DEGENERACIES IN PRESENCE OF INVISIBLE DECAY OF NEUTRINOS

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In collaboration with

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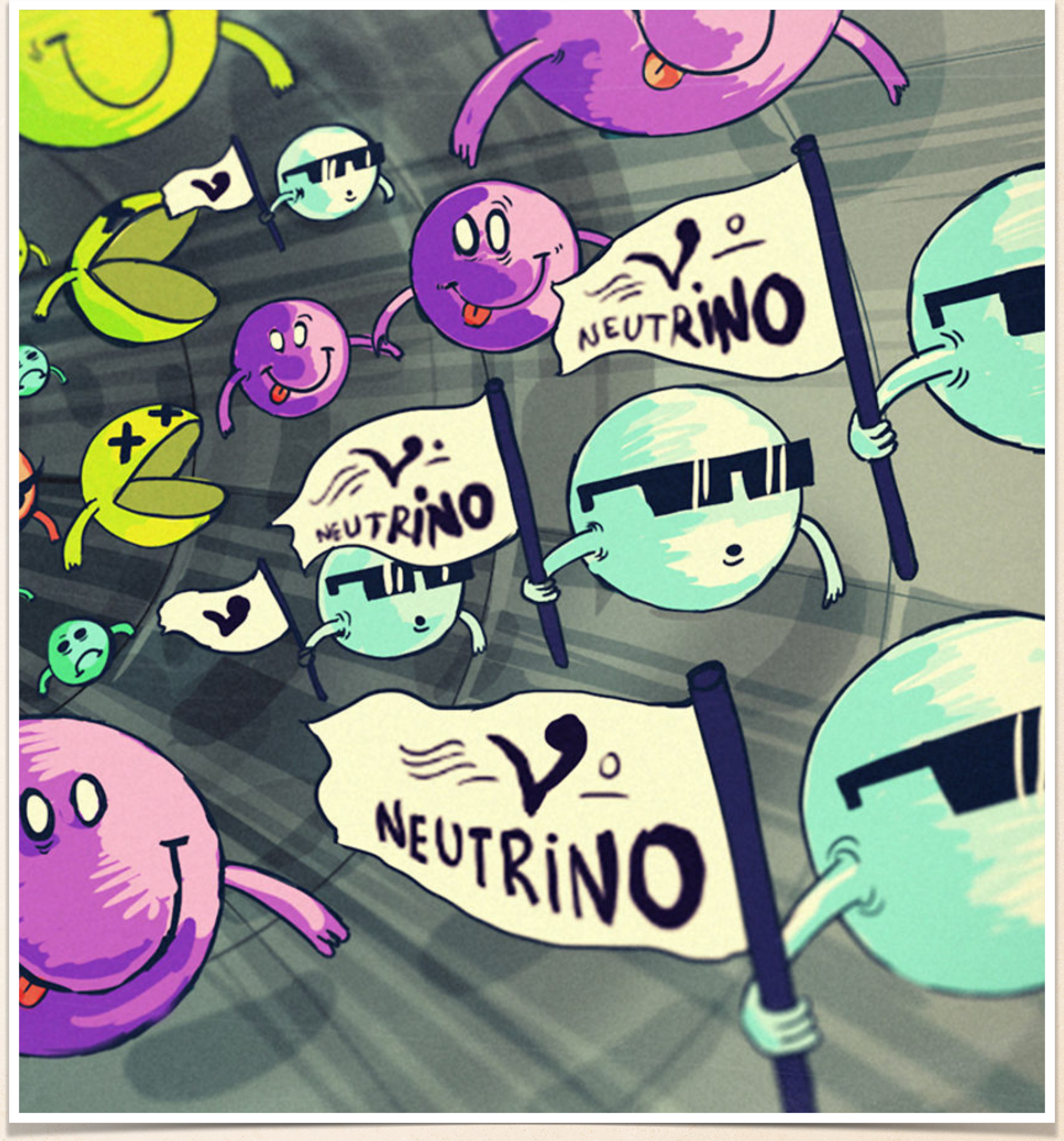
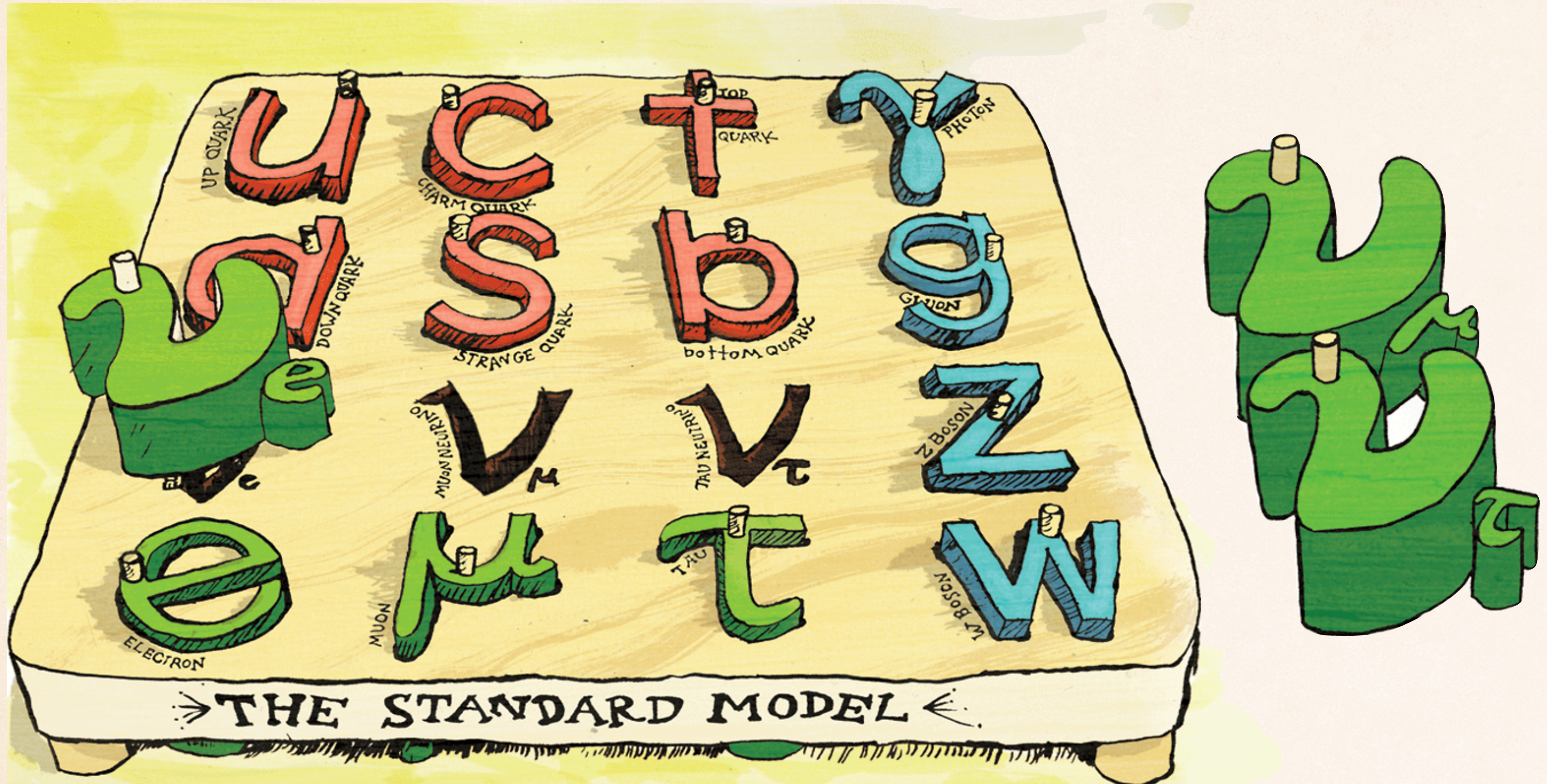


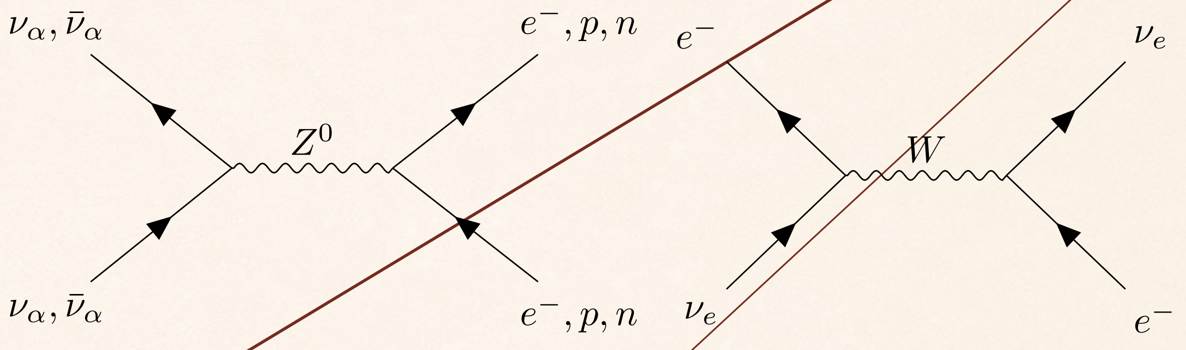
NEUTRINO OSCILLATION FRAMEWORK



Source: Internet

$$U = \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-\iota\delta_{13}} \\ 0 & 1 & 0 \\ -s_{13}e^{\iota\delta_{13}} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix}$$

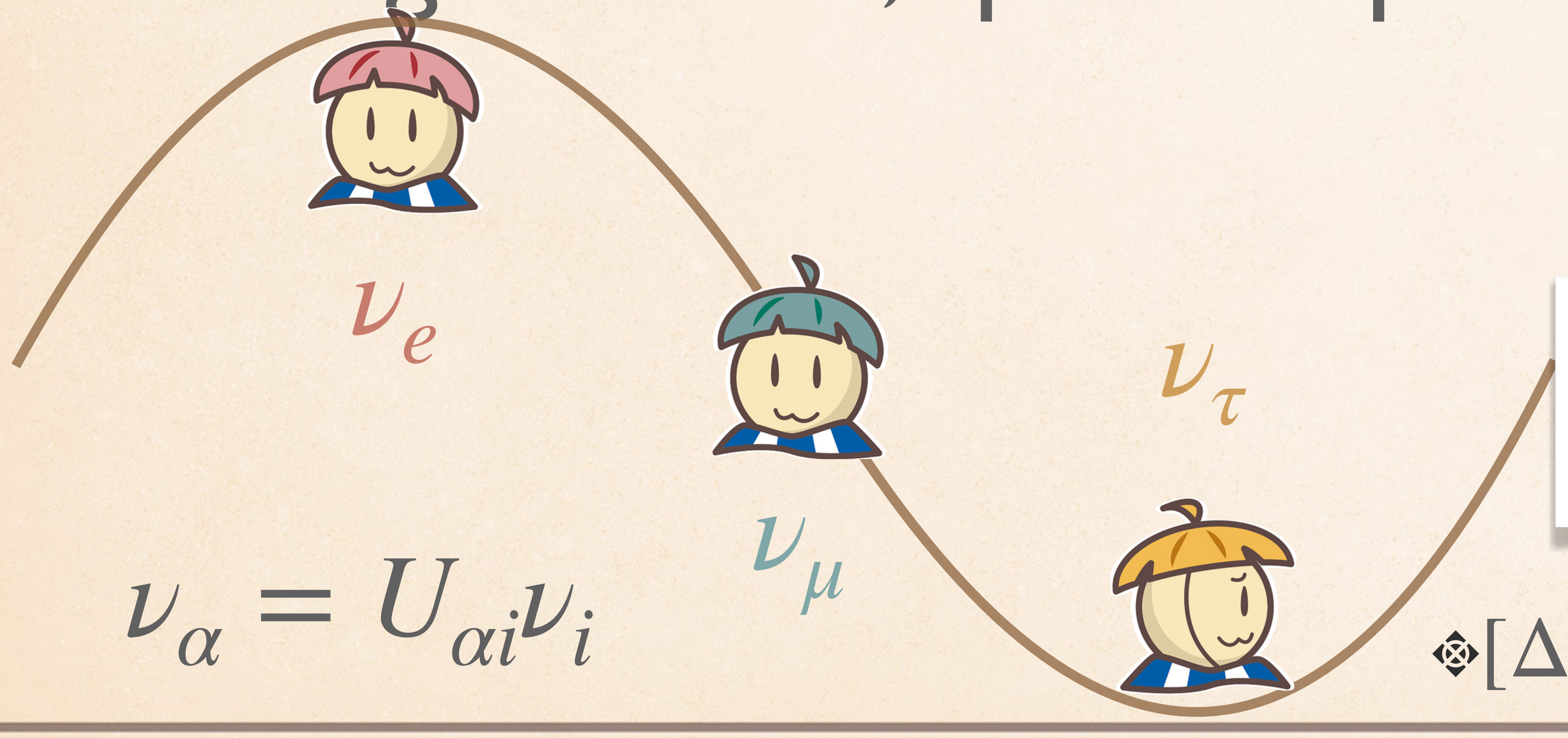
Solar Reactor Atmospheric/LBL



$$A = 2\sqrt{2}G_F N_e E_\nu = 7.6 \times 10^{-5} \frac{\rho}{\mathrm{g/cc}} \frac{E_\nu}{\mathrm{GeV}} \mathrm{eV}^2$$

