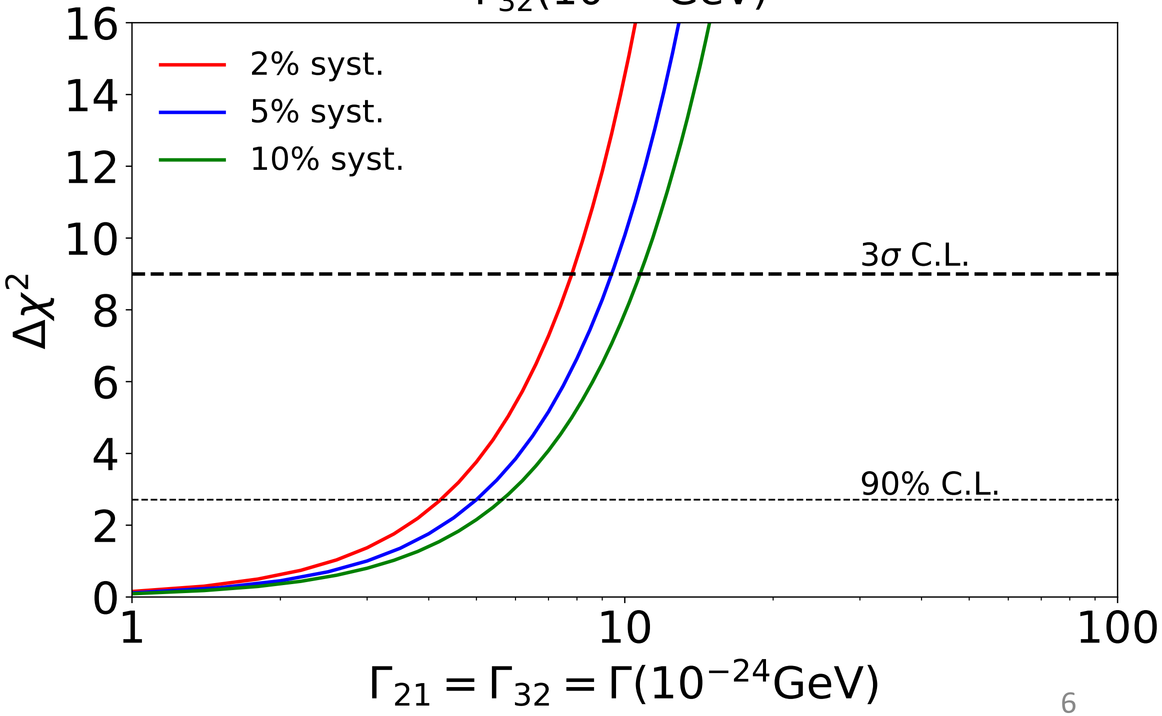
$$\Gamma_{21} < 1.2 \times 10^{-23}\ \text{GeV} \quad [\text{DUNE}, (90\%\ \text{C.L.})]$$

$$\Gamma_{32} < 4.7 \times 10^{-24}\ \text{GeV} \quad [\text{DUNE}, (90\%\ \text{C.L.})]\,.$$

