Issues Related to Matter Effect in DUNE

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Motivation

- The Earth matter effect felt by neutrinos and antineutrinos while travelling a distance of 1300 km plays an important role in determining mass hierarchy, CP violation and high-precision measurement of mixing angles.
  Therefore we ask:
- How much senstivity DUNE has towards Earth's matter effect.
- What precision information DUNE reveal about the line-averaged constant Earth matter density ($\rho_{\rm avg}$) along its trajectory.
- Understanding new degeneracies in the $[\rho_{\rm avg} - \delta_{\rm CP}]$ and $[\rho_{\rm avg} - \sin^2\theta_{23}]$ planes.

$\nu_\mu \to \nu_e$ transition in matter

$$P^{\rm mat}_{\nu_\mu\to\nu_e} \simeq \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2}}_{\rm leading} + \underbrace{\alpha^2\cos^2\theta_{23}\sin^2 2\theta_{12}\frac{\sin^2\hat{A}\Delta}{\hat{A}^2}}_{\rm least}$$

$$+ \underbrace{\alpha\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\frac{\sin(\hat{A}\Delta)}{\hat{A}}\frac{\sin[(1-\hat{A})\Delta]}{1-\hat{A}}\cos(\Delta+\delta_{\rm CP})}_{\rm sub-leading}$$

where $\alpha = \Delta m^2_{21}/\Delta m^2_{31}$, $\Delta \equiv \frac{\Delta m^2_{31}L}{4E}$, $\hat{A} \equiv \frac{A}{\Delta m^2_{31}}$, where $A = 2\sqrt{2}G_F N_e E$ is the matter potential.
Also

$$\hat{A} = \left(\frac{0.76\times 10^{-4}({\rm eV}^2)}{\Delta m^2_{31}}\right)\times\left(\frac{\rho_{\rm avg}}{{\rm g/cm^3}}\right)\times\left(\frac{\rm E}{\rm GeV}\right).$$

E.K.Akhmedov, R.Johansson, M.Lindner, T.Ohlsson, T.Schwetz, JHEP 0404 (2004)078

$\nu_\mu \to \nu_e$ transition in vacuum

In the limit $\hat{A} \to 0$,

$$P^{\rm vac}_{\nu_\mu \to \nu_e} \simeq \underbrace{\sin^2\theta_{23}\sin^2 2\theta_{13}\sin^2\Delta}_{\rm leading} + \underbrace{\cos^2\theta_{23}\sin^2 2\theta_{12}\sin^2(\alpha\Delta)}_{\rm least}$$
$$+ \underbrace{(\alpha\Delta)\sin 2\theta_{13}\cos\theta_{13}\sin 2\theta_{12}\sin 2\theta_{23}\sin\Delta\cos(\Delta+\delta_{\rm CP})}_{\rm sub-leading}.$$

E.K.Akhmedov, R.Johansson, M.Lindner, T.Ohlsson, T.Schwetz, JHEP 0404 (2004)078

We define:-

$$\Delta P = (P^{\rm mat}_{\nu_\mu \to \nu_e})_{\rm leading} - (P^{\rm vac}_{\nu_\mu \to \nu_e})_{\rm leading}$$
$$= \sin^2\theta_{23}\sin^2 2\theta_{13}\left[\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} - \sin^2\Delta\right].$$

Difference in $\nu_\mu \to \nu_e$ transition

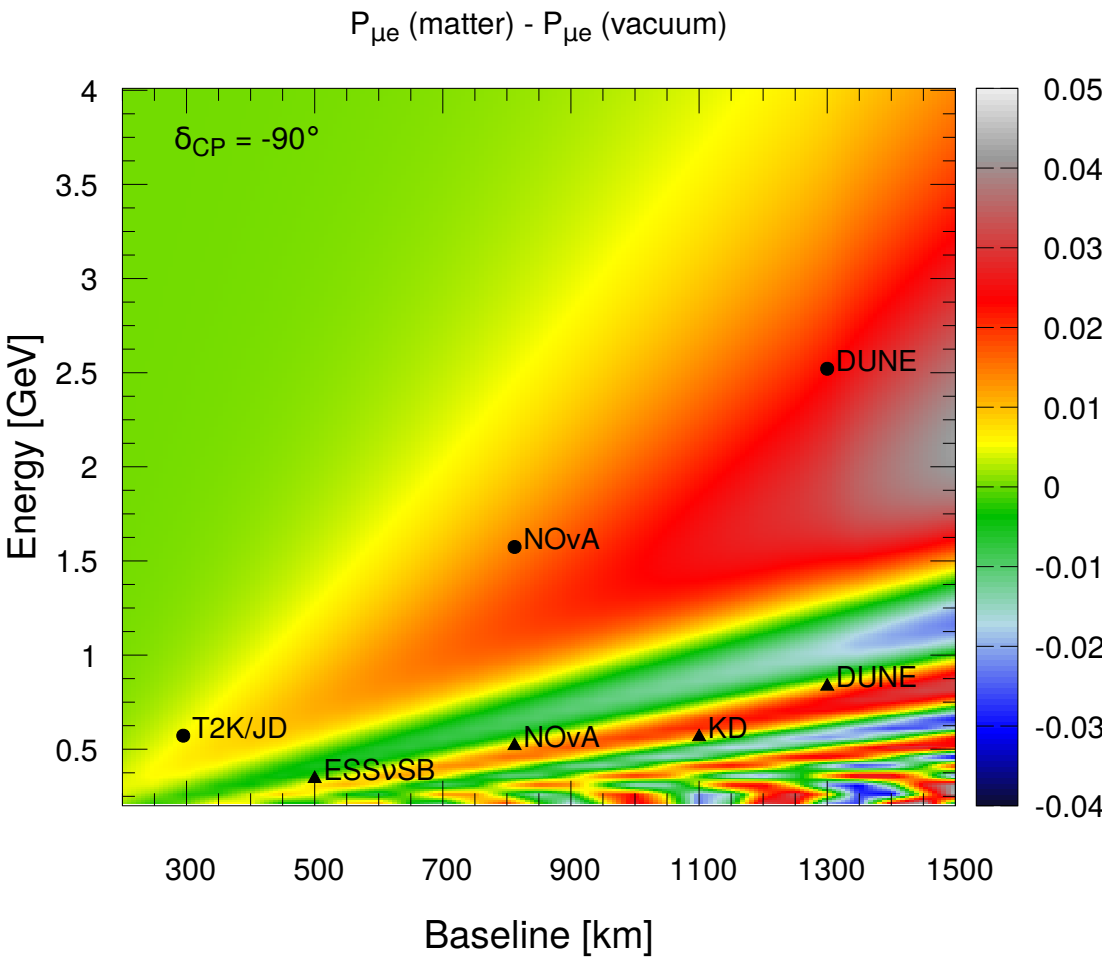
$$\Delta P = \sin^2\theta_{23}\sin^2 2\theta_{13}\left[\frac{\sin^2[(1-\hat{A})\Delta]}{(1-\hat{A})^2} - \sin^2\Delta\right].$$

As $\hat{A} << 1$, it can be simplified by binomially expanding $(1-\hat{A})^{-2}$, considering upto second order in $\hat{A}$

$(\mathbf{P}^{\rm mat}_{\nu_\mu\to\nu_e})_{\rm leading} - (\mathbf{P}^{\rm vac}_{\nu_\mu\to\nu_e})_{\rm leading}$