- ν_e, ν_μ, ν_τ are massless in SM.
- Charge neutral, spin-half particles.

$$H = \frac{1}{2E_\nu} U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U^\dagger + \begin{bmatrix} A/2E_\nu & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

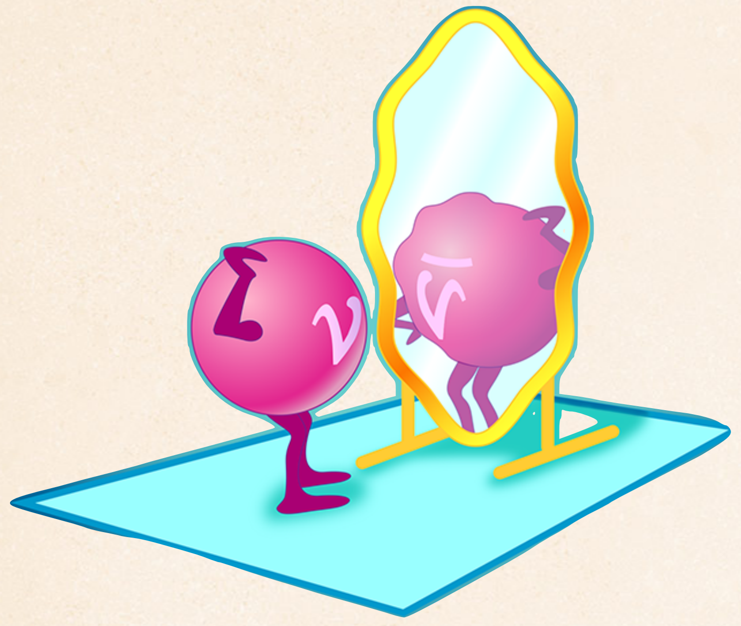


$$\nu_\alpha = U_{\alpha i}\nu_i$$

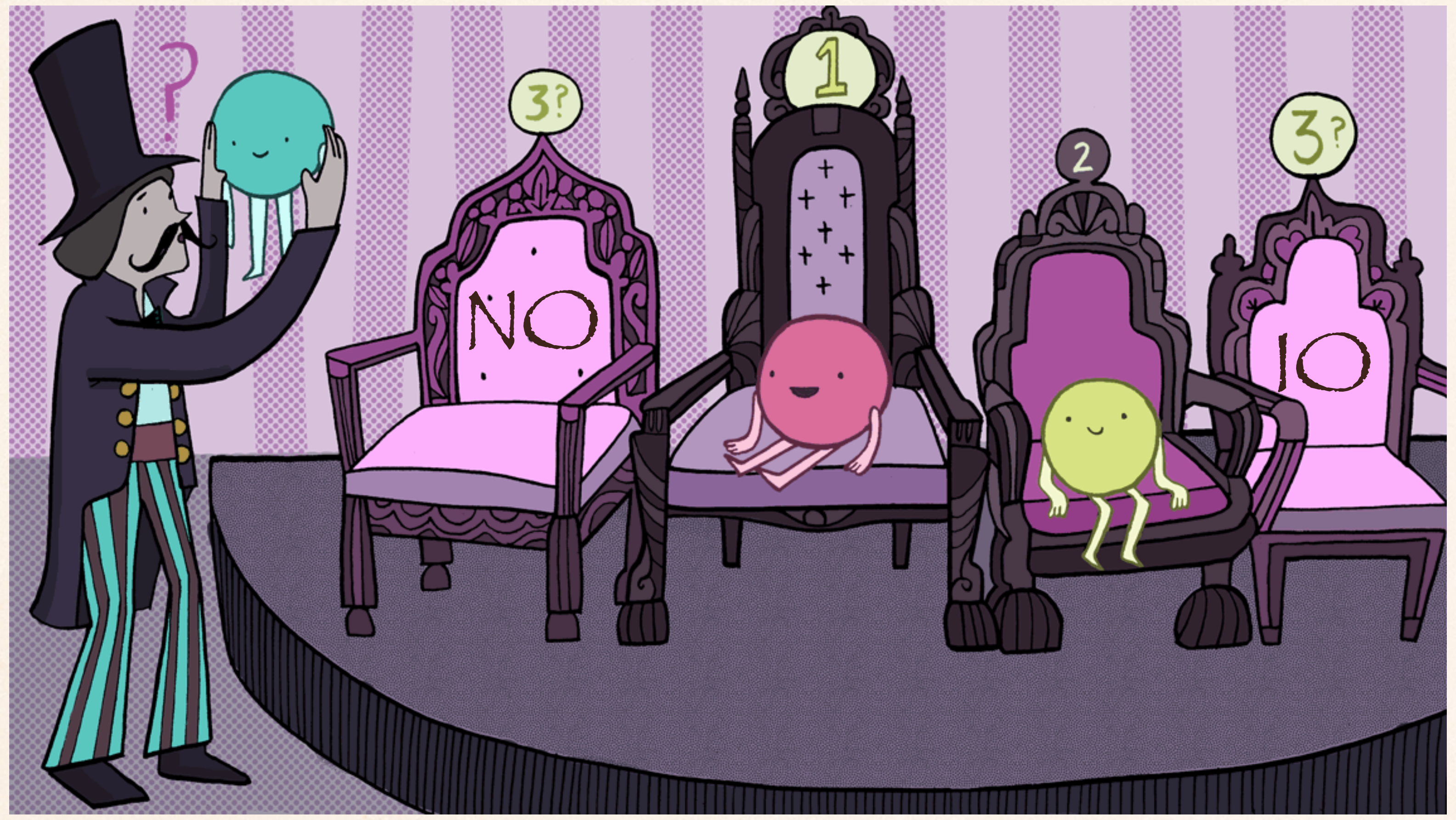
$$P_{\alpha\beta} = |<\nu_\alpha|\nu_\beta>|^2 = \delta_{\alpha\beta} - 4\sum_{i>j}^{3} \mathrm{Re}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin^2\frac{1.27\Delta_{ij}L}{E_\nu} + 2\sum_{i>j}^{3} \mathrm{Im}(U^*_{\alpha i}U_{\beta i}U_{\alpha j}U^*_{\beta j})\sin\frac{2\times 1.27\Delta_{ij}L}{E_\nu}$$

- $[\Delta_{ij} = m_i^2 - m_j^2]$: Δ_{21}(solar), Δ_{31}(atmospheric), θ_{12}(solar), θ_{13}(reactor), θ_{23}, Phase: δ_{CP}

CHALLENGES IN NEUTRINO PHYSICS



Mass Ordering: Sign of Δ_{31}



Value of δ_{13}

Octant of θ_{23}

Higher Octant ($\theta_{23} > 45°$)

Lower Octant ($\theta_{23} < 45°$)

Probing BSM Signatures

$$H^{mat} = \frac{1}{2E_\nu} U \begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} U^\dagger + H_{int} + \mathbf{H_{BSM}}$$

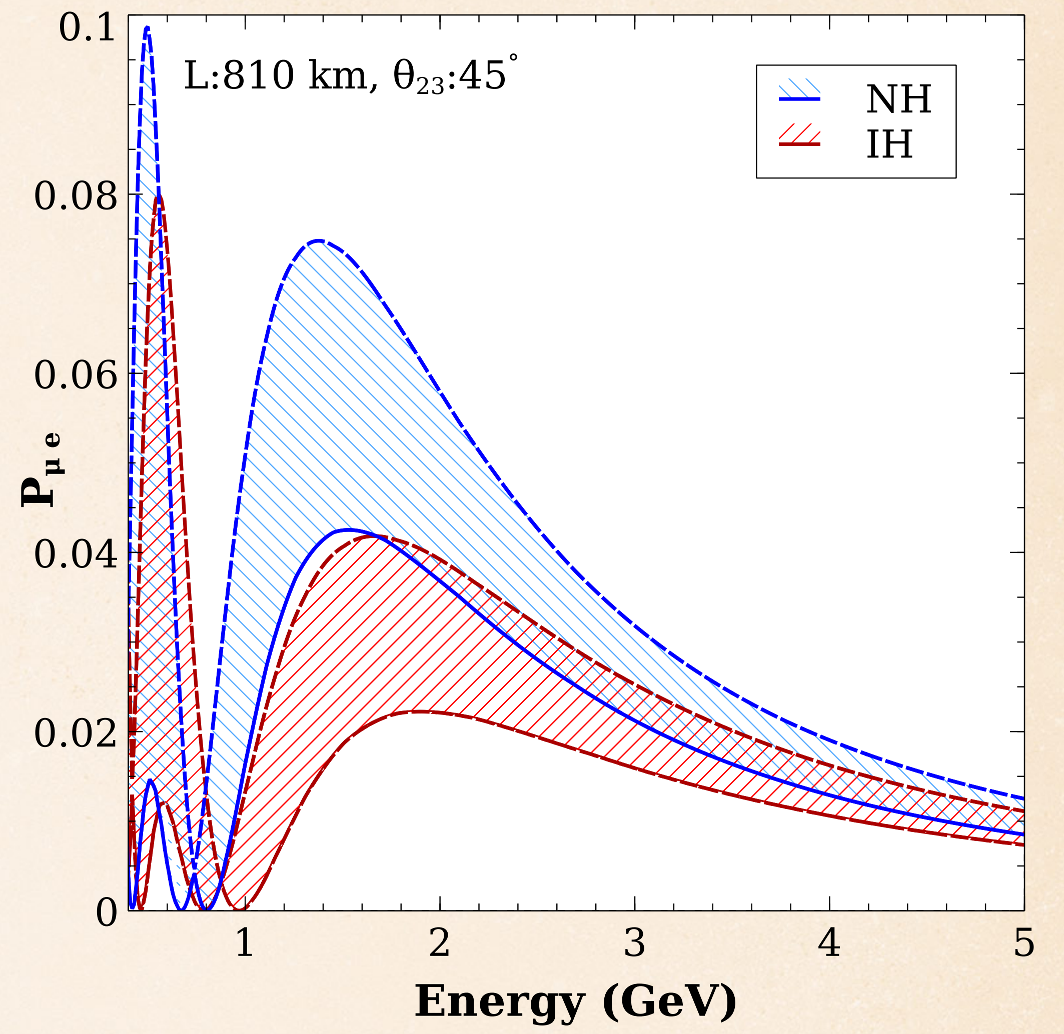
NSI, LIV, Sterile neutrino, neutrino decay,..