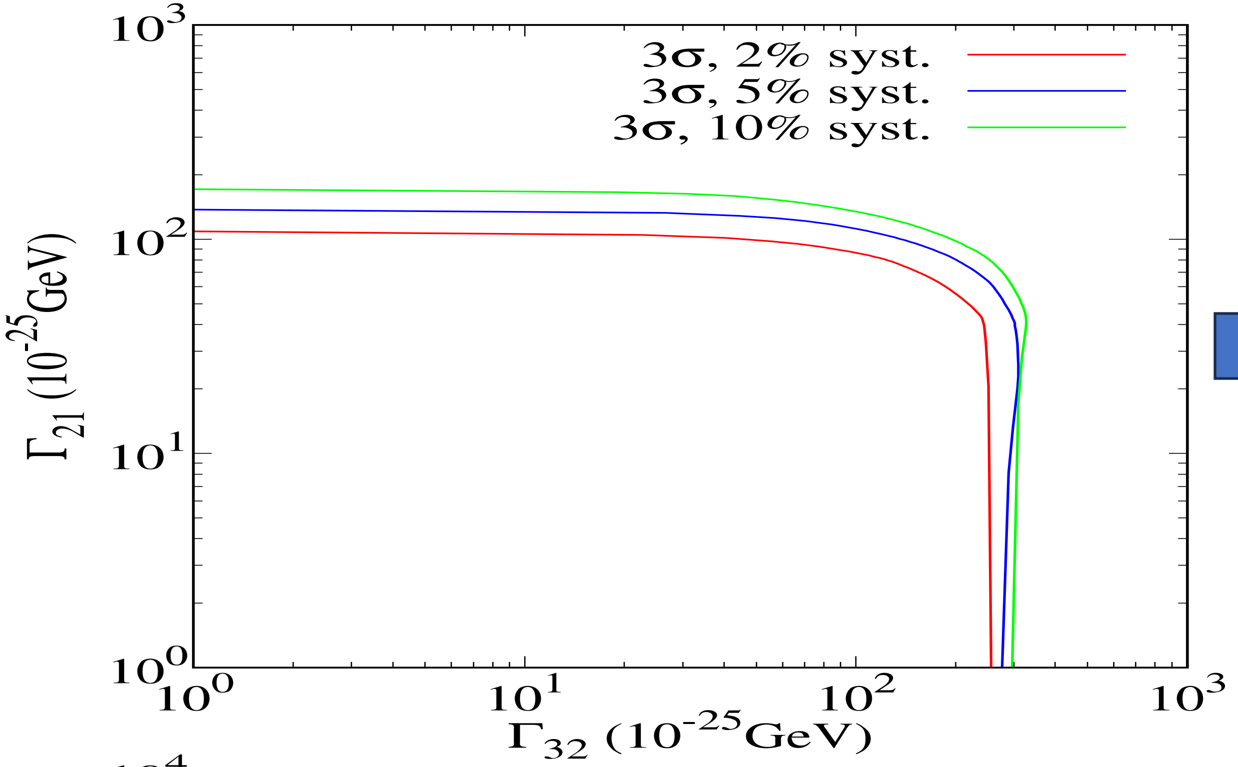
Better than MINOS and comparable to DUNE