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

Matter vs Vacuum Oscillation Probability

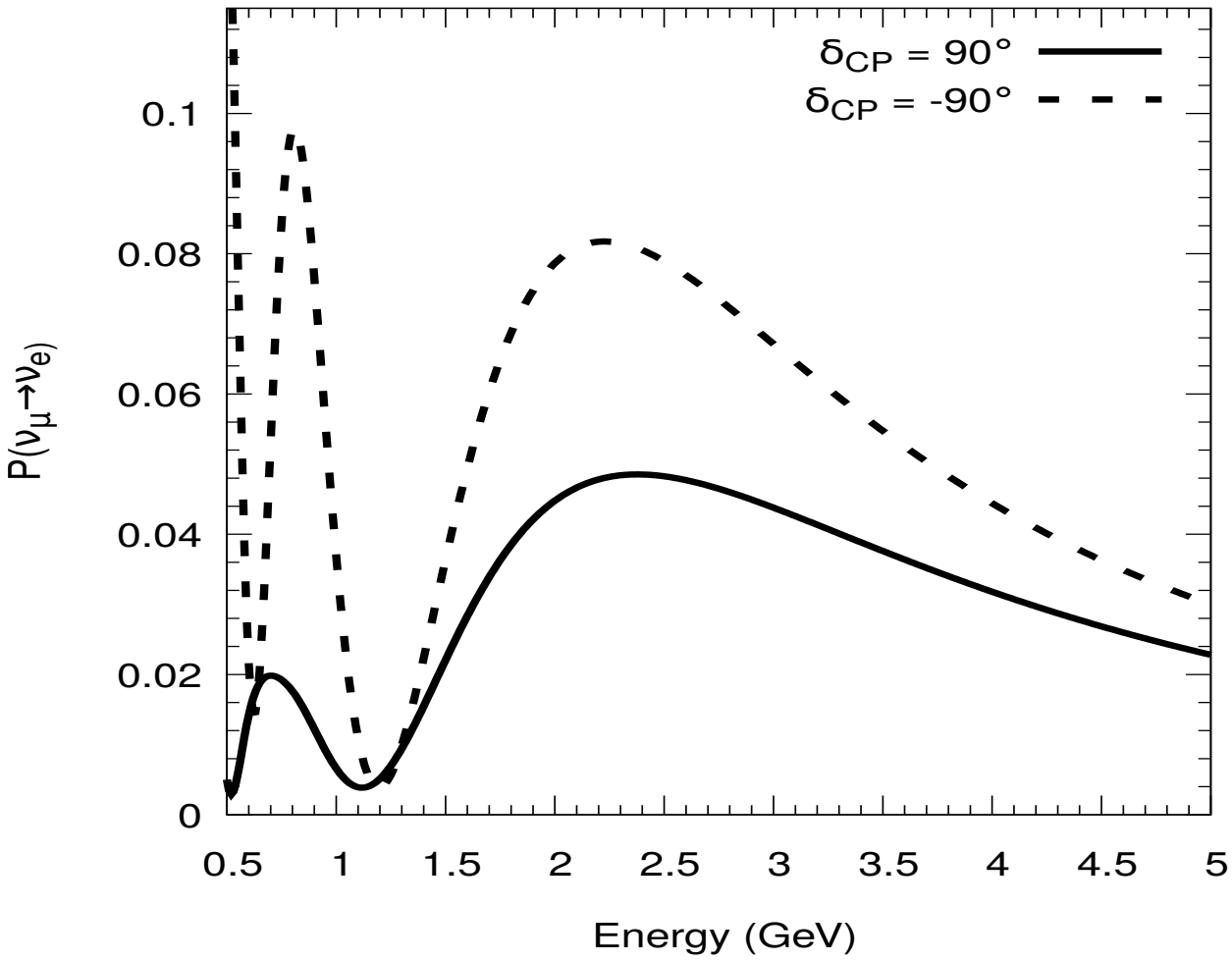


- $\theta_{23} = 45^\circ$, $\Delta m^2_{31} = 2.5 \times 10^{-3}$ eV^2, $\theta_{13} = 8.56^\circ$
- Full 3ν-flavor paradigm taken for numerical simulation
- Analytical:-

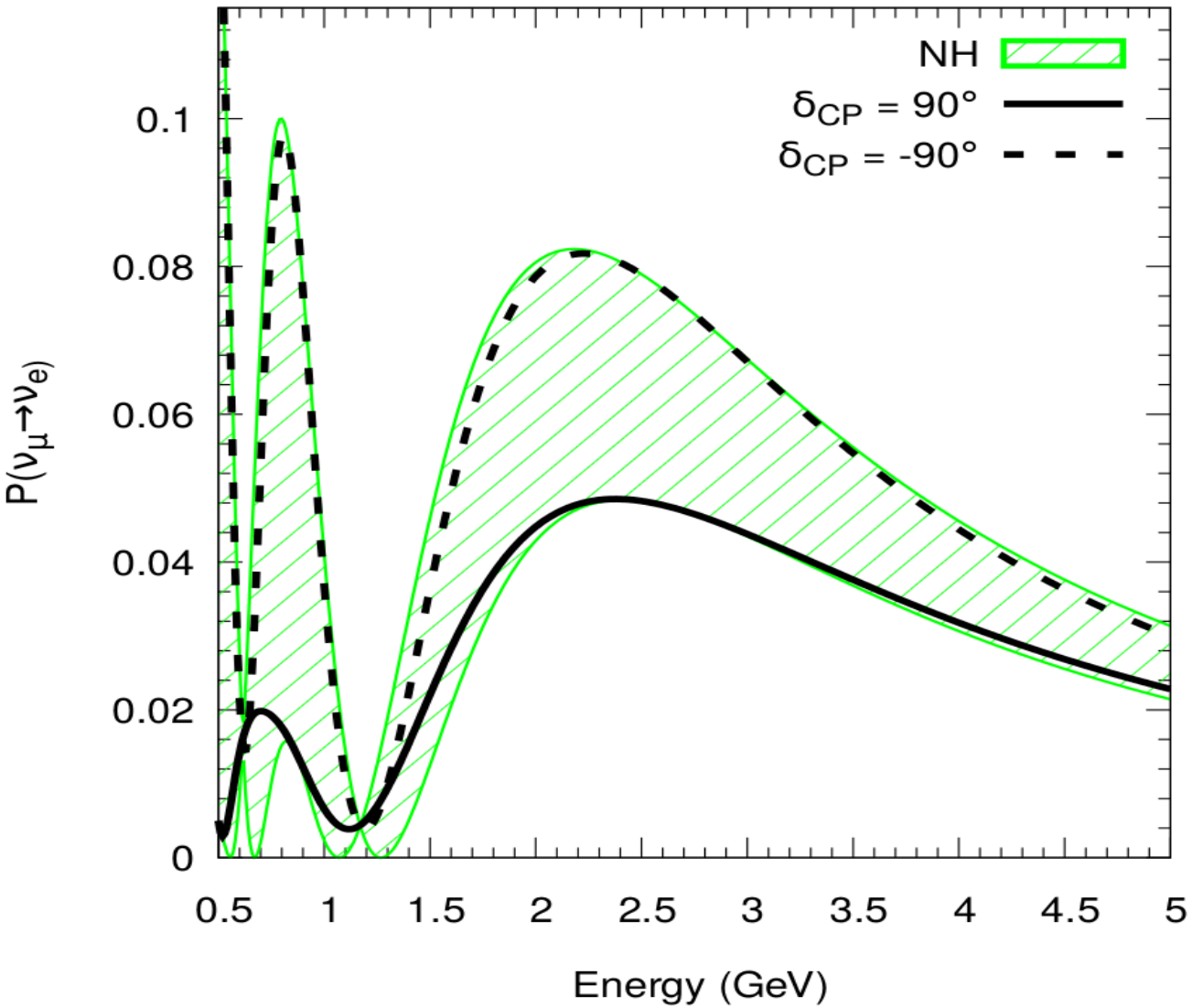
$$\Delta P = \frac{1}{2}\sin^2\theta_{23}\sin^2 2\theta_{13}[(3\hat{A}^2 + 2\hat{A} - 1) + \cos[(2n+1)\pi\hat{A}](3\hat{A}^2 + 2\hat{A} + 1)]$$

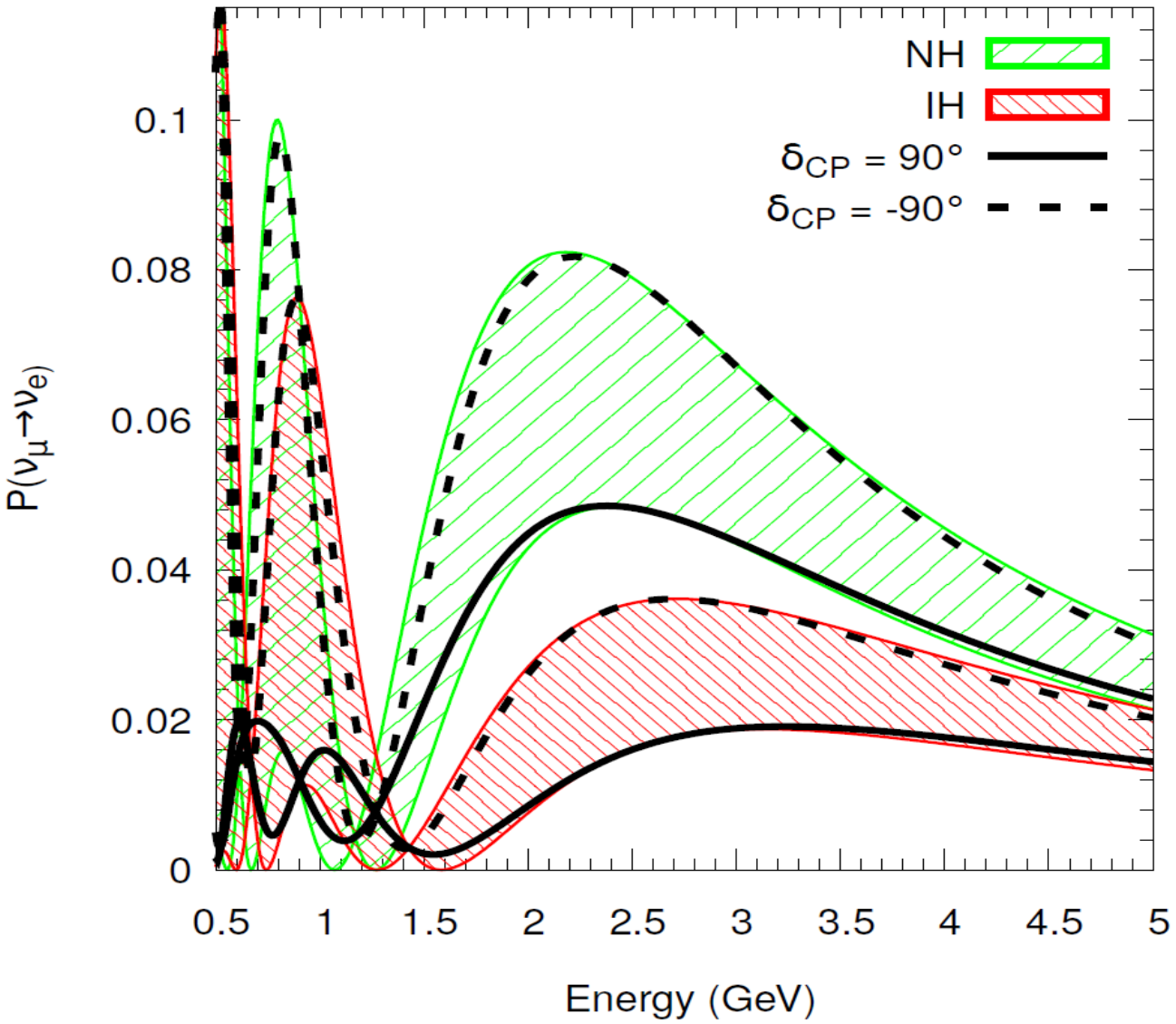
Facility	Energy (GeV)	$\hat{A}$	ΔP	
			Analytical	Numerical
DUNE	2.52(0.84)	0.219(0.073)	0.0258(0.0215)	0.0214(0.0213)

