Exploring Earth's Matter Effect in High-Precision Long-Baseline Eperiments

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1. Motivation

DUNE has substantial matter effect because of 1300 km baseline. In this work, we explore :

- **capability of DUNE in establishing matter effect** by excluding vacuum hypothesis
- **precision in the measurement of** line-averaged constant Earth matter density ($\rho_{\rm avg}$)
- **new degeneracies in** $(\rho_{\rm avg} - \delta_{\rm CP})$ and $(\rho_{\rm avg} - \theta_{23})$ **planes**

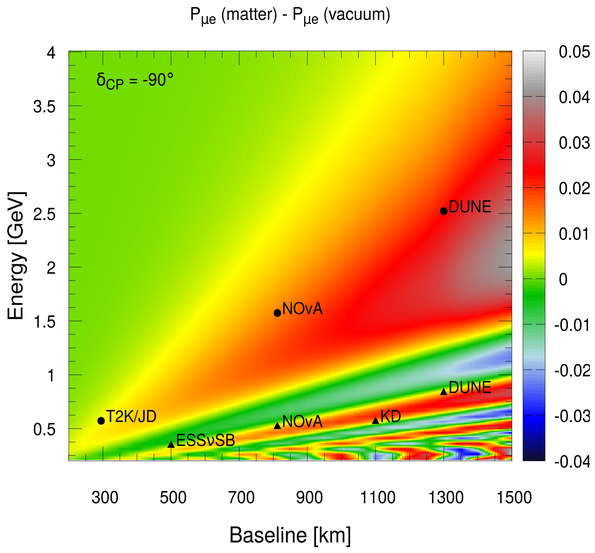
To lift these degeneracies, data from the upcoming T2HK (JD) and T2HKK (KD) are incorporated.

2. Matter vs. Vacuum

- $\Delta P \approx [P^{\rm mat}_{\nu_\mu \to \nu_e} - P^{\rm vac}_{\nu_\mu \to \nu_e}]_{\rm leading\ term}$
- Expanding $(1-\hat{A})^{-2}$ and considering terms upto second order in $\hat{A}$:

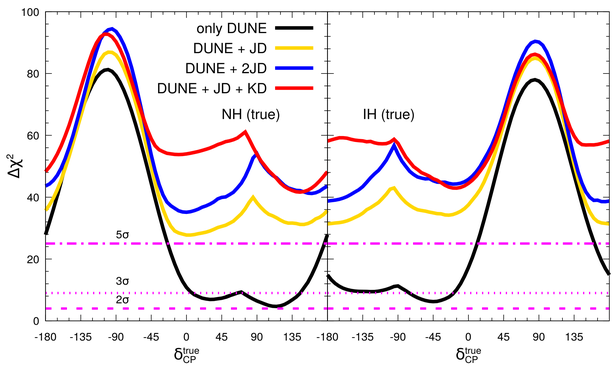
$$\Delta P = \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13}\Big[(3\hat{A}^2 + 2\hat{A} - 1) + \cos[(2n+1)\pi\hat{A}](3\hat{A}^2 + 2\hat{A} + 1)\Big],$$

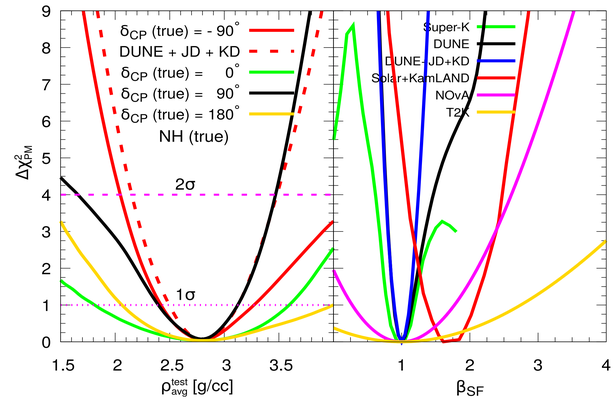
$$\hat{A} = \left(\frac{0.76\times10^{-4}({\rm eV}^2)}{\Delta m^2_{31}}\right)\times\left(\frac{\rho_{\rm avg}}{{\rm g/cm^3}}\right)\times\left(\frac{\rm E}{\rm GeV}\right).$$



ΔP as a function of baseline and neutrino energy [1]. Solid circle (triangle) shows ΔP at first (second) oscillation maxima.