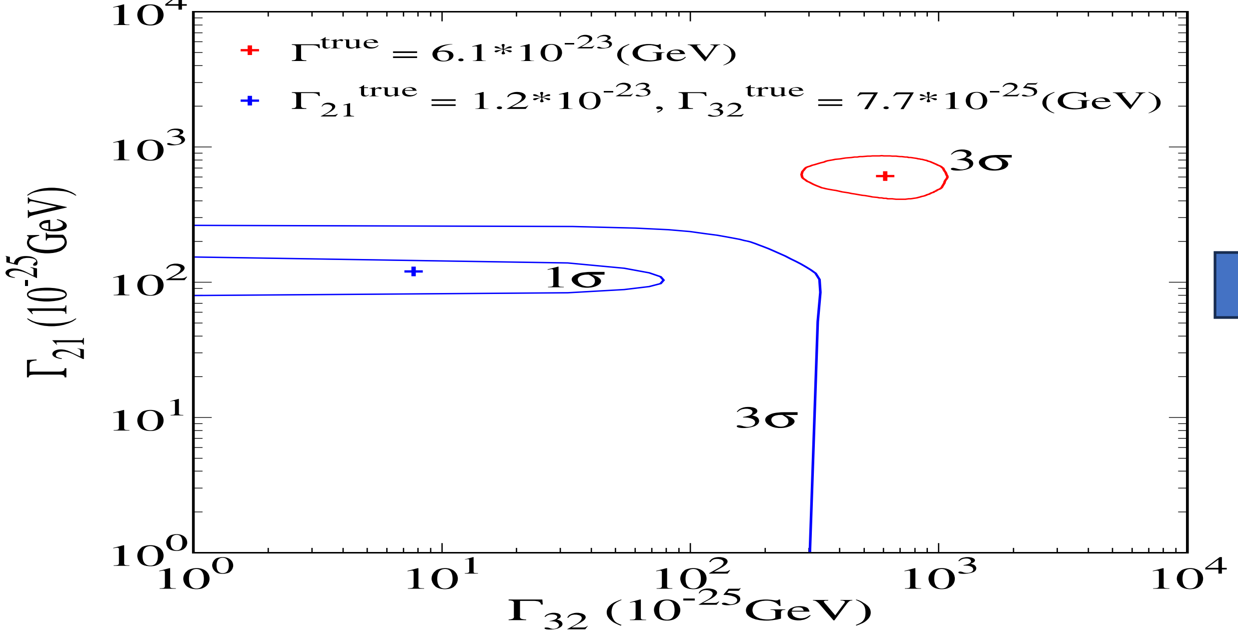


Correlation b/w Γ_{21} and Γ_{32}



-Standard scenario in simulated data
Decoherence in Theory

-No Correlation between Γ_{21} and Γ_{32}



-Decoherence in both simulated data and theory

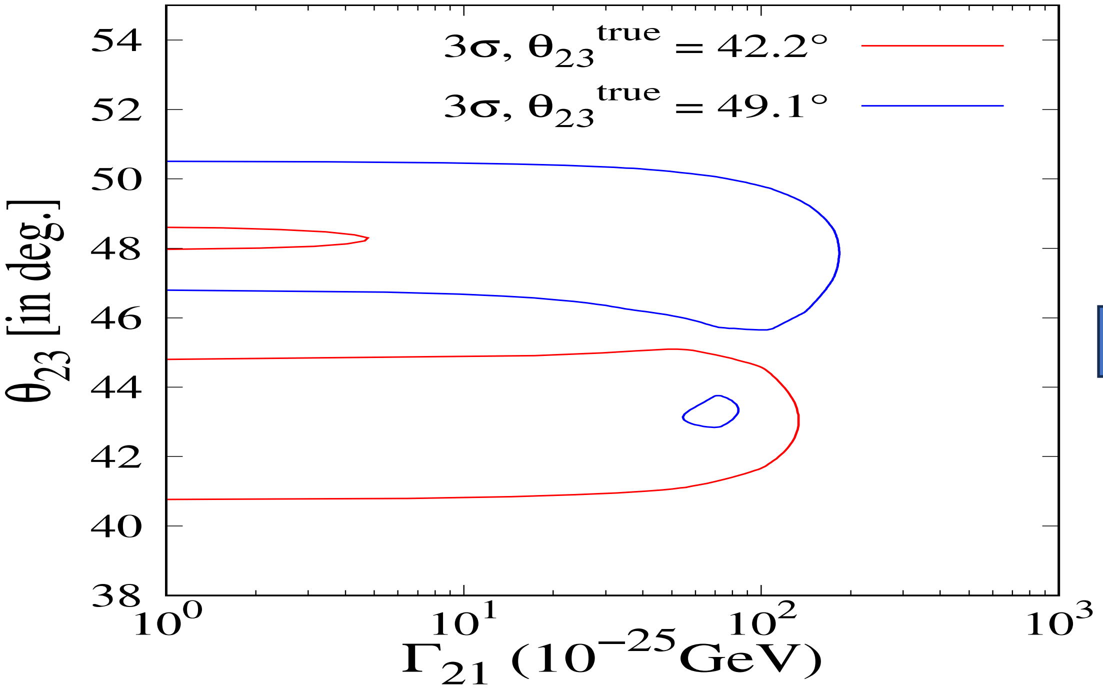
-Two benchmark values

$\Gamma_{21} = \Gamma_{21} = 1.2 \times 10^{-23}$ GeV (90% bound from T2K+MINOS)
De Romeri, Giunti, Stuttard and Ternes, JHEP 09 (2023), 097

$\Gamma_{21} = 1.2 \times 10^{-23}$ GeV (90% bound from DUNE HE flux)
$\Gamma_{32} = 7.7 \times 10^{-25}$ GeV