NuFIT 4.0 (2018), www.nu-fit.org, JHEP 01 (2019) 106 [arXiv:1811.05487]

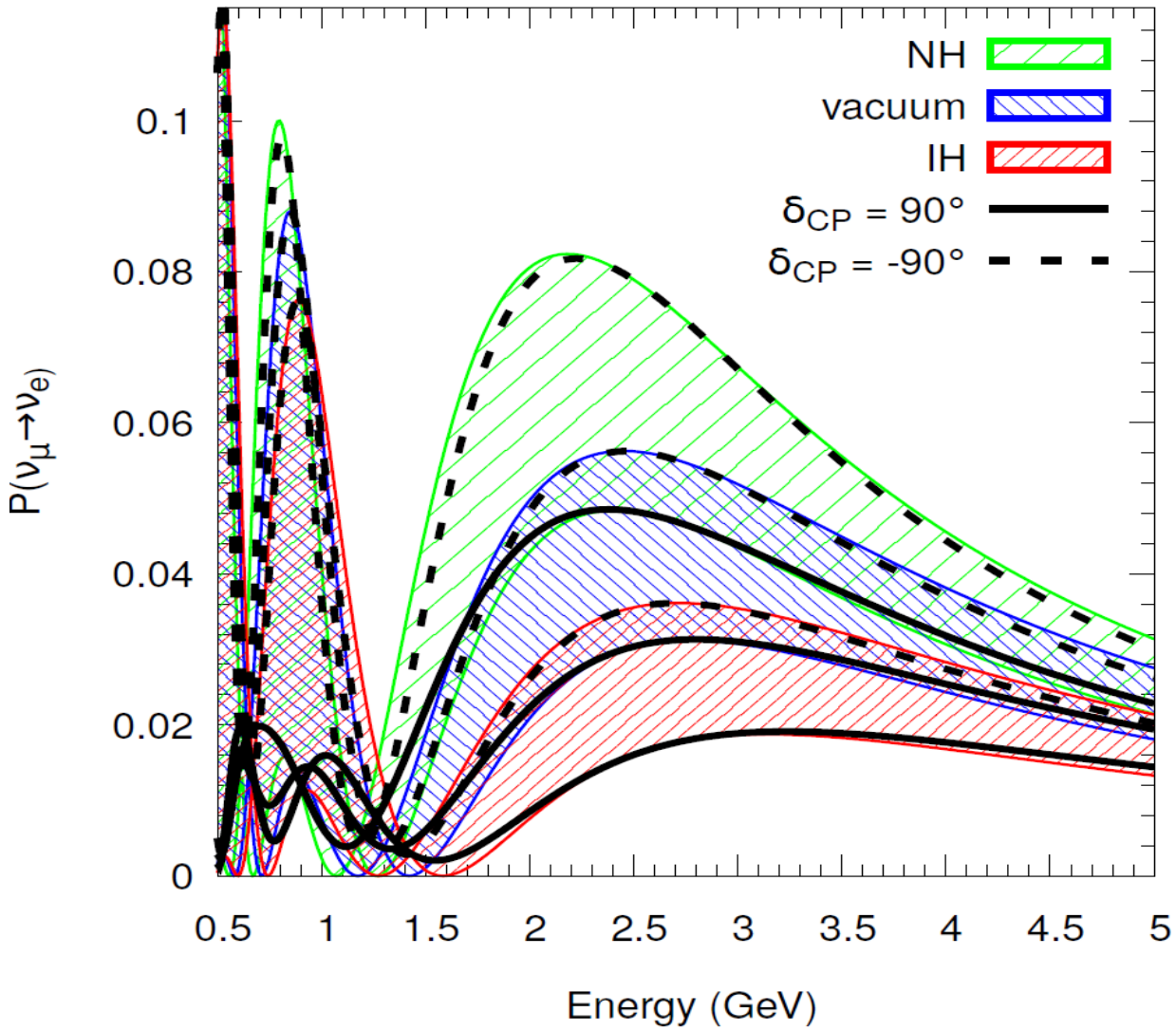

δCP = 90°
δCP = -90°
0.1
0.08
0.06
0.04
0.02
0
P(νμ→νe)
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Energy (GeV)

NH, L = 1300 km

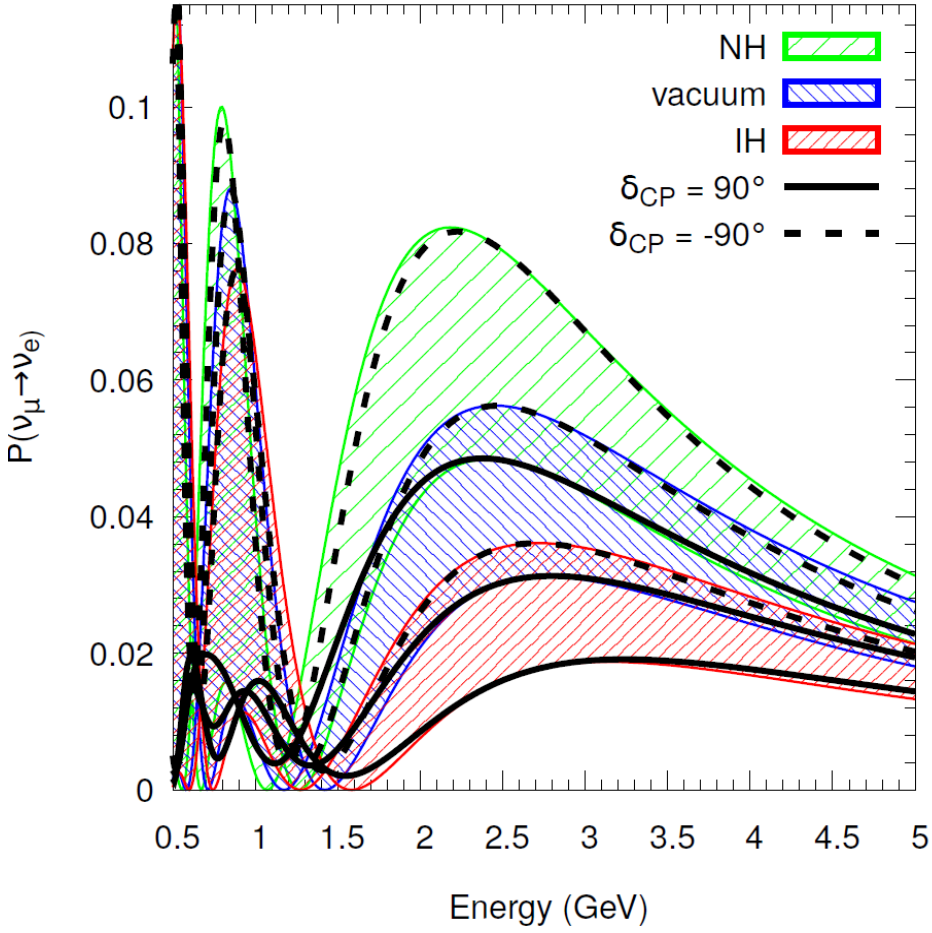

NH
δCP = 90°
δCP = -90°
P(νμ→νe)
0.1
0.08
0.06
0.04
0.02
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
5
Energy (GeV)