3. Our Findings

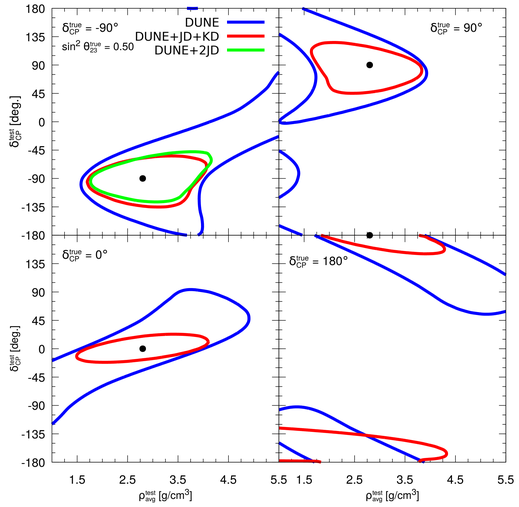




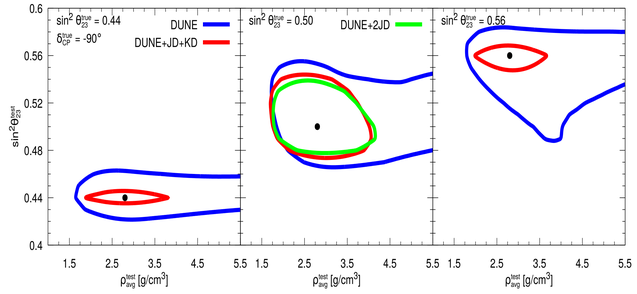
- **Establishing Earth matter effect**
- Capability of different set-ups to exclude vacuum solution as a function of $\delta^{\rm true}_{\rm CP}$ at maximal $\theta^{\rm true}_{23}$. True NH (IH) in left (right) panel.
- At 5σ C.L. : vacuum is excluded $\sim 46\%$ for CP phases in DUNE, while $\sim 100\%$ in combined set-ups.

- **Precision in $\rho_{\rm avg}$**
- Left panel : Relative 1σ precision in $\rho_{\rm avg}$ in DUNE is 15% (13%) for $\delta^{\rm true}_{\rm CP}$ = -90° (90°) while in DUNE + JD + KD, it is 23% for $\delta^{\rm true}_{\rm CP}$ = -90° with true NH.
- Right panel : If $\delta^{\rm true}_{\rm CP}$ = -90°/90°, DUNE is better than Solar + KamLAND [2], Super-K [3], and ongoing T2K, NOνA.
- Combined data from DUNE and T2HKK achieves the best precision.

- **Exploring the degeneracies**



Allowed region in $\rho^{\rm test}_{\rm avg} - \delta^{\rm test}_{\rm CP}$ plane at 3σ (1 d.o.f.) for four different choices of $\delta^{\rm true}_{\rm CP}$ in DUNE (blue), DUNE+JD+KD(red).



- Allowed region in $\rho^{\rm test}_{\rm avg} - \theta^{\rm test}_{23}$ plane at 3σ (1 d.o.f.) for $\delta^{\rm true}_{\rm CP}$ = -90°
- Uncertainty in $\rho^{\rm test}_{\rm avg}$ is not much affected by choices of $\sin^2\theta_{23}$, but is significantly dependent on the uncertainty in $\delta_{\rm CP}$.
- Complementarity between DUNE and T2HKK helps in incredibly reducing the degenracies in both the planes.

4. Key Takeaways

- **Irrespective of the values of oscillation parameters, DUNE establishes Earth's matter at more than 2σ C.L.**
- **Combined data from DUNE and T2HKK enhances** this measure to **more than 5σ C.L. no matter what the choices of mass ordering, $\delta_{\rm CP}$, and θ_{23}.**
- If in Nature, **$\delta^{\rm true}_{\rm CP}$ = -90°/90°, DUNE + T2HKK followed by DUNE outperforms Super-K, solar+KamLAND and other long-baseline (T2K and NOνA) experiments in measuring $\rho_{\rm avg}$**
- **Understanding the degeneracies in $(\rho_{\rm avg} - \delta_{\rm CP})$ and $(\rho_{\rm avg} - \theta_{23})$ planes are crucial to correctly assess the outcome of DUNE.**
- **Complementarity between DUNE and T2HKK data significantly minimizes dependency of $\rho_{\rm avg}$ on the uncertainties of $\delta_{\rm CP}$ and θ_{23}.**

5. References

[1] Masoom Singh *et al.* Matter effect and associated degeneracies in DUNE. *IP/BBSR/2020-1* (2020).

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[3] K.Abe *et al.* Phys.Rev., D97(7):072001, 2018

6. Acknowledgement

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