-Good precision for high Γ
Poor precison for low Γ

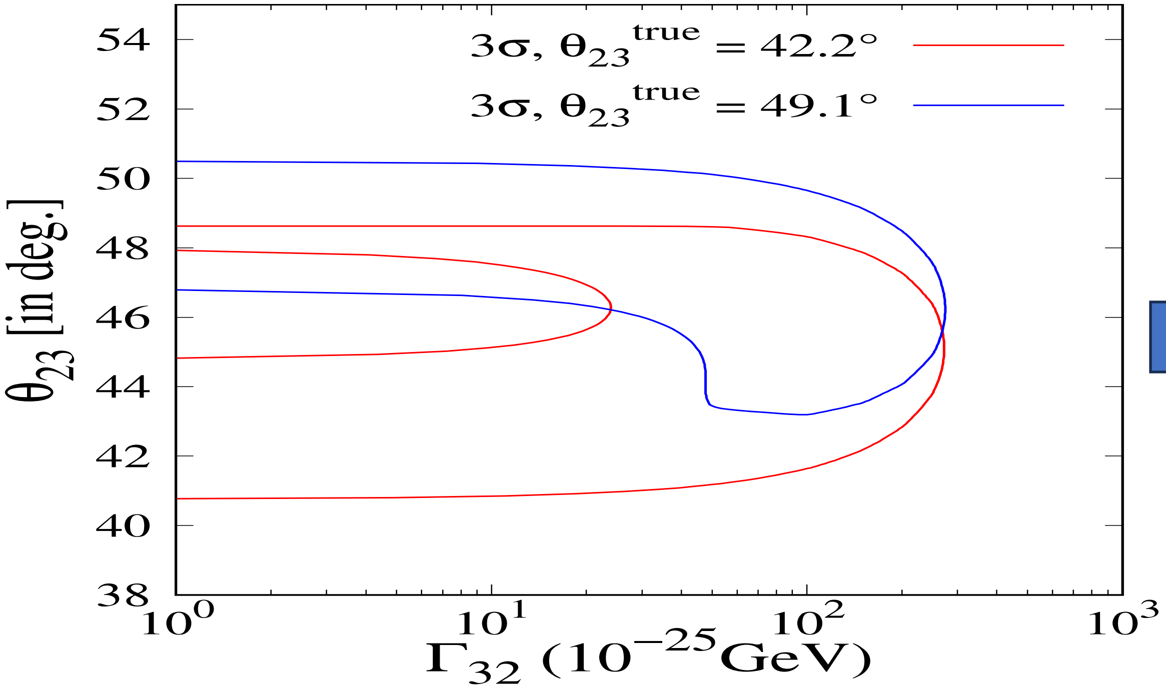
Correlation with θ_{23}



-Octant degeneracy for LO if there is no decoherence

-Std can be fitted with Γ_{21}without octant degeneracy

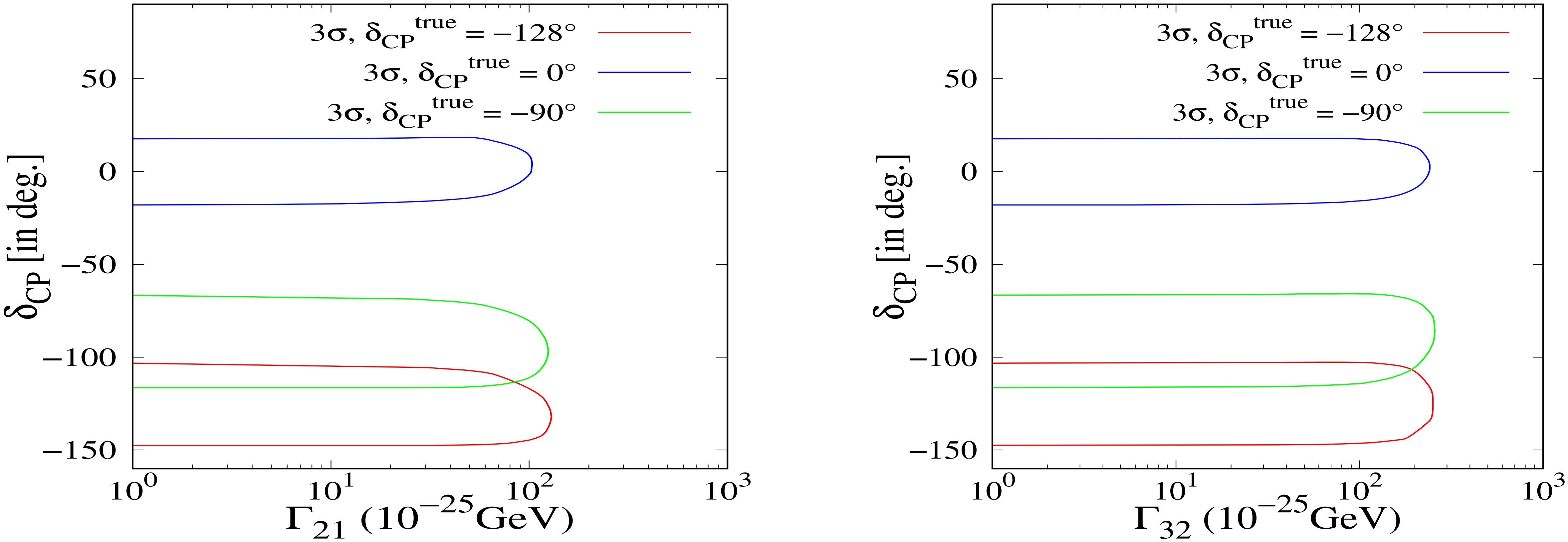