Dirac/ Majorana nature of neutrinos

Hierarchy-δ_{13}

$$P_{\mu e}(\Delta_{31}[NO], \delta_{13}) = P_{\mu e}(\Delta_{31}[IO], \delta'_{13})$$

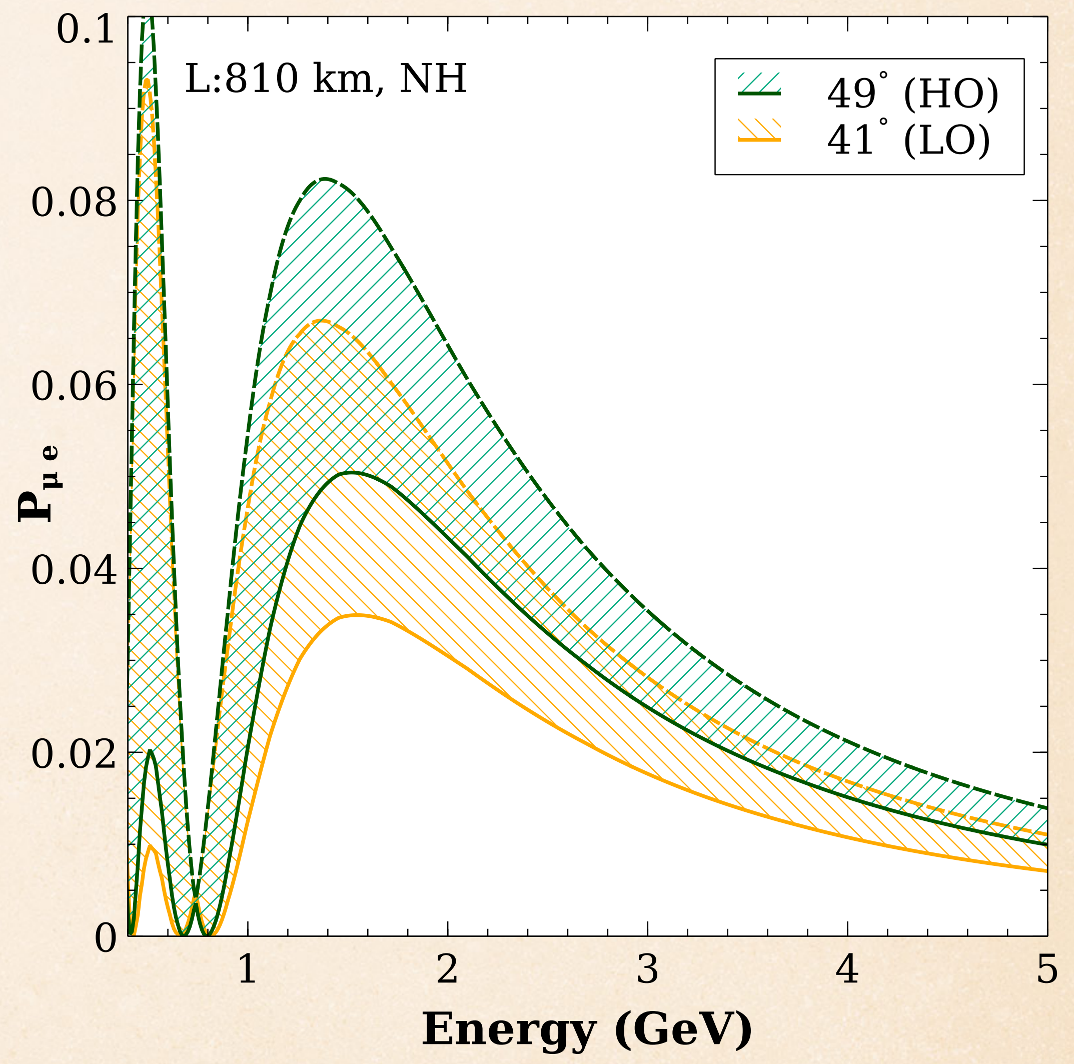
[Minakata, Nunokawa, *JHEP* 10 (2001) 001]



Octant-δ_{13}

$$P_{\mu e}(\theta_{23}[HO], \delta_{13}) = P_{\mu e}(\theta_{31}[LO], \delta'_{13})$$

[Gandhi, Ghoshal, Goswami, Shankar, hep-ph/0506145]



INVISIBLE NEUTRINO DECAY $[\nu_i \to \nu + X]$

$$\boxed{H = \frac{1}{2E_\nu} U\left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{bmatrix} \right) U^\dagger + \begin{bmatrix} A/2E_\nu & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}$$

$$\alpha_3 = m_3/\tau_3$$

$$\kappa_3 = \alpha_3 L/E$$

$\tau_3/m_3 > 9 \times 10^{-11}\mathrm{s/eV}$

$$P_{\mu e} = \boxed{s_{13}^2 s_{23}^2 \left(1 + e^{-4\kappa_3} - 2e^{-2\kappa_3} + 4e^{-2\kappa_3}\sin^2[(\hat{A}-1)\Delta]\right)} \frac{\alpha_3^2 + \Delta_{31}^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin \hat{A}\Delta}{\hat{A}} \times$$

$$\left[\left(\sin[(\hat{A}-1)\Delta + \delta_{CP} - \Delta]e^{-2\kappa_3} + \sin[\hat{A}\Delta - \delta_{CP}]\right)\frac{\Delta_{31}^2(\hat{A}-1) - \alpha_3^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \left(\cos[\hat{A}\Delta - \delta_{CP}] - \cos[(\hat{A}-1)\Delta + \delta_{CP} - \Delta]e^{-2\kappa_3}\right)\frac{A\alpha_3}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2}\right]$$

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23}[1 + 2\sin^2\Delta e^{-2\kappa_3} - e^{-2\kappa_3}] - s_{23}^2(1 - e^{-4\kappa_3}) - \kappa_3(4s_{23}^4 + \sin^2 2\theta_{23}\cos 2\Delta) - 4s_{13}^2 s_{23}^2 \frac{\sin^2[(\hat{A}-1)\Delta]}{(\hat{A}-1)^2}$$

$$-\frac{2}{\hat{A}-1}s_{13}^2 \sin^2 2\theta_{23}\left(\sin\Delta\cos[\hat{A}\Delta]\frac{\sin[(\hat{A}-1)\Delta]}{\hat{A}} - \frac{\hat{A}}{2}\Delta\sin[2\Delta]\right) + \alpha c_{12}^2 \sin^2 2\theta_{23}\Delta\sin[2\Delta] + \kappa_3^2(8s_{23}^4 + \sin^2 2\theta_{23}\cos 2\Delta)$$

[Chattopadhyay, Chakraborty, Dighe, Goswami; *JHEP* 2023, 51 (2023)]

INVISIBLE NEUTRINO DECAY [$\nu_i \to \nu + X$]

$$\boxed{H = \frac{1}{2E_\nu} U\left(\begin{bmatrix} 0 & 0 & 0 \\ 0 & \Delta_{21} & 0 \\ 0 & 0 & \Delta_{31} \end{bmatrix} + \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -i\alpha_3 \end{bmatrix} \right) U^\dagger + \begin{bmatrix} A/2E_\nu & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}}$$

$$\alpha_3 = m_3/\tau_3$$

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$$\tau_3/m_3 > 9 \times 10^{-11}\,\mathrm{s/eV}$$

$$P_{\mu e} = s_{13}^2 s_{23}^2 \left(1 + e^{-4\kappa_3} - 2e^{-2\kappa_3} + \boxed{4e^{-2\kappa_3}\sin^2[(\hat{A}-1)\Delta]}\right) \frac{\alpha_3^2 + \Delta_{31}^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{23} \frac{\sin \hat{A}\Delta}{\hat{A}} \times$$

$$\left[\boxed{\left(\sin[(\hat{A}-1)\Delta + \delta_{CP} - \Delta] e^{-2\kappa_3} + \sin[\hat{A}\Delta - \delta_{CP}] \right)} \frac{\Delta_{31}^2(\hat{A}-1) - \alpha_3^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \left(\cos[\hat{A}\Delta - \delta_{CP}] - \cos[(\hat{A}-1)\Delta + \delta_{CP} - \Delta] e^{-2\kappa_3} \right) \frac{A\alpha_3}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} \right]$$

$$P_{\mu\mu} = 1 - \frac{1}{2}\sin^2 2\theta_{23}[1 + 2\sin^2\Delta e^{-2\kappa_3} - e^{-2\kappa_3}] - s_{23}^2(1 - e^{-4\kappa_3}) - \kappa_3(4s_{23}^4 + \sin^2 2\theta_{23}\cos 2\Delta) - 4s_{13}^2 s_{23}^2 \frac{\sin^2[(\hat{A}-1)\Delta]}{(\hat{A}-1)^2}$$

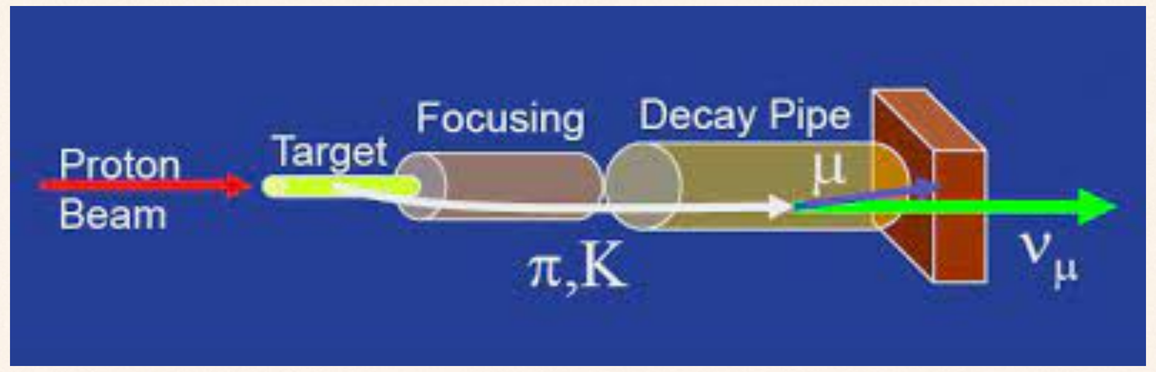
$$-\frac{2}{\hat{A}-1} s_{13}^2 \sin^2 2\theta_{23} \left(\boxed{\sin\Delta \cos[\hat{A}\Delta] \frac{\sin[(\hat{A}-1)\Delta]}{\hat{A}}} - \frac{\hat{A}}{2}\Delta \sin[2\Delta] \right) + \alpha c_{12}^2 \sin^2 2\theta_{23} \Delta \sin[2\Delta] + \kappa_3^2(8s_{23}^4 + \sin^2 2\theta_{23}\cos 2\Delta)$$

[Chattopadhyay, Chakraborty, Dighe, Goswami; *JHEP* 2023, 51 (2023)]

EXPERIMENTAL SPECIFICATIONS

2588 km (P2O)

- Water Cherenkov detector: 4 M ton
- Beam: 90 kW, POT: $4 \times 10^{20}/\mathrm{yr}$
- Average density: 3.8 g/cc
- 2588 km is close to bimagic baseline
- Runtime: 3 yr(ν) + 3 yr($\bar{\nu}$)
- Peak energy: 2-3 GeV
- Relatively large background



Accelerator ν_μ

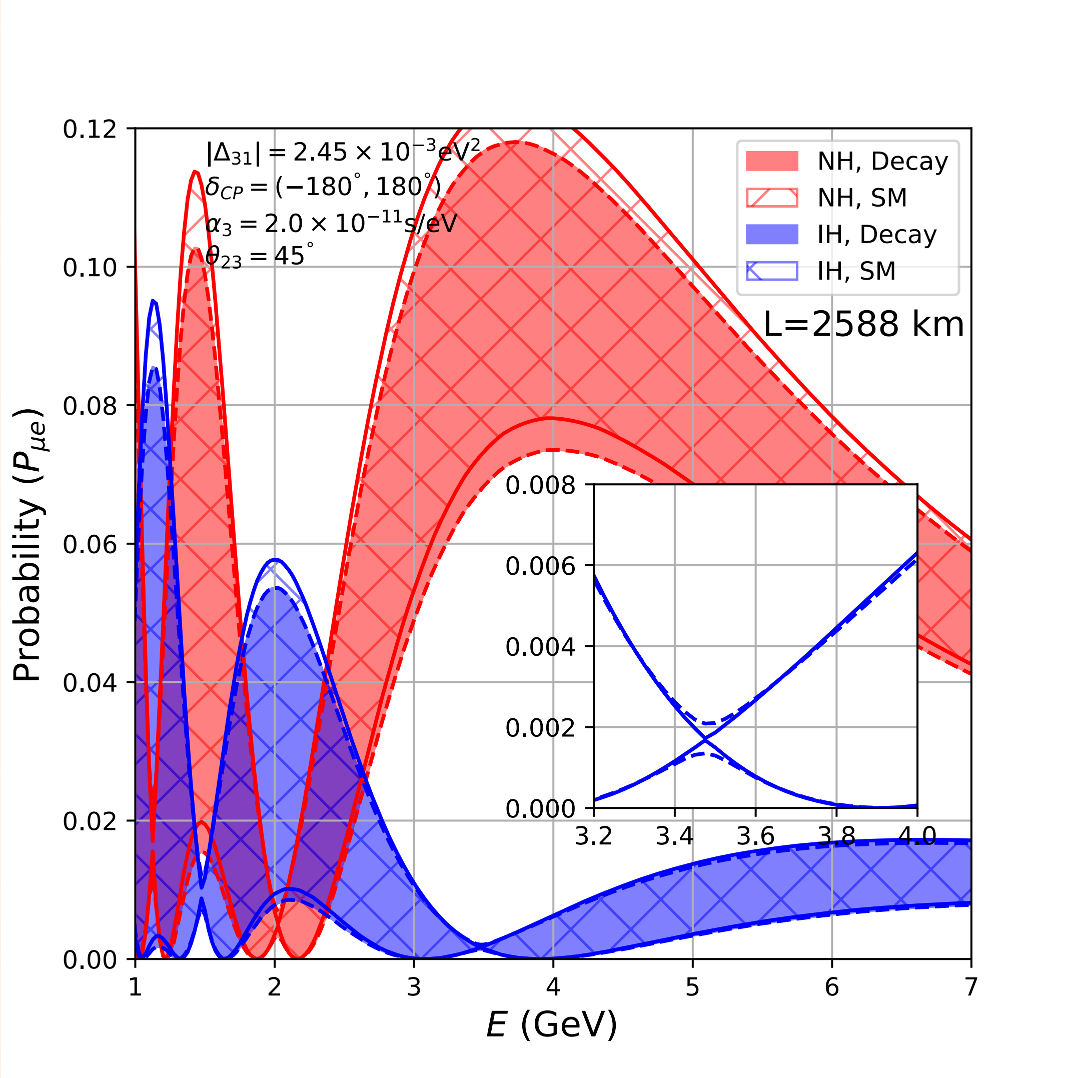
Parameters	True values	Test values
θ_{12}	$33.4°$	$33.4°$
θ_{13}	$8.42°$	$8.42°$
θ_{23} (Hierarchy)	$41°$	$39° : 51°$
θ_{23} (Octant)	$41°\ (49°)$	$45° : 51°\ (39° : 45°)$
δ_{CP}	$-180° : 180°$	$-180° : 180°$
δ_{CP}(CP sensitivity)	$-180° : 180°$	$-180°, 0, 180°$
Δm^2_{21}	7.53×10^{-5}	7.53×10^{-5}
Δm^2_{31}(Hierarchy)	$\pm 2.45 \times 10^{-3}\ \mathrm{eV}^2$	$\mp[2.35 : 2.6] \times 10^{-3}\ \mathrm{eV}^2$
Δm^2_{31}(Octant)	$\pm 2.45 \times 10^{-3}\ \mathrm{eV}^2$	$\pm[2.35 : 2.6] \times 10^{-3}\ \mathrm{eV}^2$
α_3^{-1}	2.0×10^{-11} s/eV	$[1.0 : 3.0] \times 10^{-11}$ s/eV