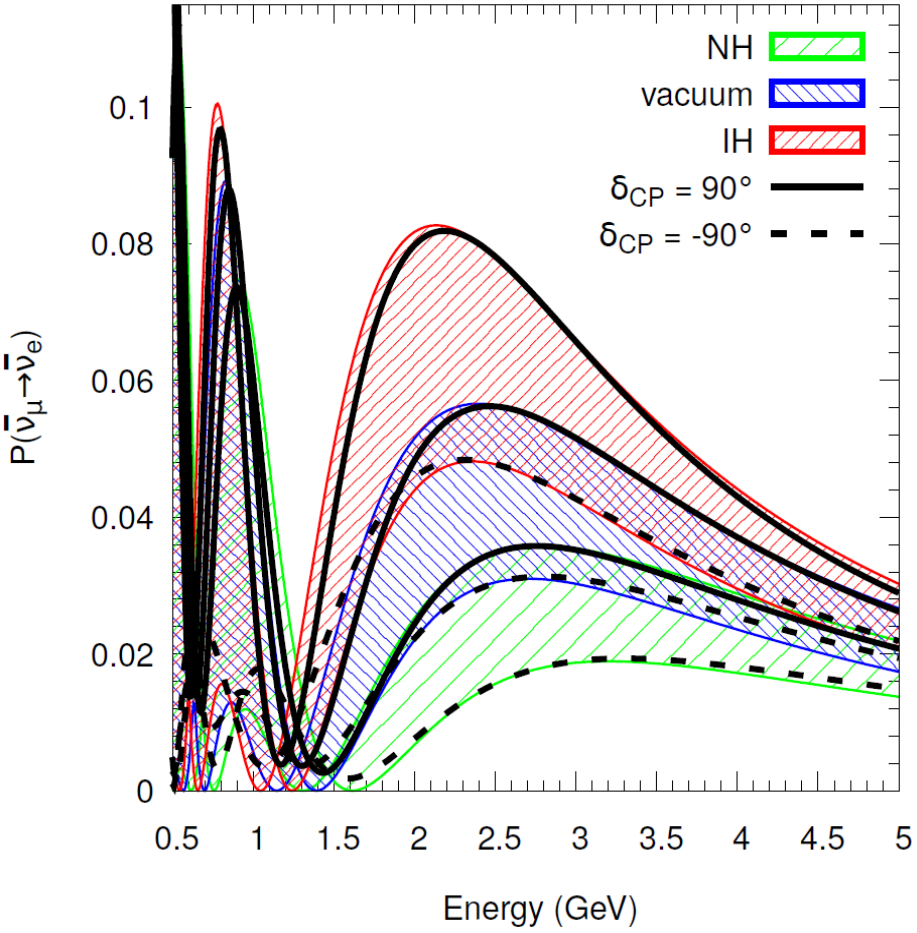


DUNE can very well differentiate between hierarchy.



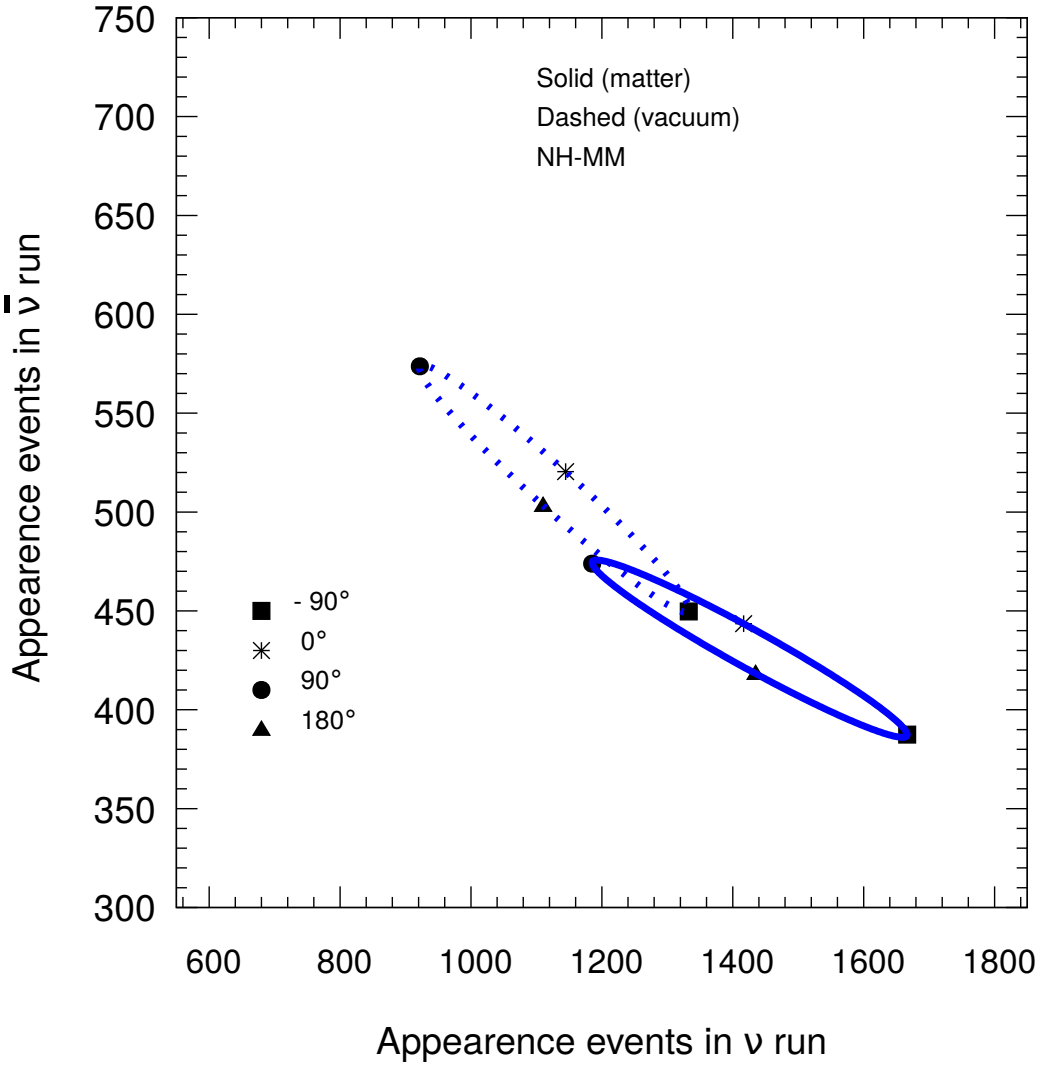
- Measuring Earth matter effect (differentiating between matter and vacuum solutions) in DUNE is much more difficult than determining hierarchy assuming matter solution.





Complementarity between ν and $\bar{\nu}$ modes will help to differentiate matter and vacuum oscillation in the unfavorable combinations of $\delta_{\rm CP}$ and θ_{23}.