Standard scenario in simulated data
Decoherence in Theory



-Octant degeneracy for LO if there is no decoherence

-Std can't be fitted with Γ_{21}without octant degeneracy

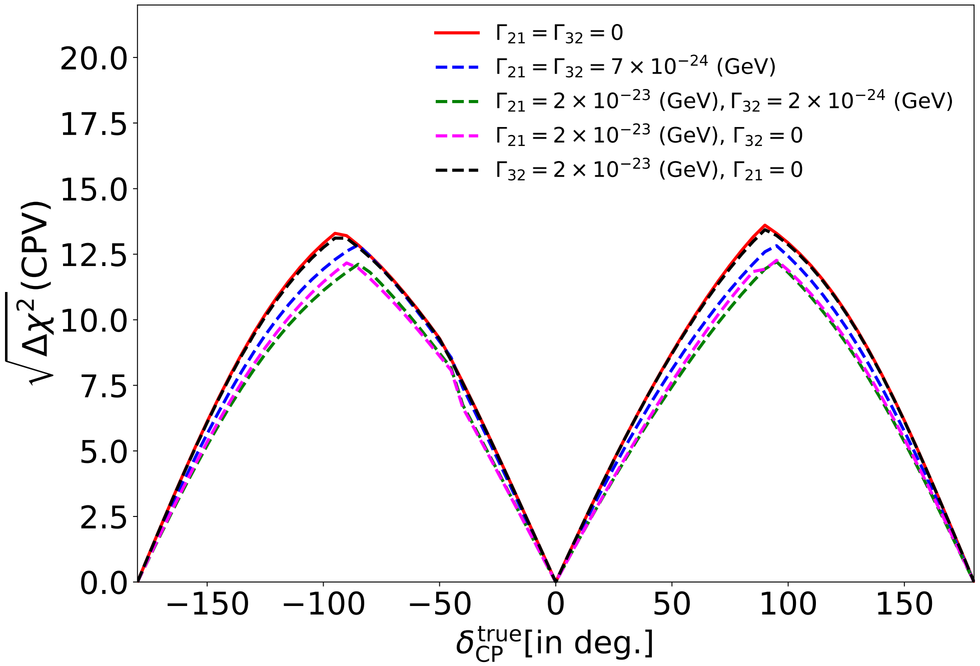
Correlation with δ_{cp}



CP sensitivity remains unaffected.