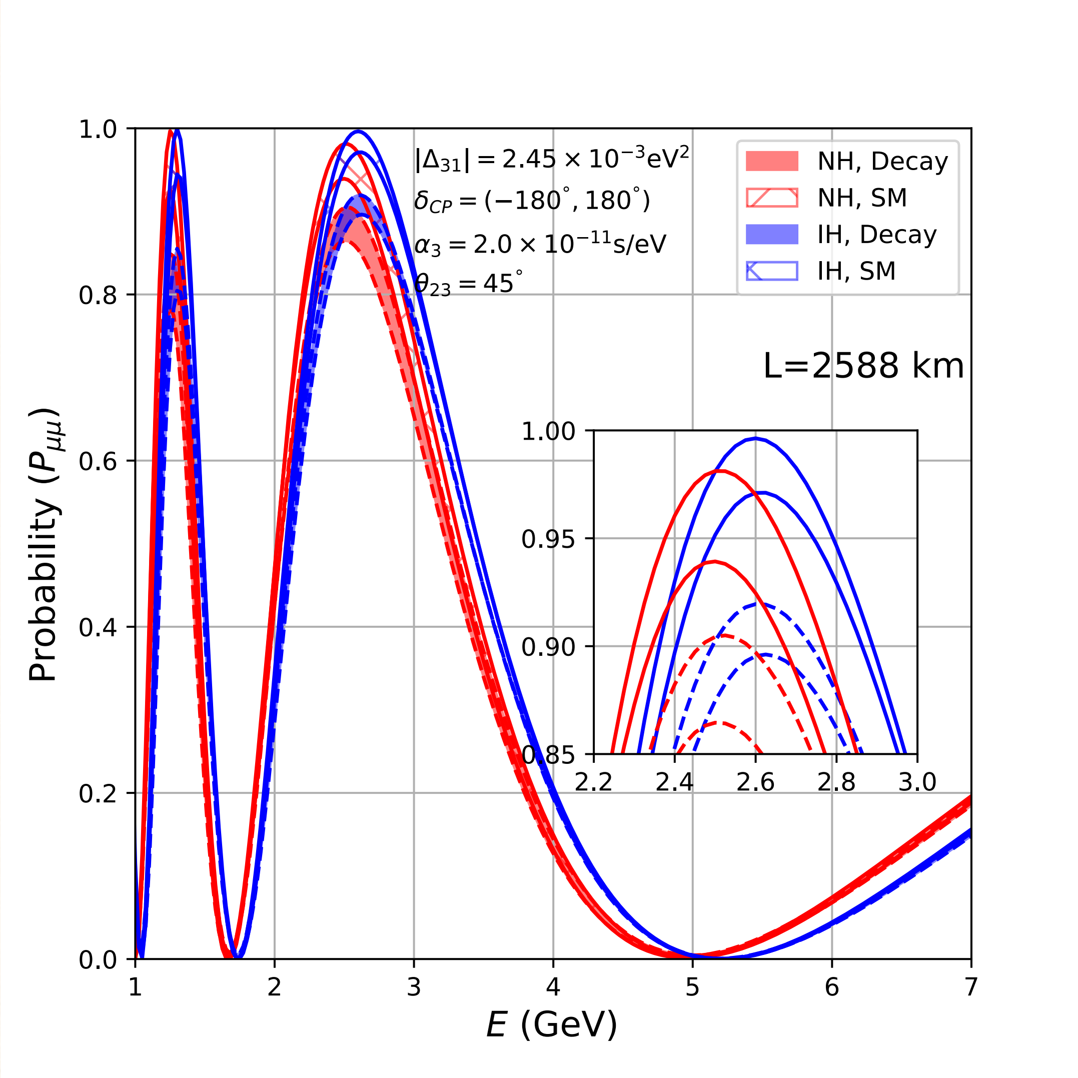
Table 1. The true and test values of oscillation parameters.

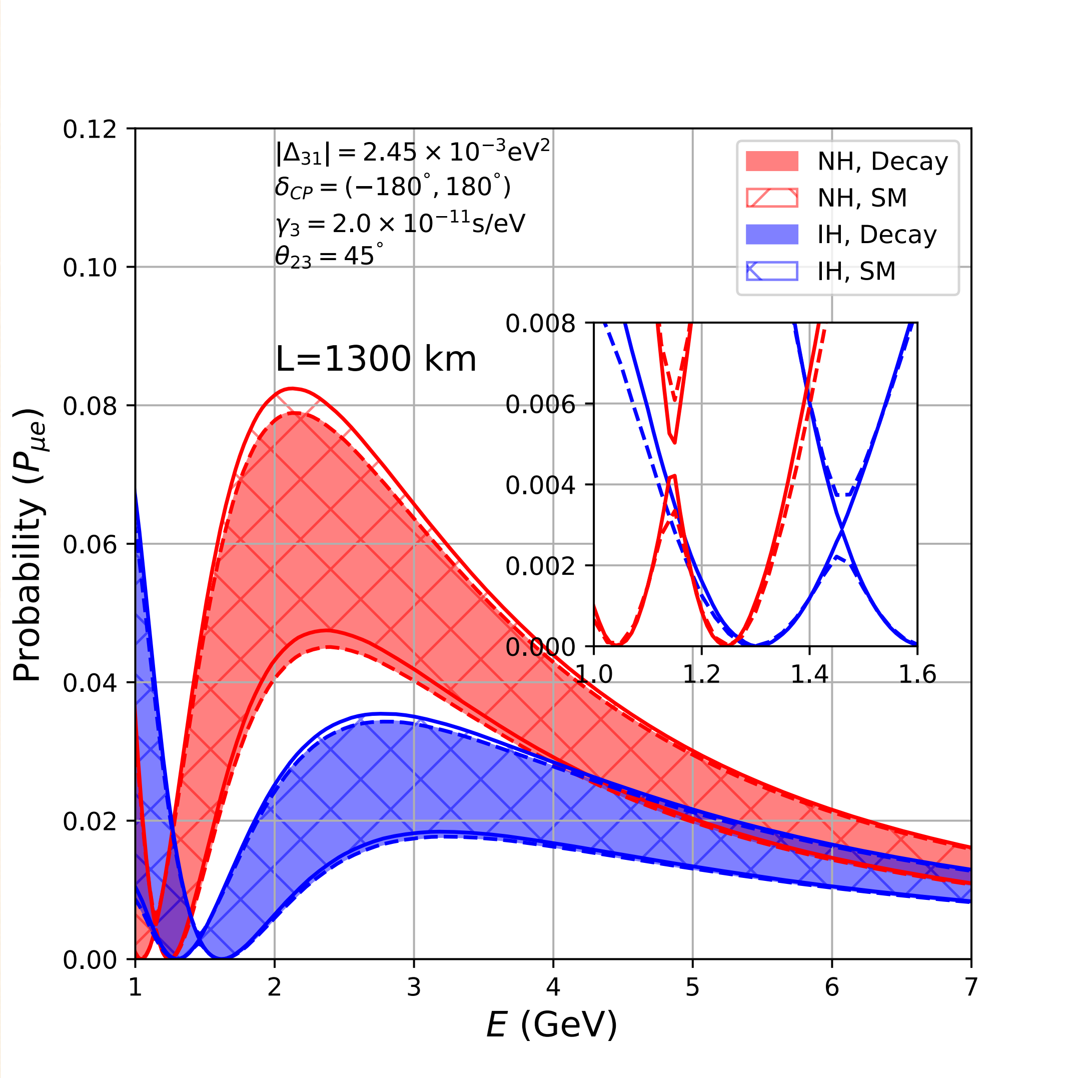
1300 km (DUNE)

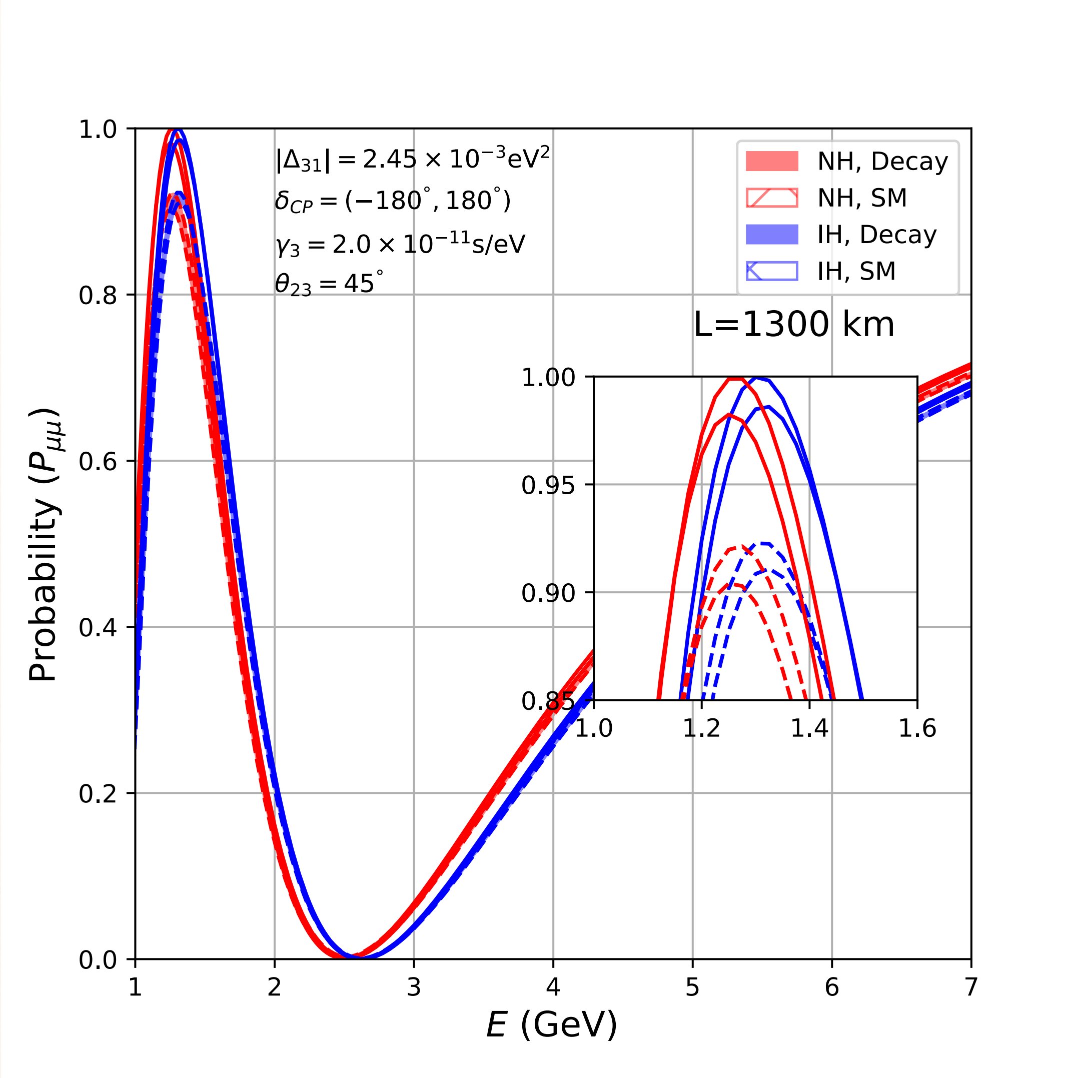
- Liquid Argon detector: 40 k ton
- Beam: 1.2 MW, POT: $10 \times 10^{20}/\mathrm{yr}$
- Average density: 2.85 g/cc
- 1300 km baseline
- Runtime: 3.5 yr(ν) + 3.5 yr($\bar{\nu}$)
- Peak energy: 4-5 GeV
- Lesser background