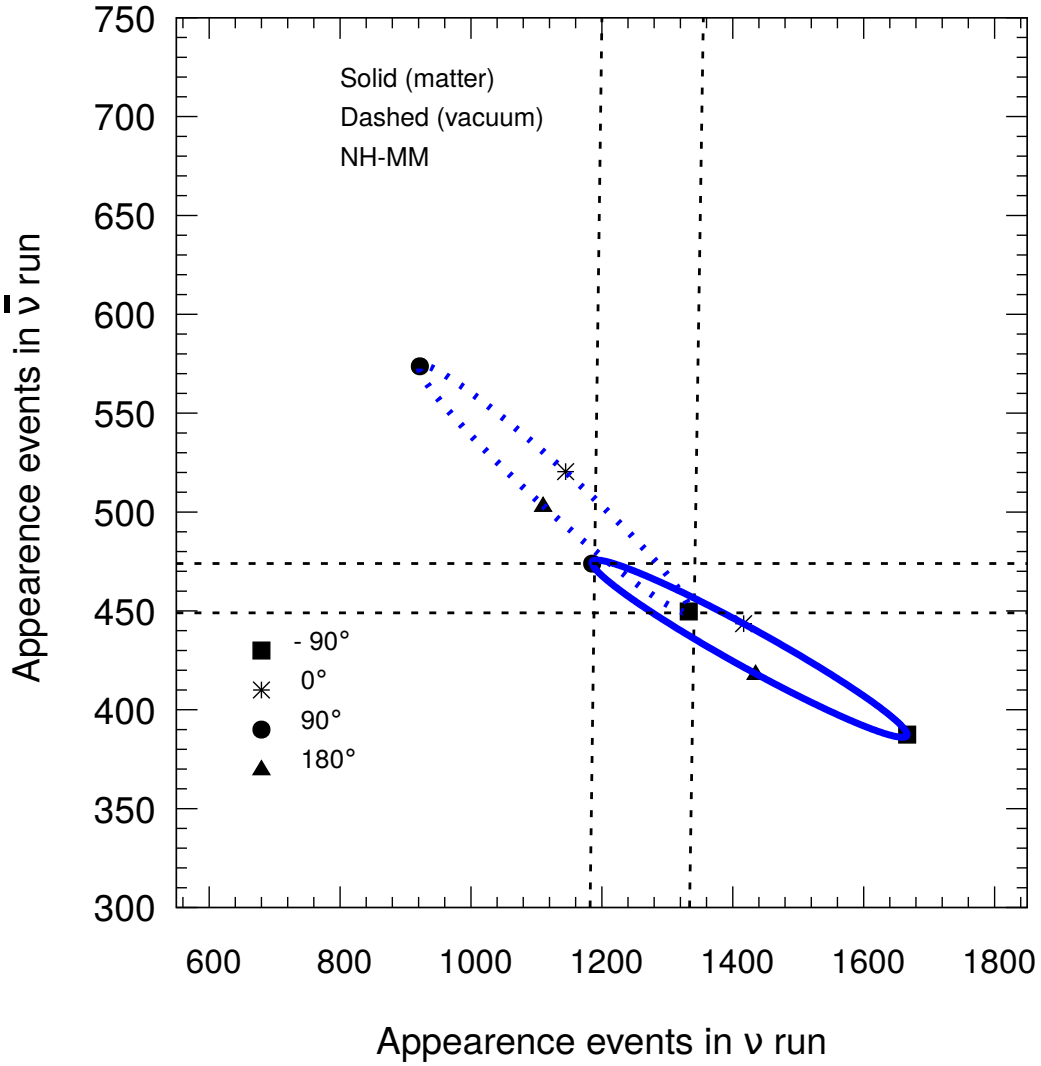
Bi-event analysis



Experimental Details

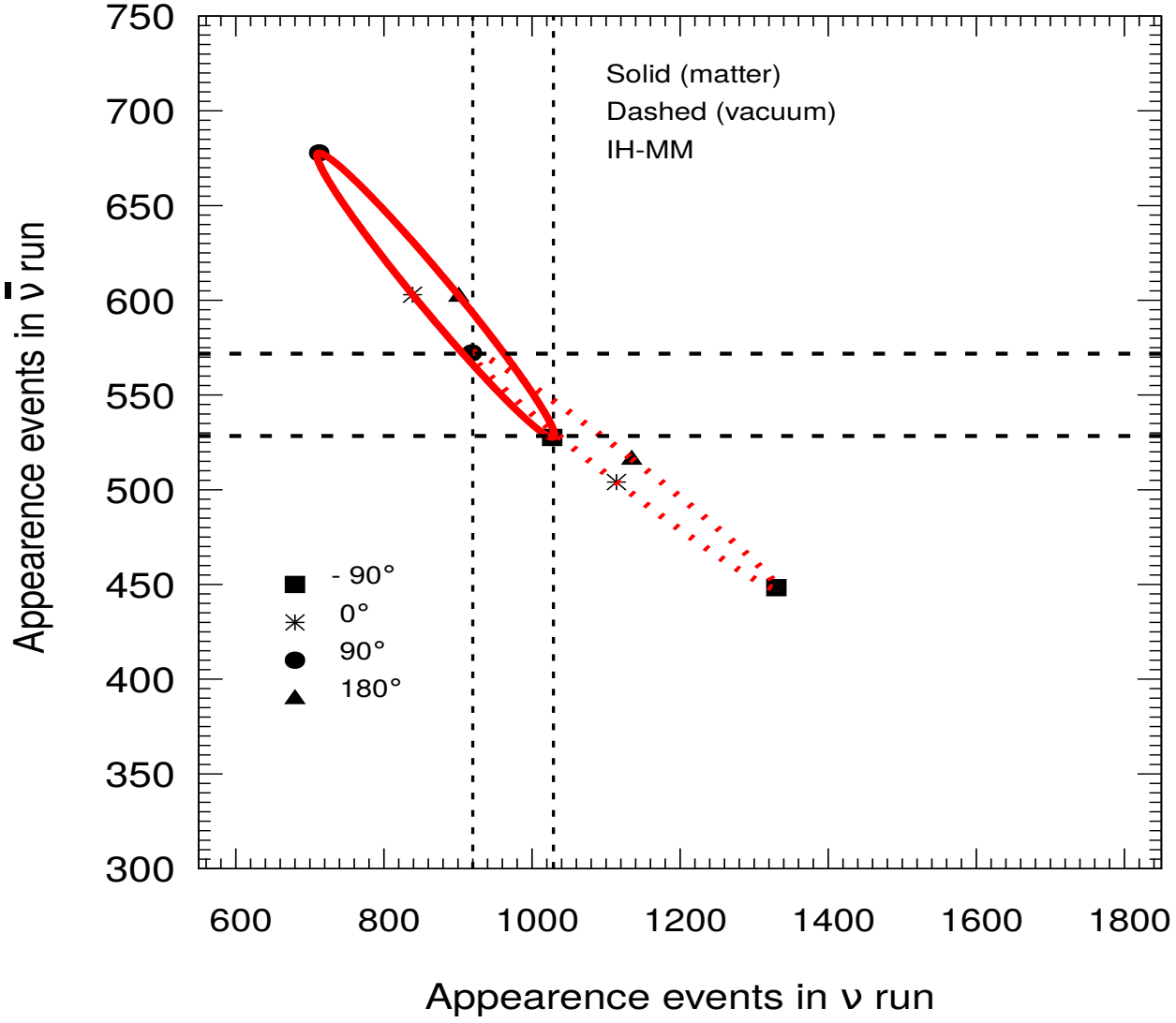
- 300 kt·MW·years of exposure
- Total run time of 7 years - $[3.5\ \nu + 3.5\ \bar{\nu}]$
- Toatal POT - 1.47×10^{21} per year.

Bi-event analysis

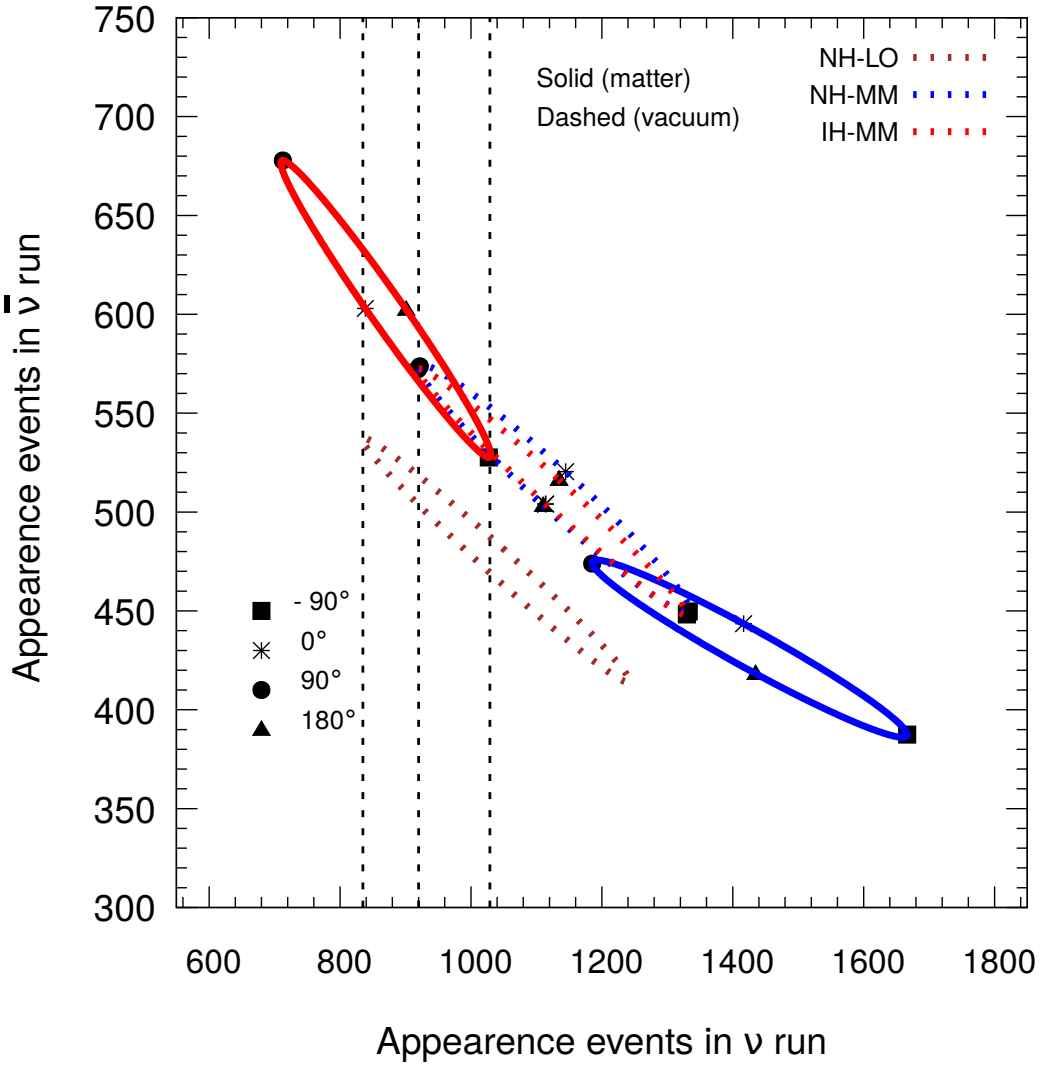


- For a given hierarchy, certain CP phases in matter overlap with certain CP phases in vacuum in both ν and $\bar{\nu}$ modes giving rise to $[\rho_{\rm avg} - \delta_{\rm CP}]$ degeneracy .