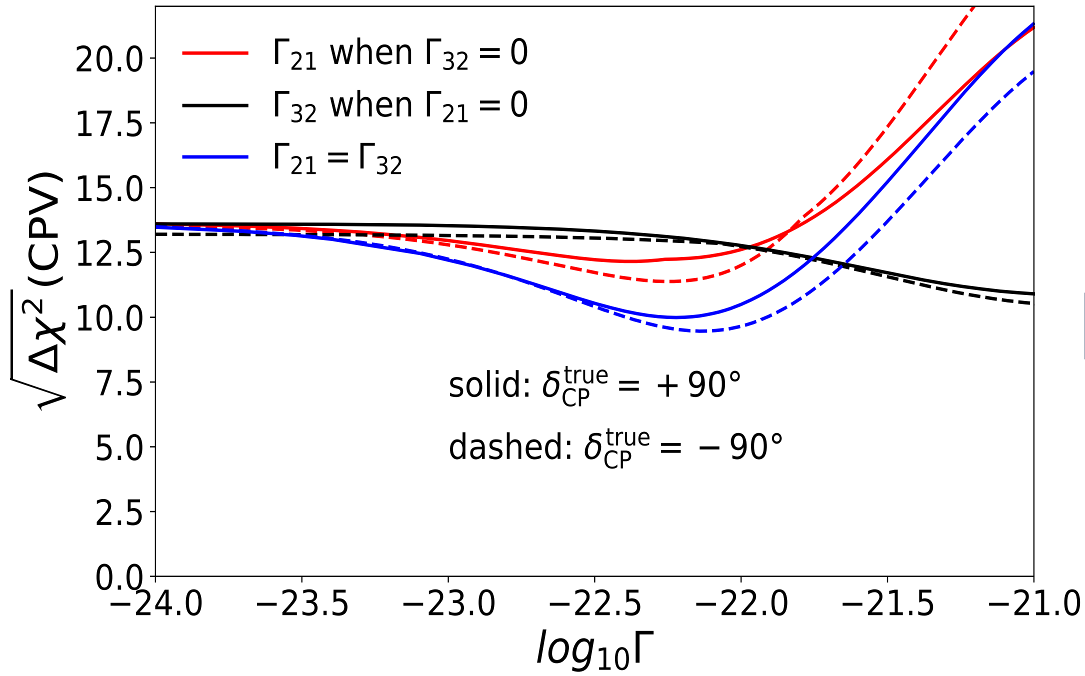
Standard scenario in simulated data
Decoherence in Theory

CP Violation



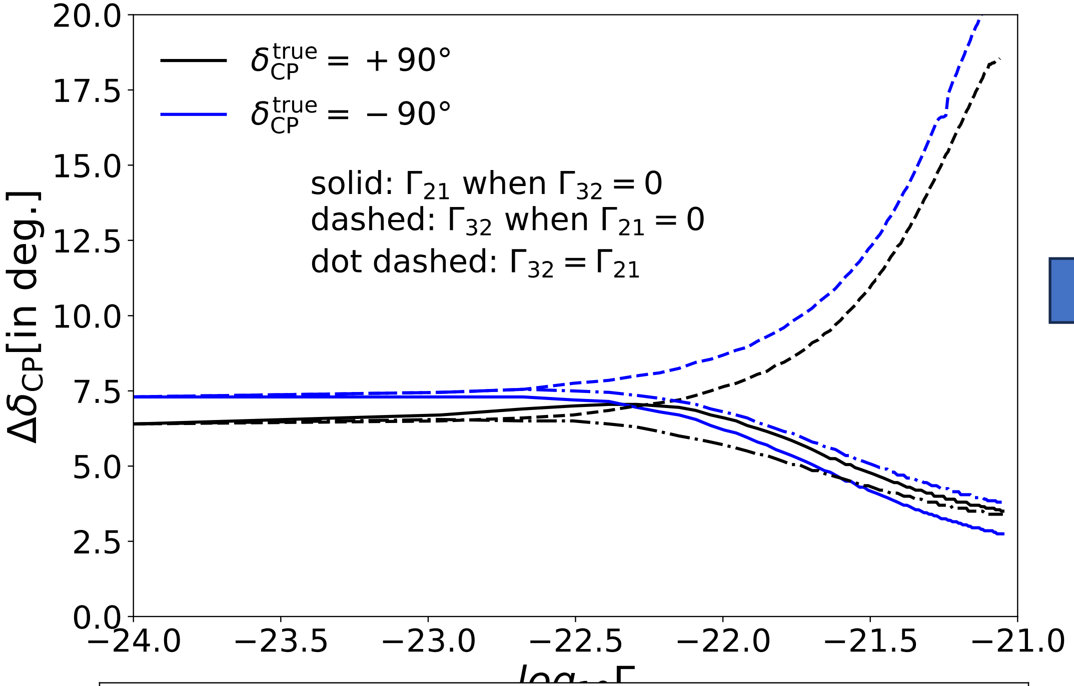
-Several Reeference choices
-Red is Std
- Sensitivity decreases slightly in presence of Decoherence