DEGENERACY RELATED TO MASS ORDERING









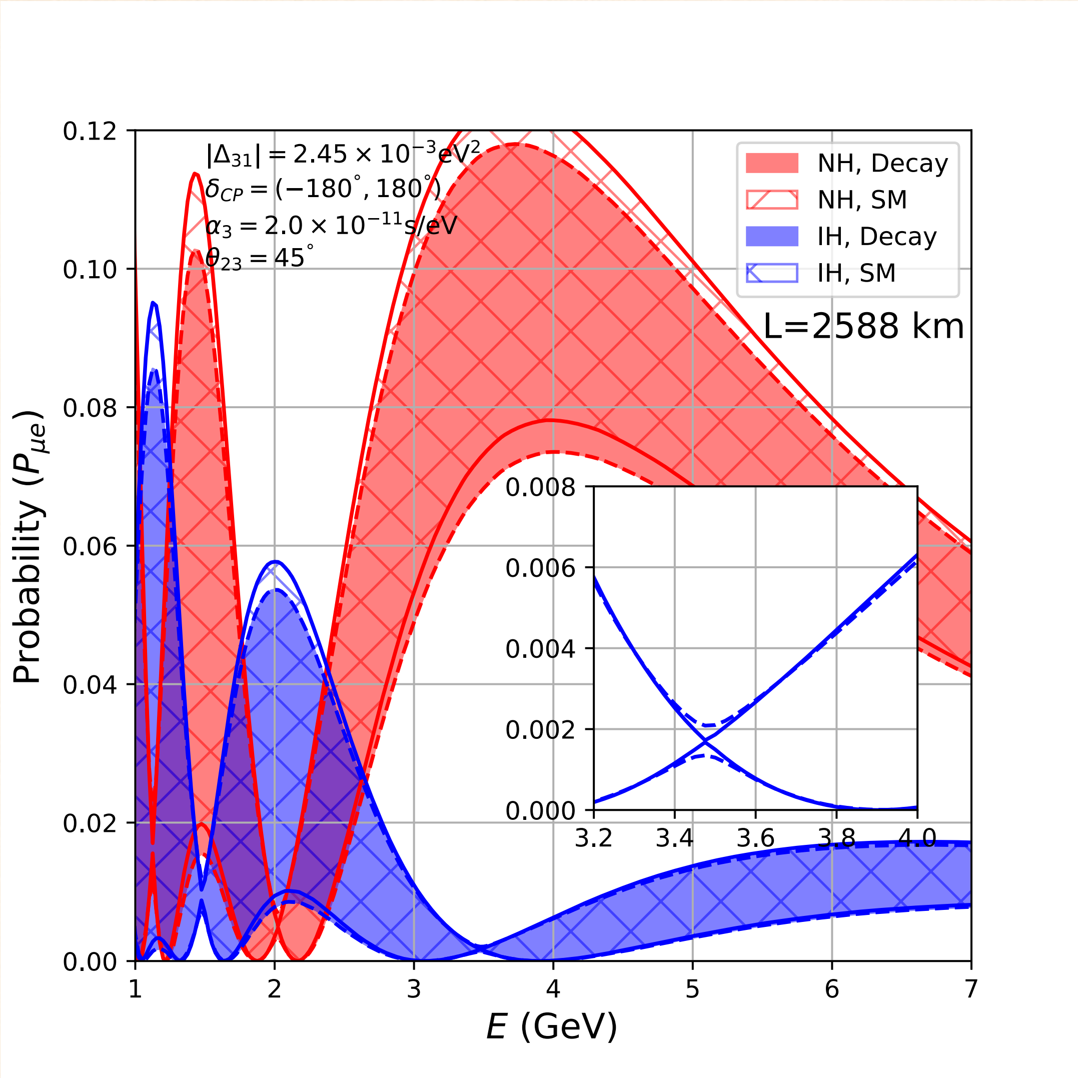
- Lowering of NH band in $P_{\mu e}$ $\Rightarrow$ decreased sensitivity
- Broadening of bands at minimum energy corresponding to NH, IH in $P_{\mu e}$ (inset). This effect leads violation of bimagic conditions at 2588 km.

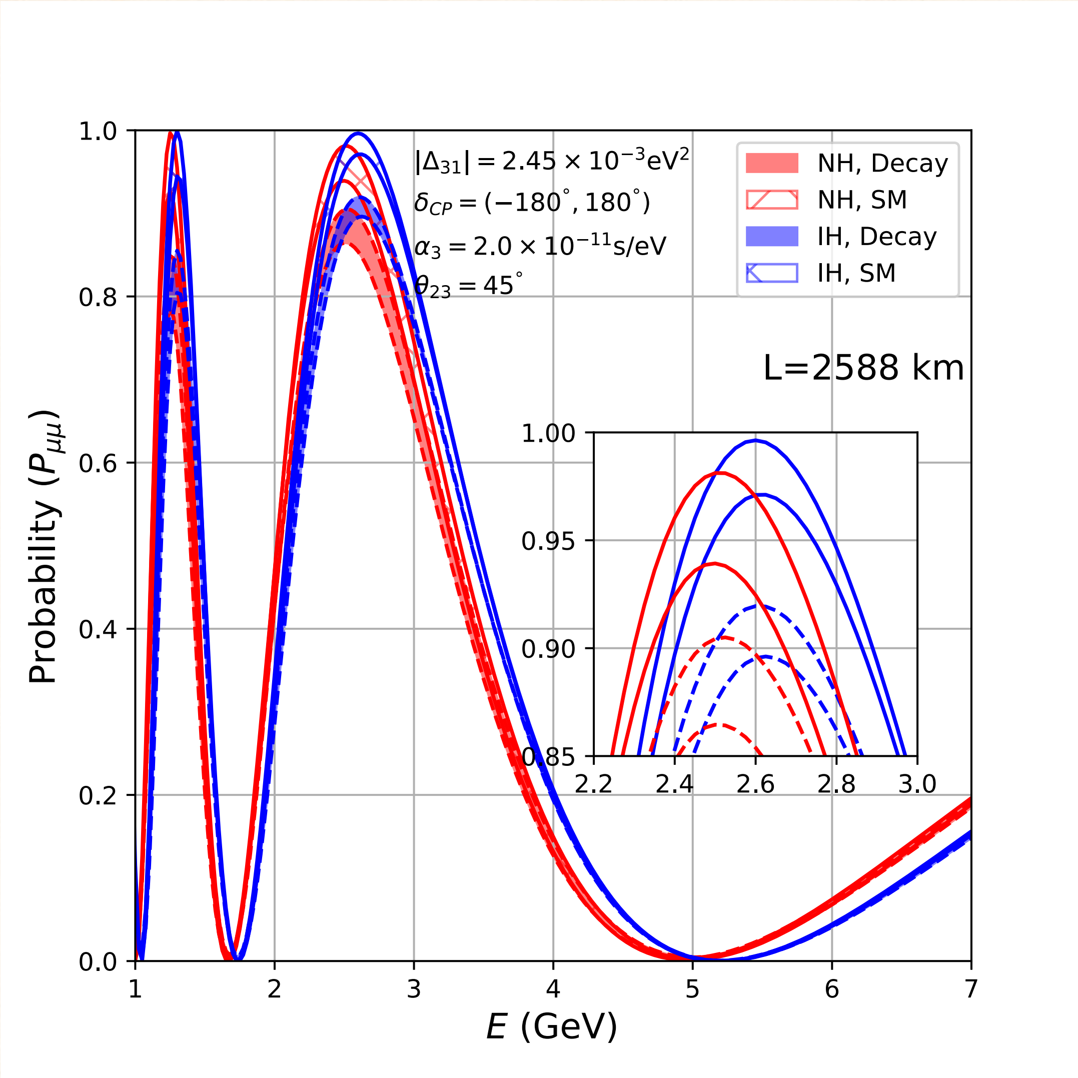
$$P_{\mu e}^{\mathrm{BM}} = s_{13}^2 s_{23}^2 \left(1 + e^{-4\kappa_3} - 2e^{-2\kappa_3}\right) \frac{\alpha_3^2 + \Delta_{31}^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{13} \frac{\sin \hat{A}\Delta}{\hat{A}} \times$$

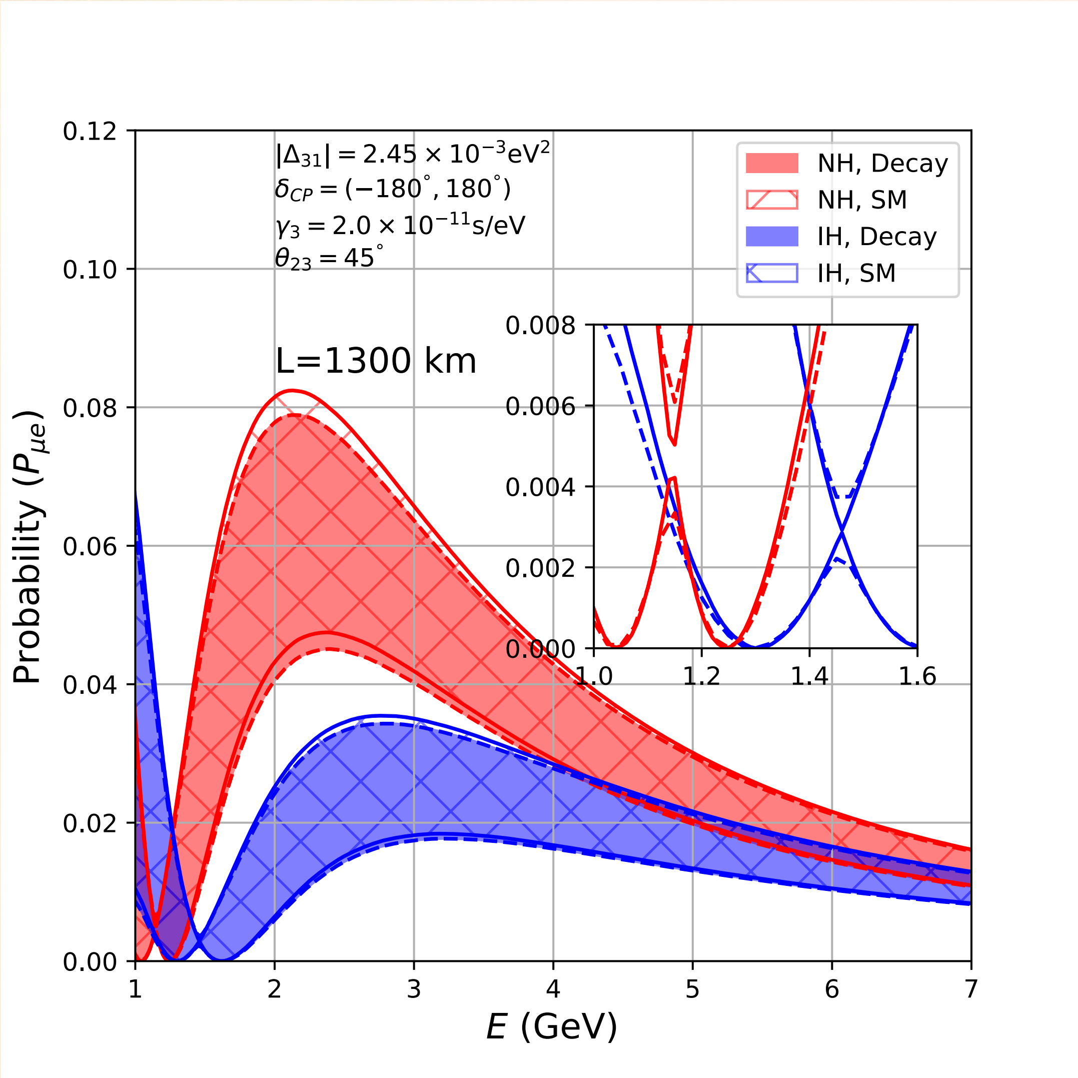
$$\left[\left(\sin[\delta_{CP} - \Delta]e^{-2\kappa_3} + \sin[\hat{A}\Delta - \delta_{CP}]\right)\frac{\Delta_{31}^2(\hat{A}-1) - \alpha_3^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \left(\cos[\hat{A}\Delta - \delta_{CP}] - \cos[\delta_{CP} - \Delta]e^{-2\kappa_3}\right)\frac{A\alpha_3}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2}\right]$$