Bi-event analysis

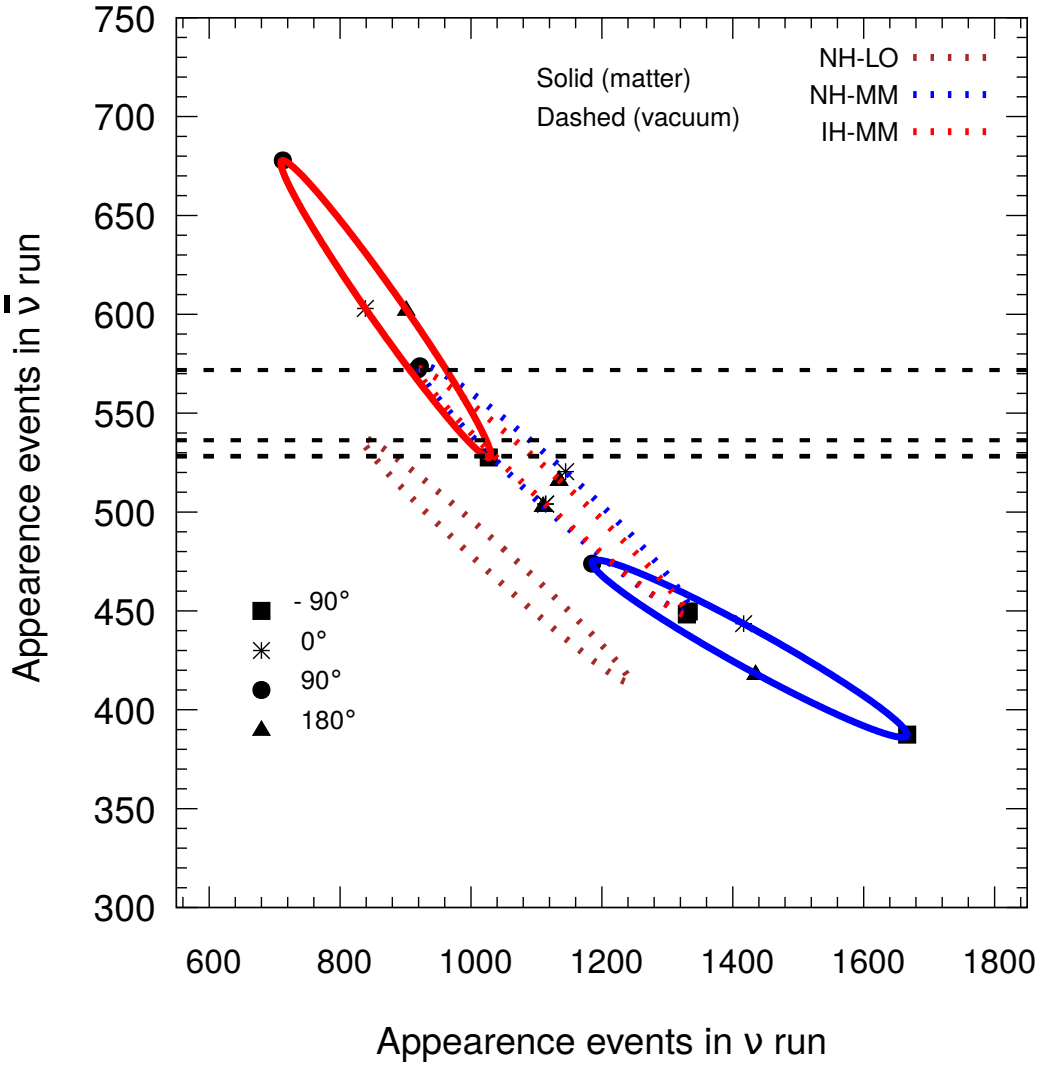


Bi-event analysis



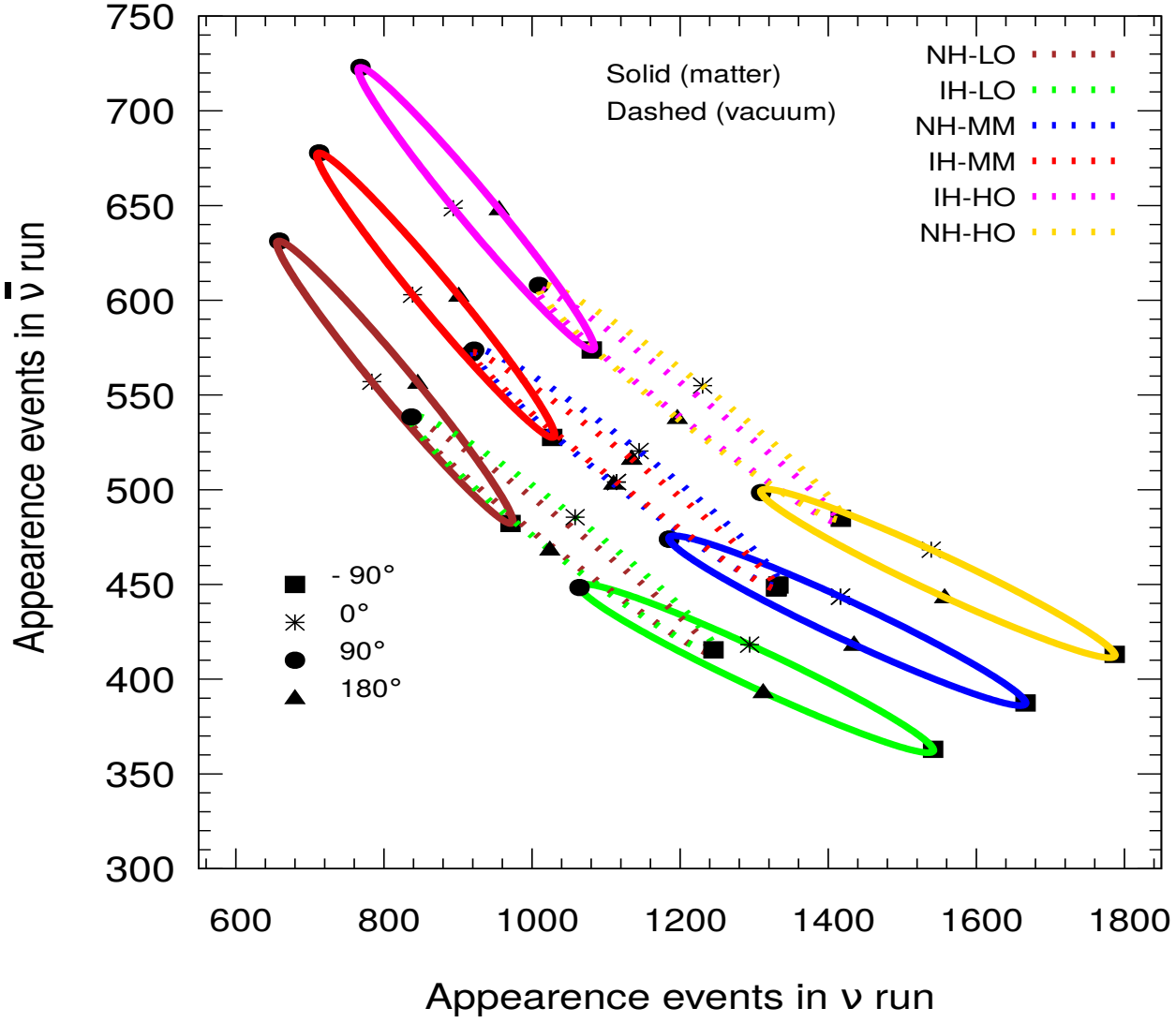
- For a given hierarchy, additional CP phases in matter with $\sin^2\theta_{23}$ =0.5 overlap with certain CP phases in vacuum with LO of $\sin^2\theta_{23}$ in ν mode, thus contributing to degeneracy in $[\rho_{\rm avg} - \sin^2\theta_{23}]$ plane