Decoherence in both simulated data and Theory



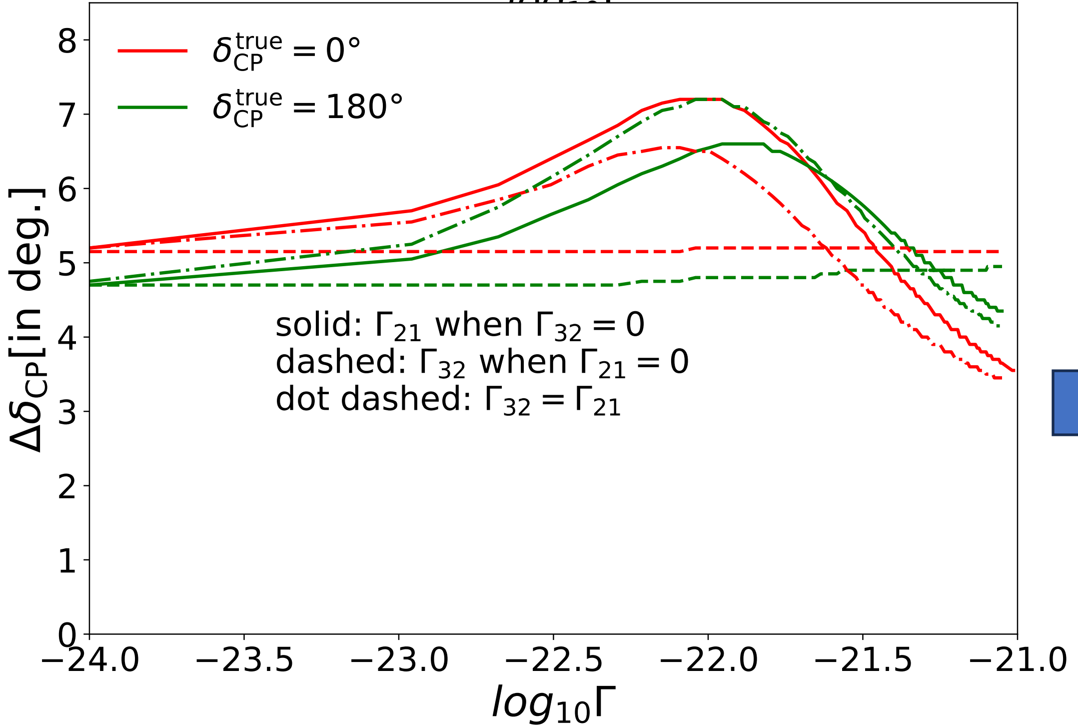
-Sensitivity changes for very large values of Γ
- Γ_{21} has dominant effect

CP Precision



-CP precision for CP violating values
- Imrovement for large Γ_{21}
- Deteriorates for large Γ_{32}

Decoherence in both simulated data and Theory



-CP precision for CP conserving values
- Γ_{21} has dominant effect
- Firs deteriorates then improves

Summary

- ESSnuSB is a good experiment to study quantum decoherence
- Bounds will be better than MINOS and comparable to DUNE
- The parameter Γ_{21} and Γ_{32} are not correlated
- CP violation and CP precision sensitivity mostly remain unaffected for small Γ_{21} and Γ_{32}
- All the results can be explained from the oscillation probabilities

Summary

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Thank You