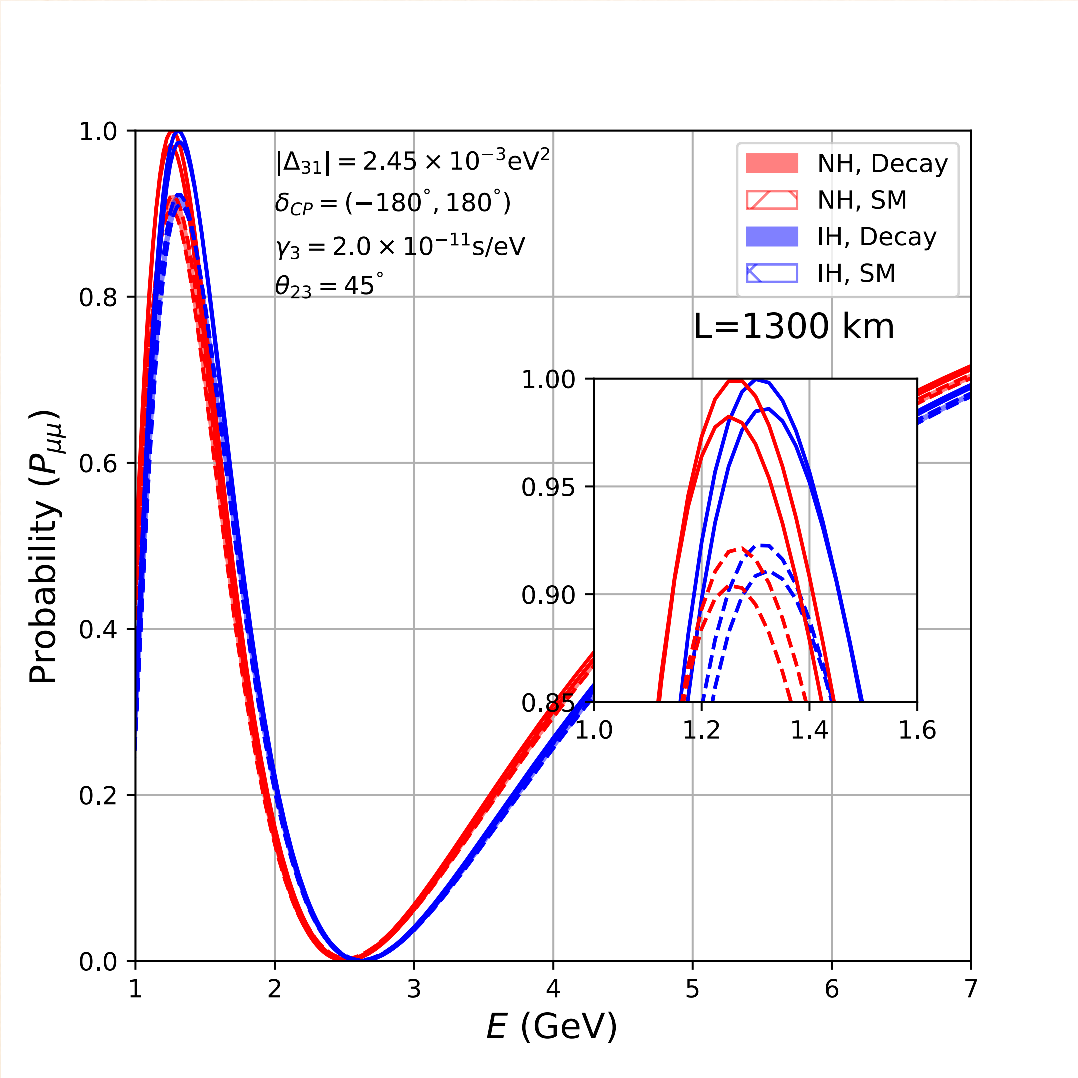
- Bands of NH, IH both lowered in $P_{\mu\mu}$ $\Rightarrow$ separation between bands stays similar $\Rightarrow$ unchanged sensitivity

DEGENERACY RELATED TO MASS ORDERING









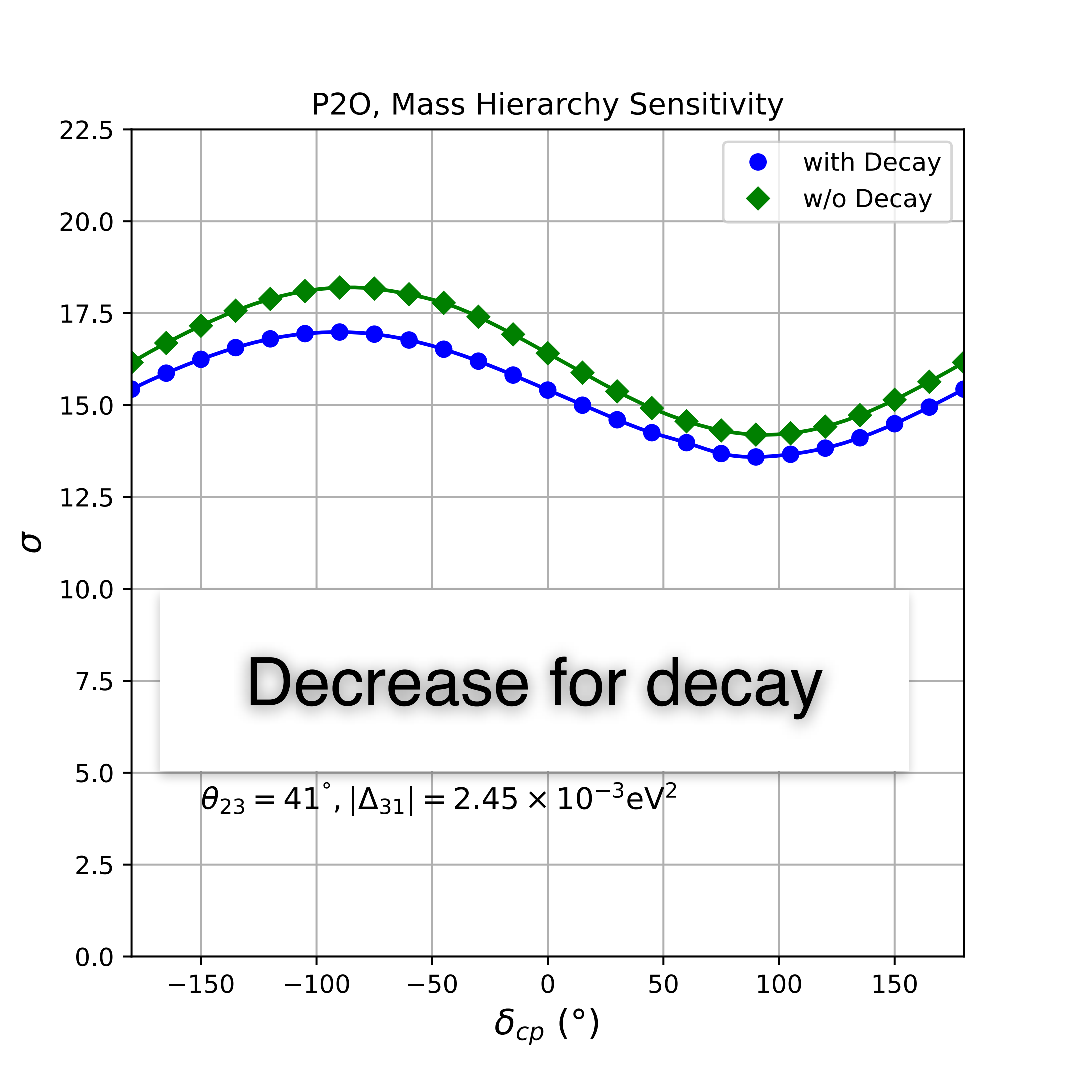
- Lowering of NH band in $P_{\mu e}$⇒decreased sensitivity
- Broadening of bands at minimum energy corresponding to NH, IH in $P_{\mu e}$ (inset). This effect leads violation of bimagic conditions at 2588 km.

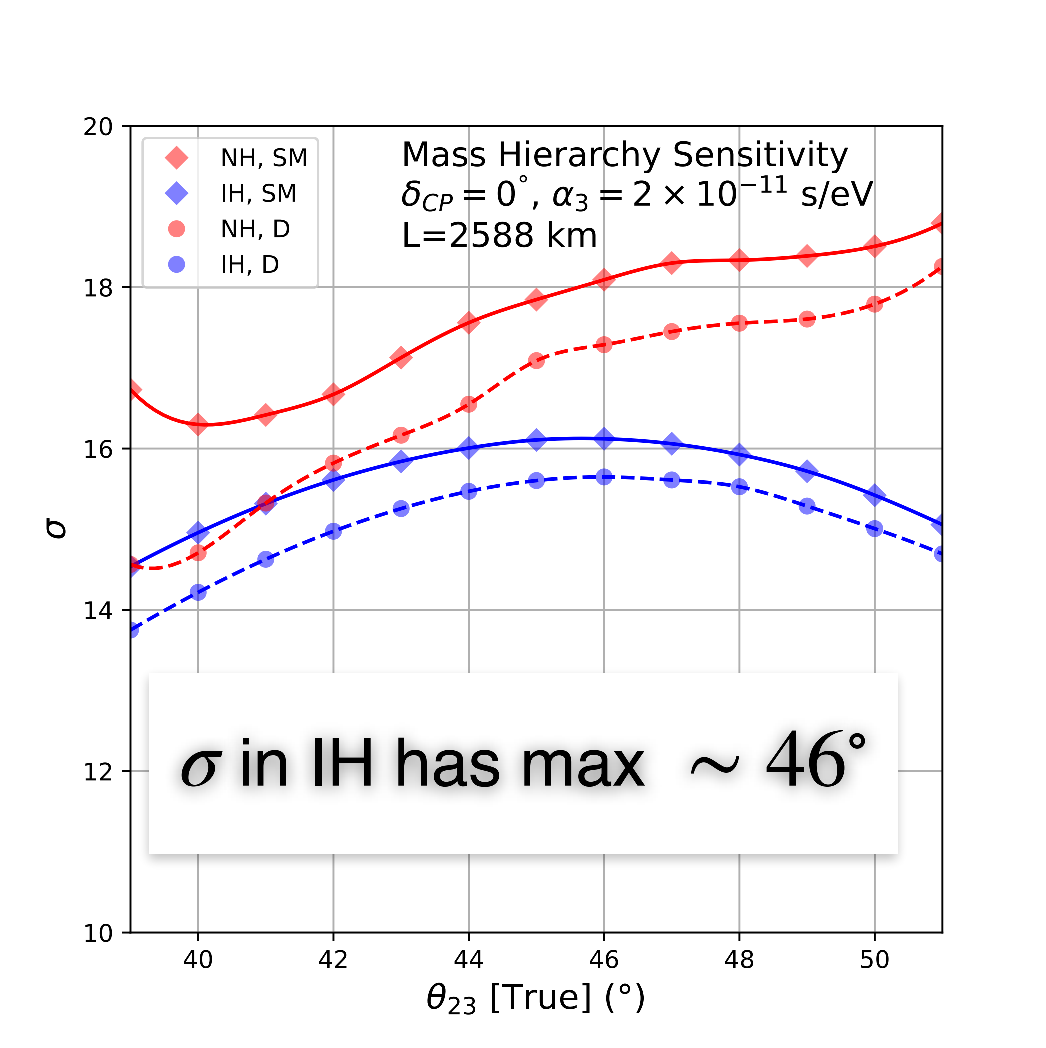
$$P_{\mu e}^{\mathrm{BM}} = s_{13}^2 s_{23}^2 \left(1 + e^{-4\kappa_3} - 2e^{-2\kappa_3}\right) \frac{\alpha_3^2 + \Delta_{31}^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \alpha s_{13} \sin 2\theta_{12} \sin 2\theta_{13} \frac{\sin \hat{A}\Delta}{\hat{A}} \times$$