Bi-event analysis

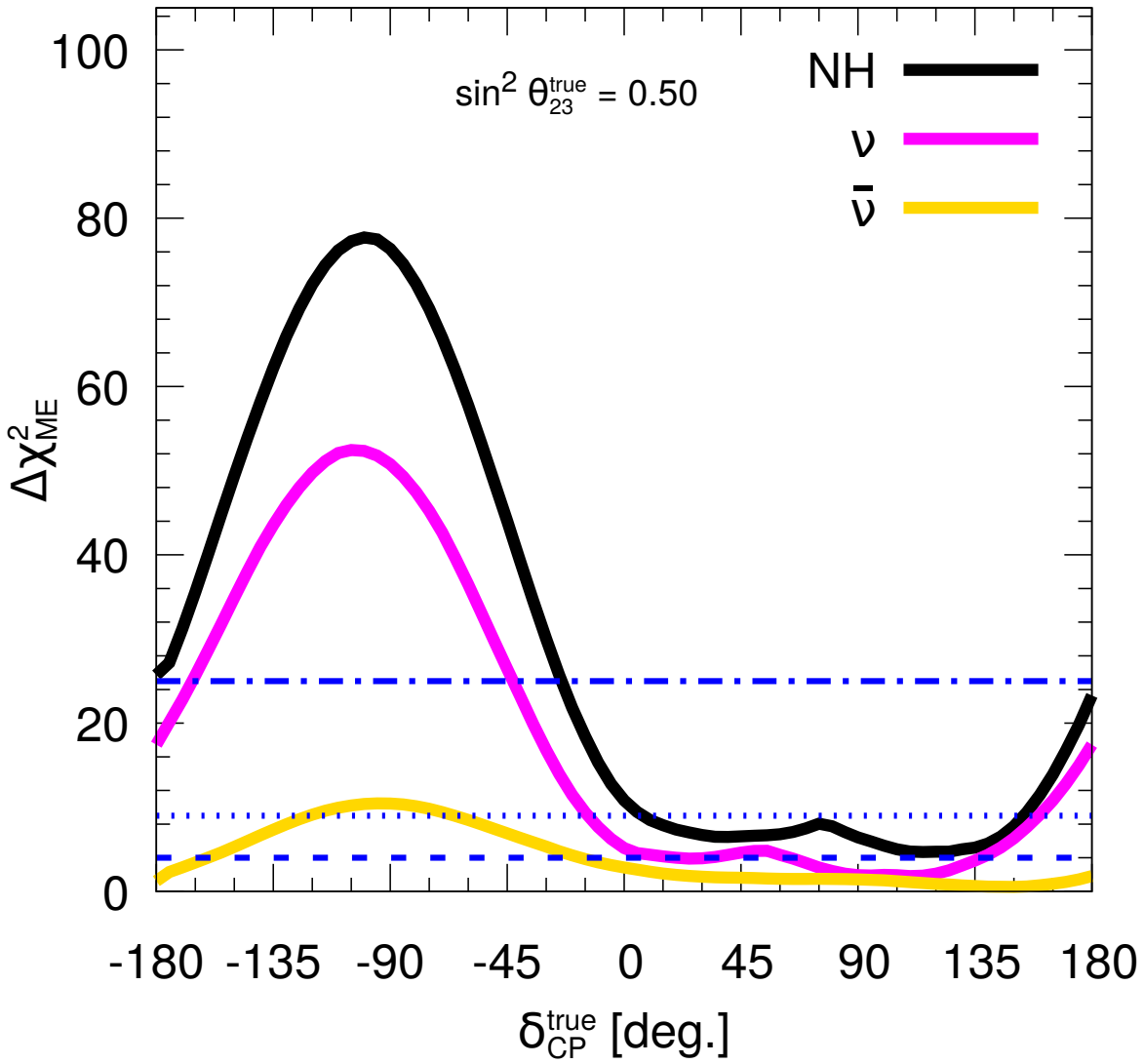


- Overlapping in $\bar{\nu}$ mode is not much. This complementarity between ν and $\bar{\nu}$ mode will help in establishing Earth matter in the unfavorable zone.

Bi-event analysis

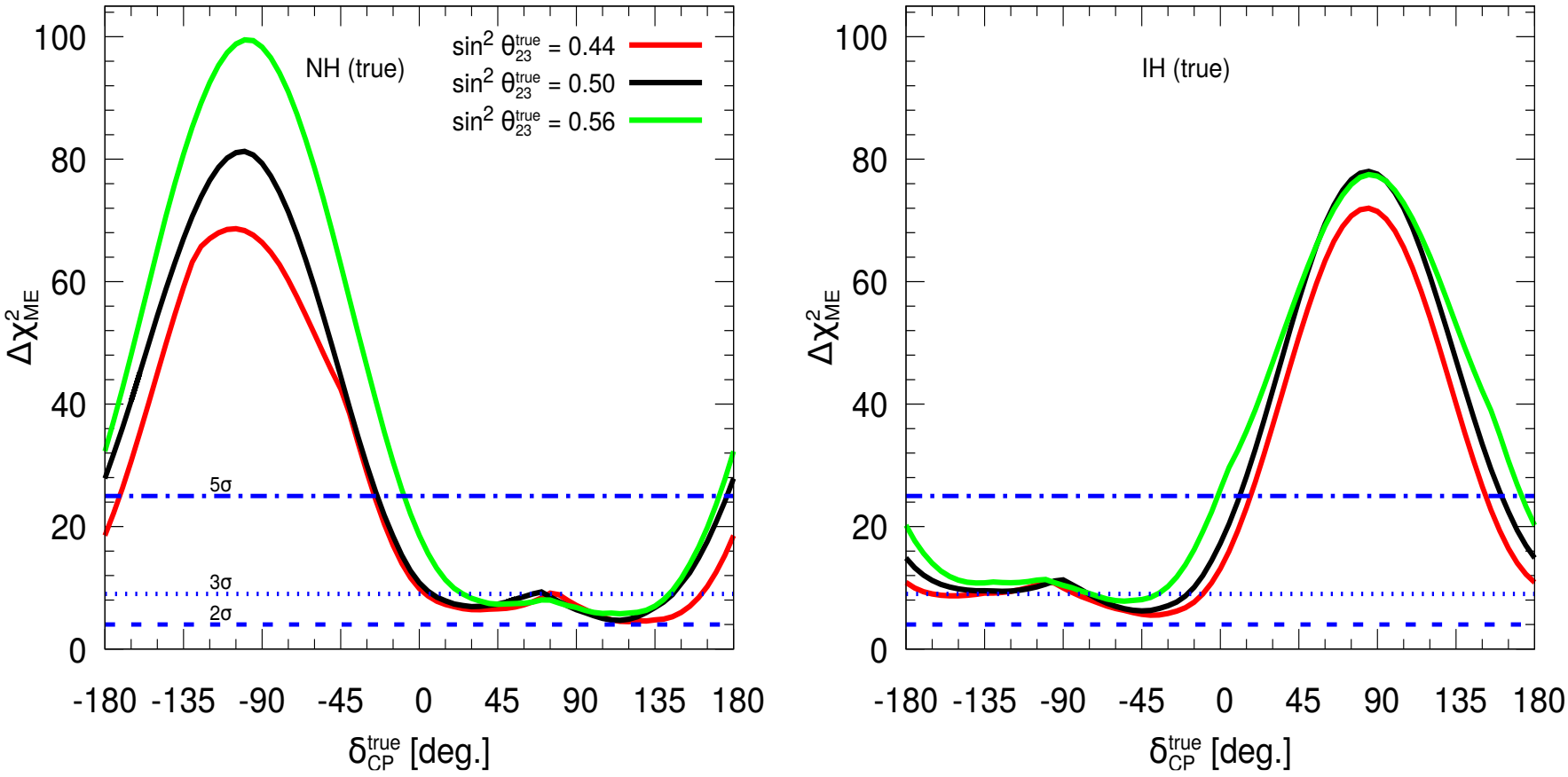


Sensitivity of DUNE in establishing Earth matter



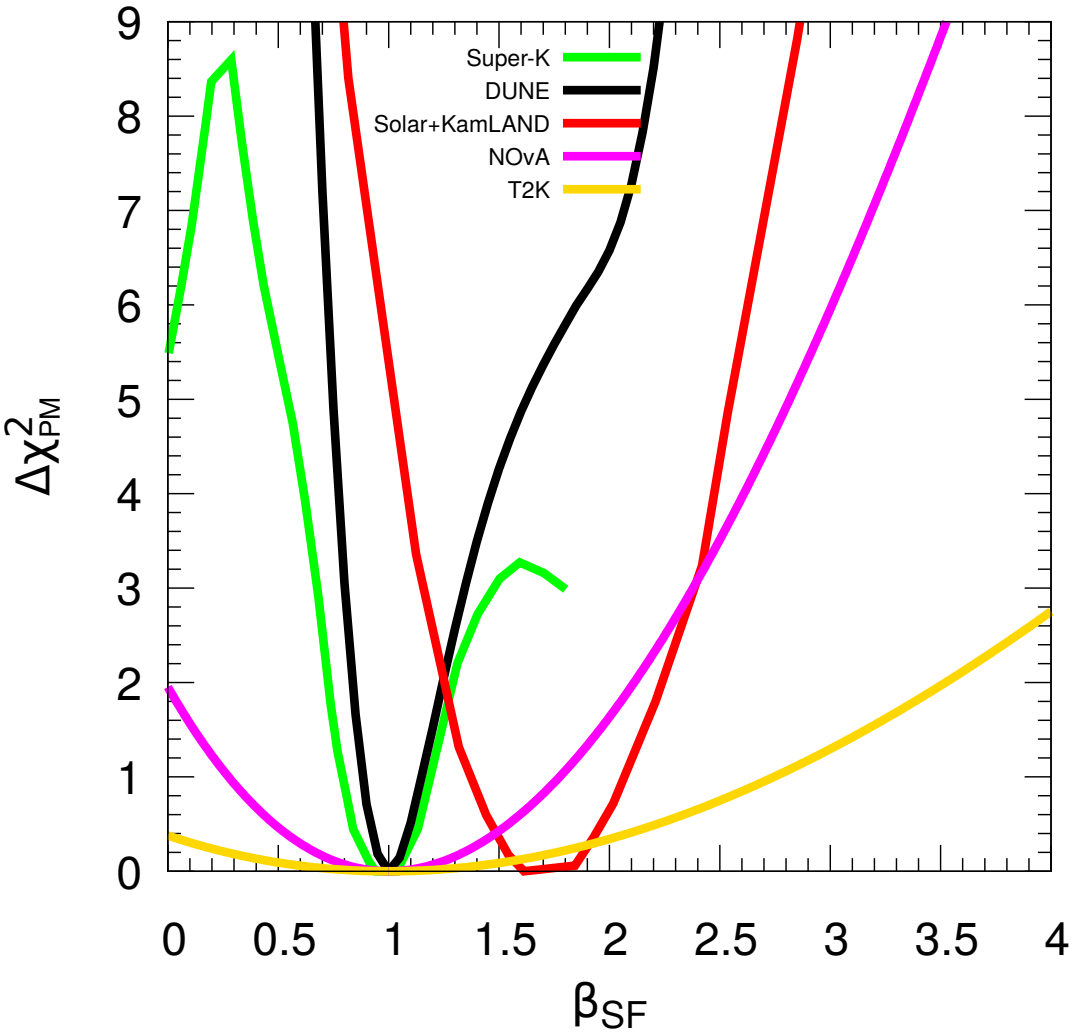
Non-zero $\Delta\chi^2_{\rm ME}$ in the unfavorable zone could be attained due to excellent energy resolution provided by the LArTPC detector technology.

Sensitivity of DUNE in establishing Earth matter



Irrespective of the choices of hierarchy, $\delta_{\rm CP}$, and θ_{23}, DUNE can confirm the presence of Earth's matter effect at 2σ

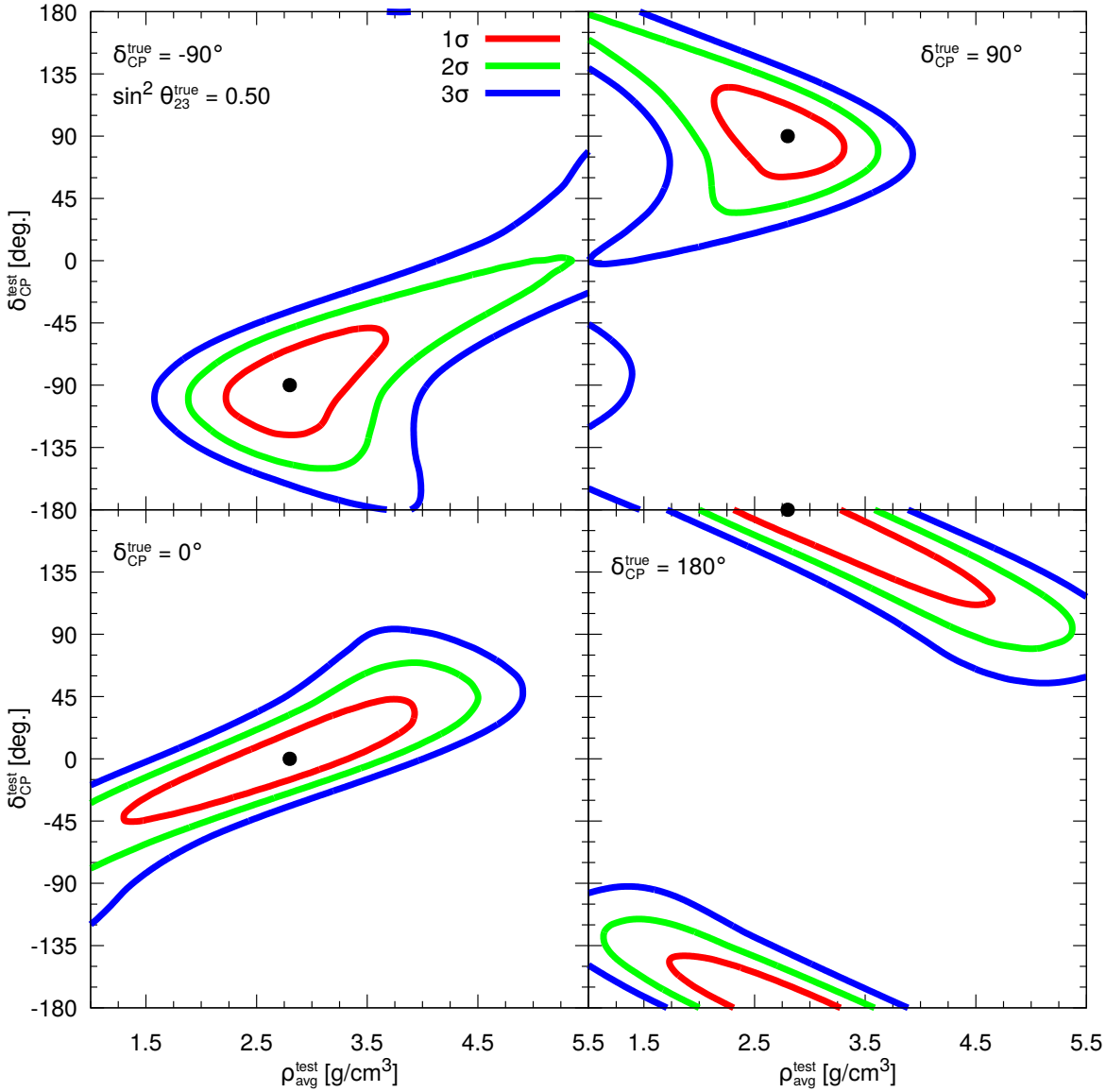
Comparing DUNE with other Experiments



$$\rho_{\rm avg} \rightarrow \beta_{SF} \cdot \rho_{\rm avg}$$

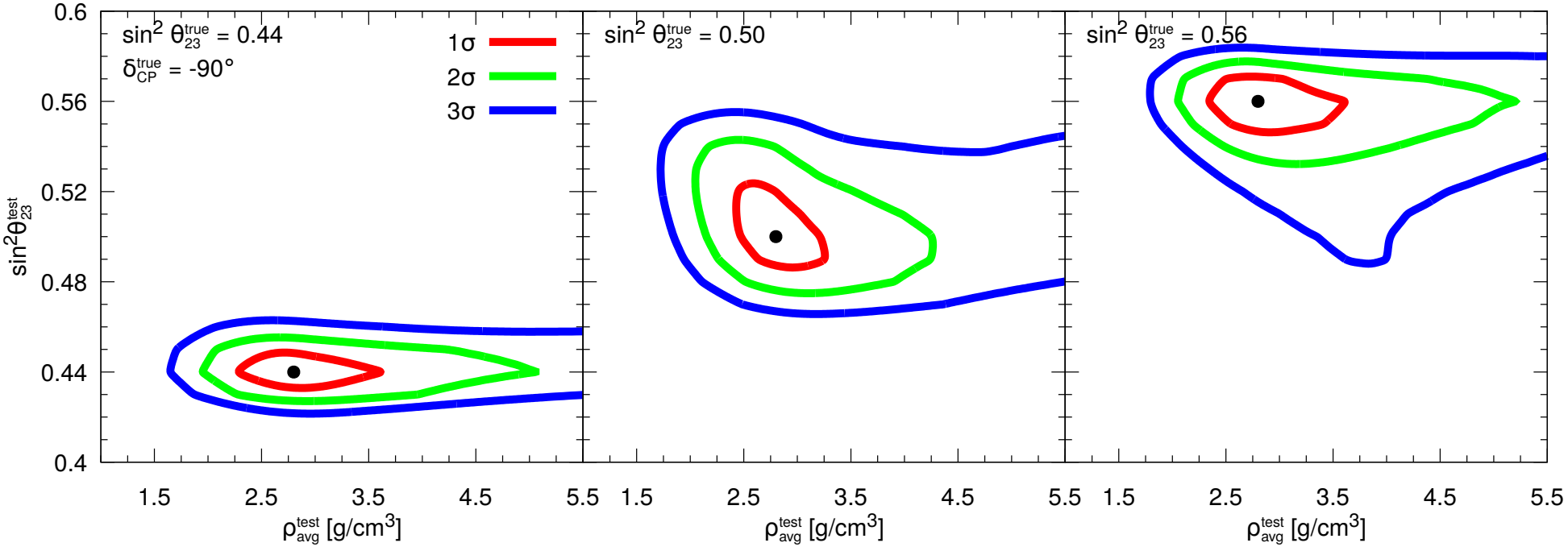
- Solar+KamLAND : Maltoni et al., *Eur.Phys.J.* A52 (2016), no. 487
- Super-Kamiokande : K. Abe et al., *Phys.Rev.* D97 (2018), no. 7 072001
- NOνA and T2K - full exposure, equally divided in $\nu + \bar{\nu}$
- Tension in the determination of Δm^2_{21} between Solar and KamLAND, shifts $\beta_{\rm SF}$ to 1.66 instead of 1 g/cm^3.
- $\delta_{\rm CP}^{\rm true} = -90^\circ$, $\sin^2\theta_{23} = 0.5$

Allowed region in $[\rho_{\rm avg} - \delta_{\rm CP}]$ plane



- Data generated with $\rho_{\rm avg}^{\rm true} = 2.86$ g/cm^3, fit is simulated by varying $\delta_{\rm CP}^{\rm test}$ and $\rho_{\rm avg}^{\rm test}$.
- Marginalized $\Delta\chi^2$ is obtained by doing minimization over $\sin^2\theta_{23}$ and Δm^2_{31}
- true NH and $\sin^2\theta_{23}^{\rm true} = 0.5$, exhibiting three C.L. at 1 d.o.f.

Allowed region in $[\rho_{\rm avg} - \sin^2\theta_{23}]$ plane



After comparing both the degeneracies, the uncertainty in $\delta_{\rm CP}$ affects the measurement of $\rho_{\rm avg}$ more than that of θ_{23}.

Concluding Remarks

- Irrespective of the values of oscillation parameter DUNE can establish Earth's matter effect at 2σ.
- Matter effect can be established at 3σ (5σ) with a $\delta_{\rm CP}$ coverage of 64% (46%) for NH, whereas for IH, it is 82% (43%) respectively.
- Achievable relative 1σ precision on $\rho_{\rm avg}$ at DUNE is 10% to 15% depending on true MH.
- If $\delta_{\rm CP}^{\rm true}$ = -90° /90° , DUNE outperforms Super-K, Solar+KamLAND and other long-baseline (T2K and NOνA) experiments in measuring $\rho_{\rm avg}$.
- Uncertainty in $\rho_{\rm avg}^{\rm test}$ is significantly dependent on $\delta_{\rm CP}$
- New degeneracies exist in $(\rho_{\rm avg}^{\rm test} - \delta_{\rm CP}^{\rm test})$ and $(\rho_{\rm avg}^{\rm test} - \sin^2\theta_{23}^{\rm test})$ planes.
- Understanding these degeneracies are crucial to correctly assess the outcome of DUNE.