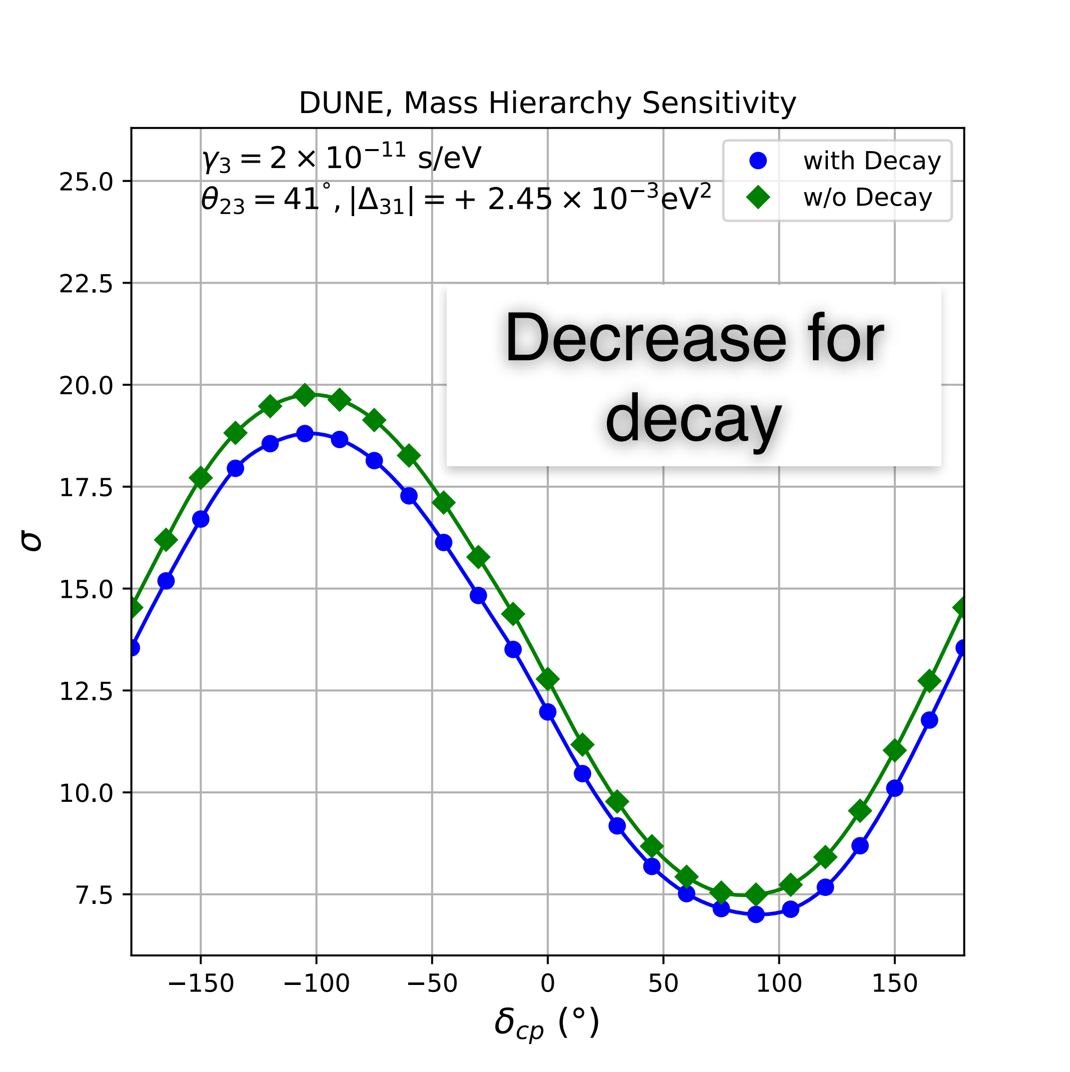
$$\left[\left(\sin[\delta_{CP} - \Delta] e^{-2\kappa_3} + \sin[\hat{A}\Delta - \delta_{CP}]\right) \frac{\Delta_{31}^2(\hat{A}-1) - \alpha_3^2}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2} + \left(\cos[\hat{A}\Delta - \delta_{CP}] - \cos[\delta_{CP} - \Delta] e^{-2\kappa_3}\right) \frac{A\alpha_3}{\Delta_{31}^2(\hat{A}-1)^2 + \alpha_3^2}\right]$$

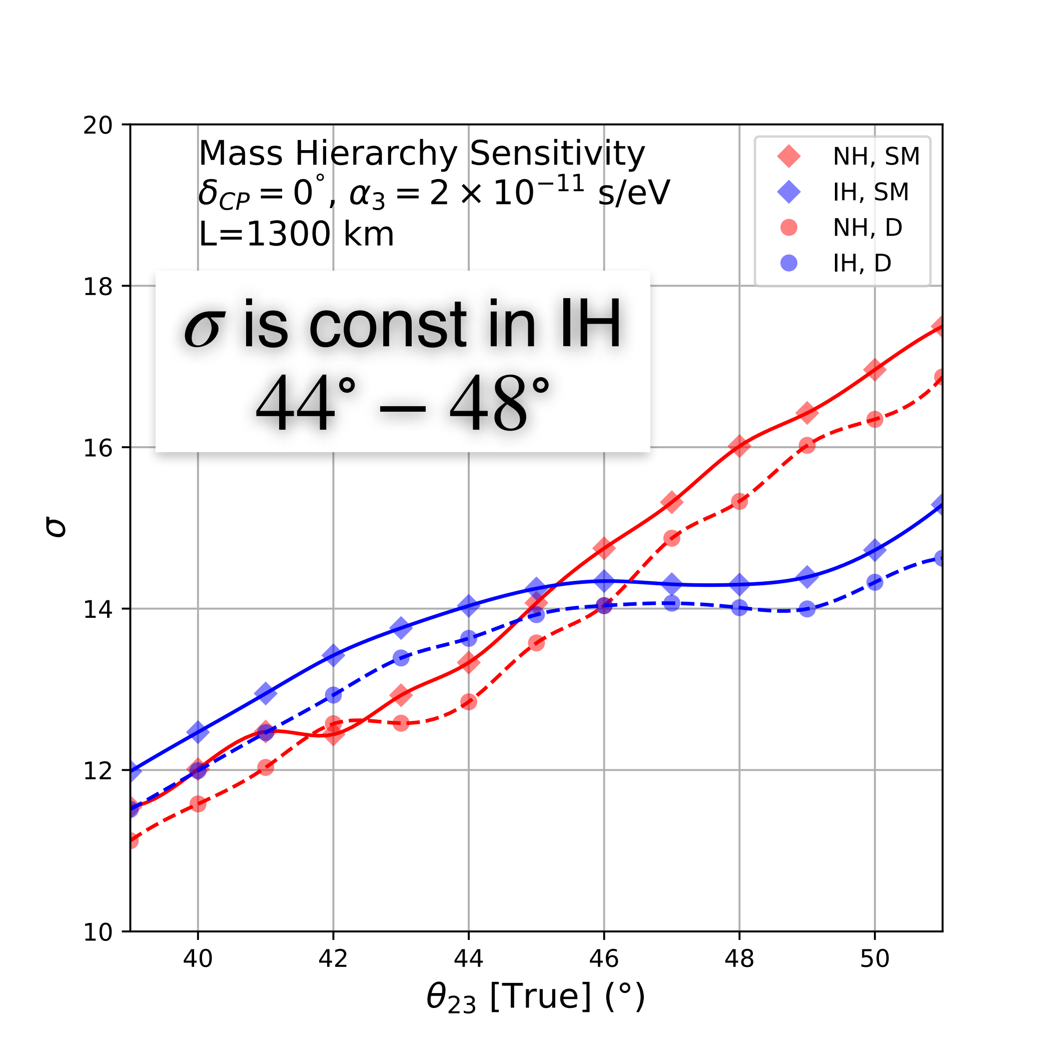
- Bands of NH, IH both lowered in $P_{\mu\mu}$ ⇒ separation between bands stays similar ⇒ unchanged sensitivity

MASS ORDERING SENSITIVITY

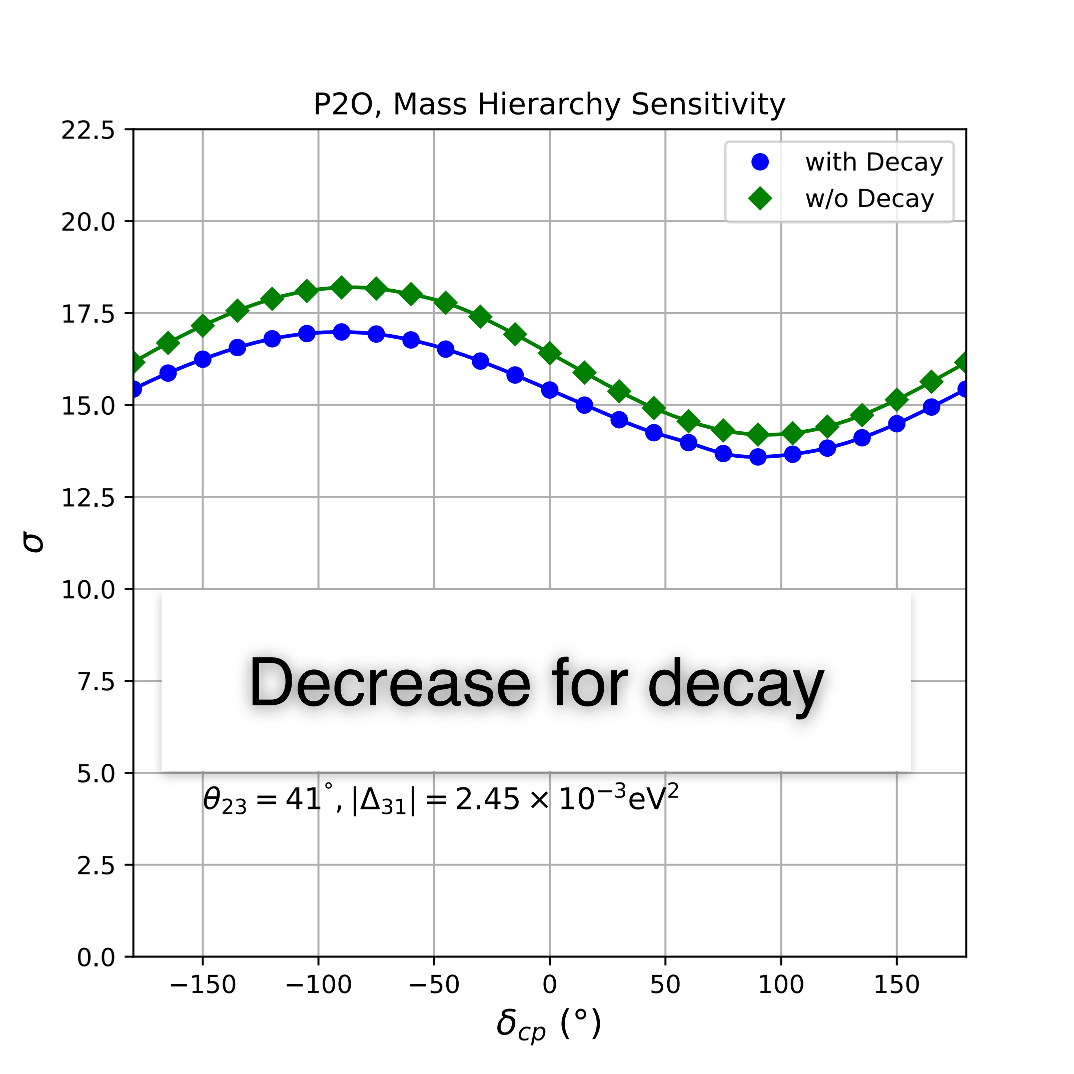


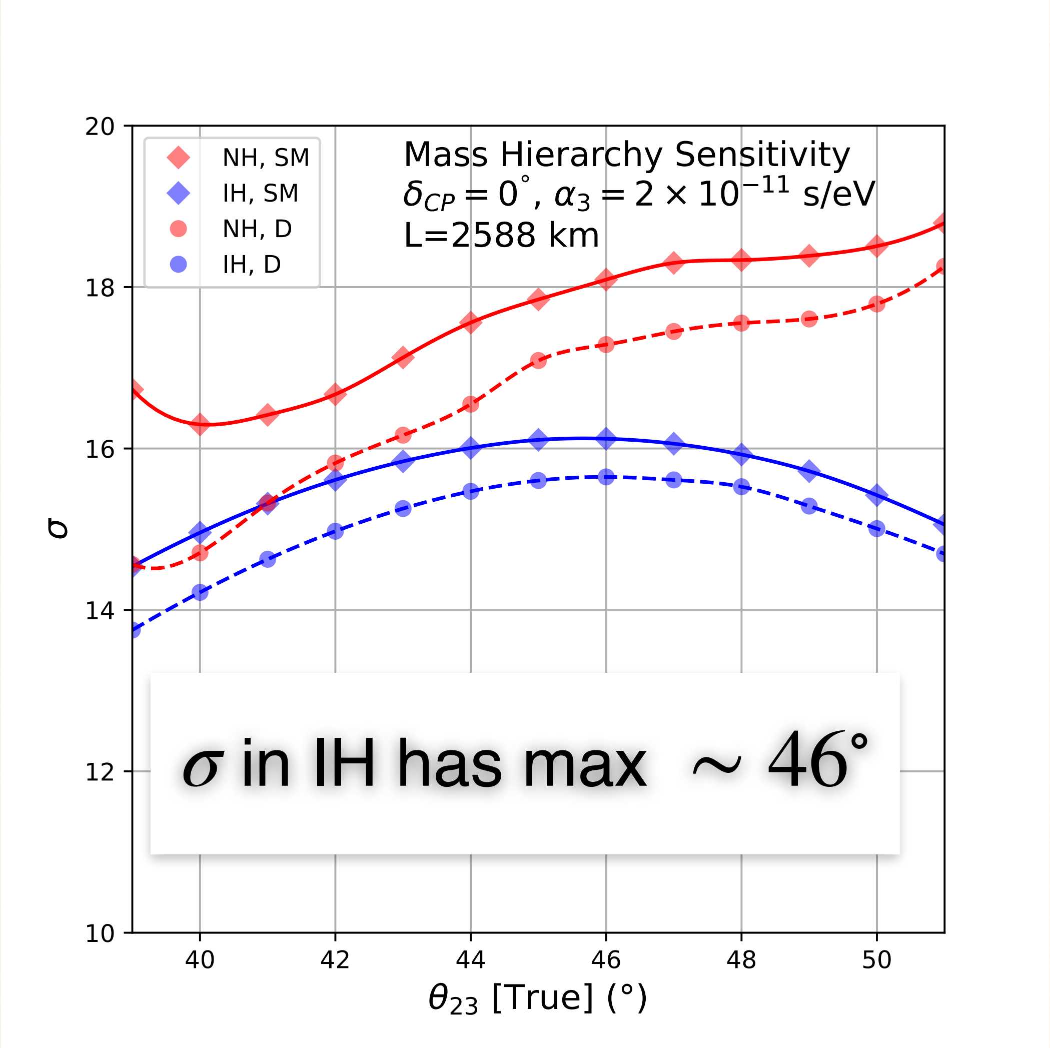


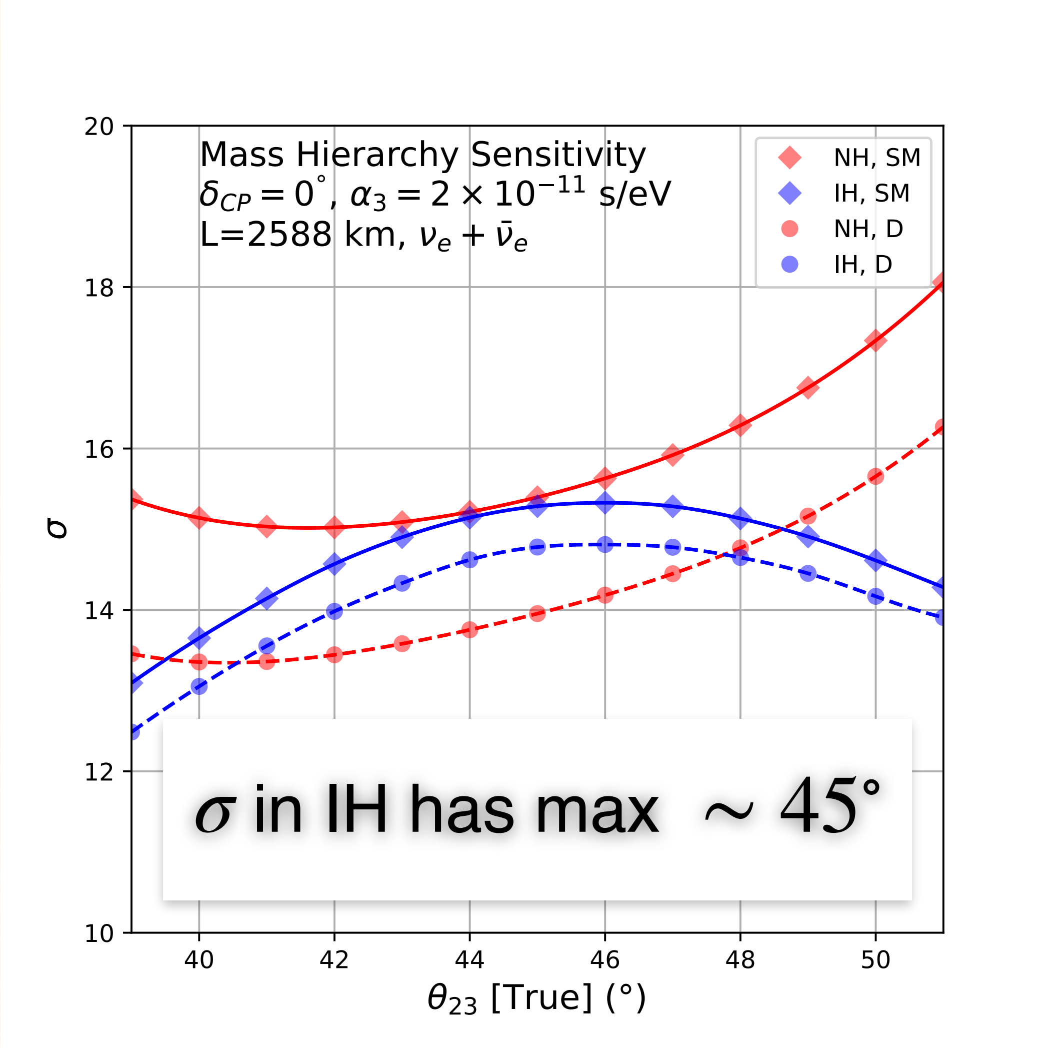


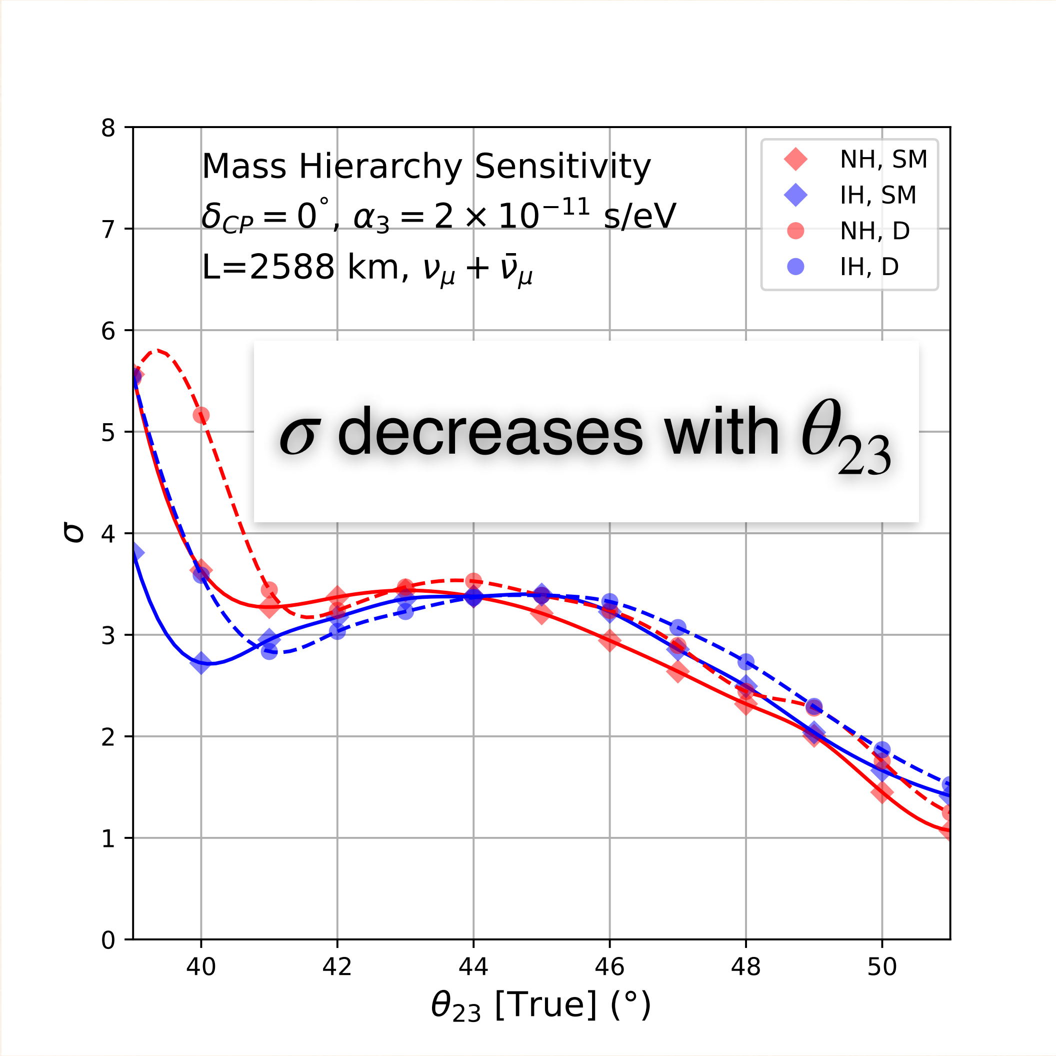


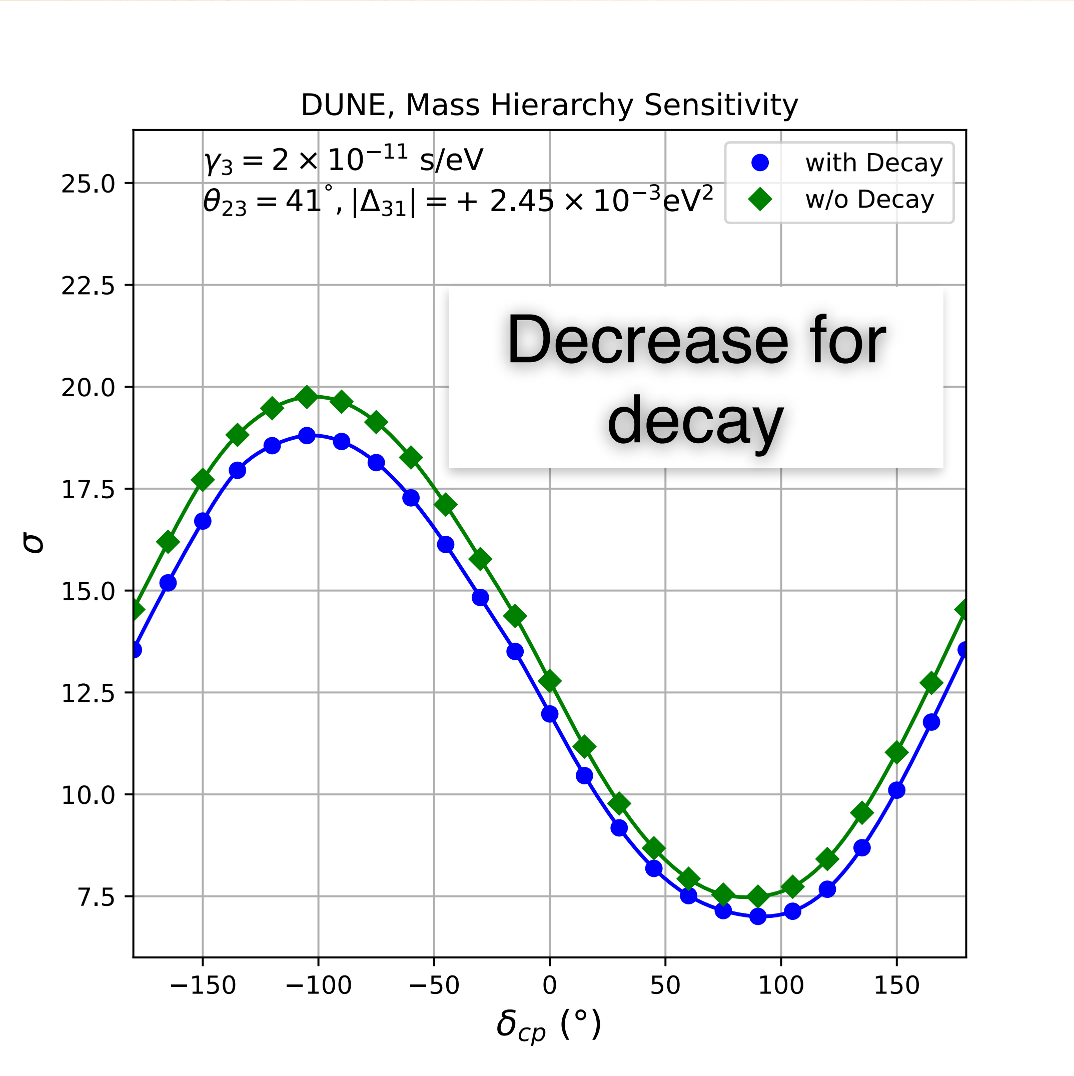
MASS ORDERING SENSITIVITY

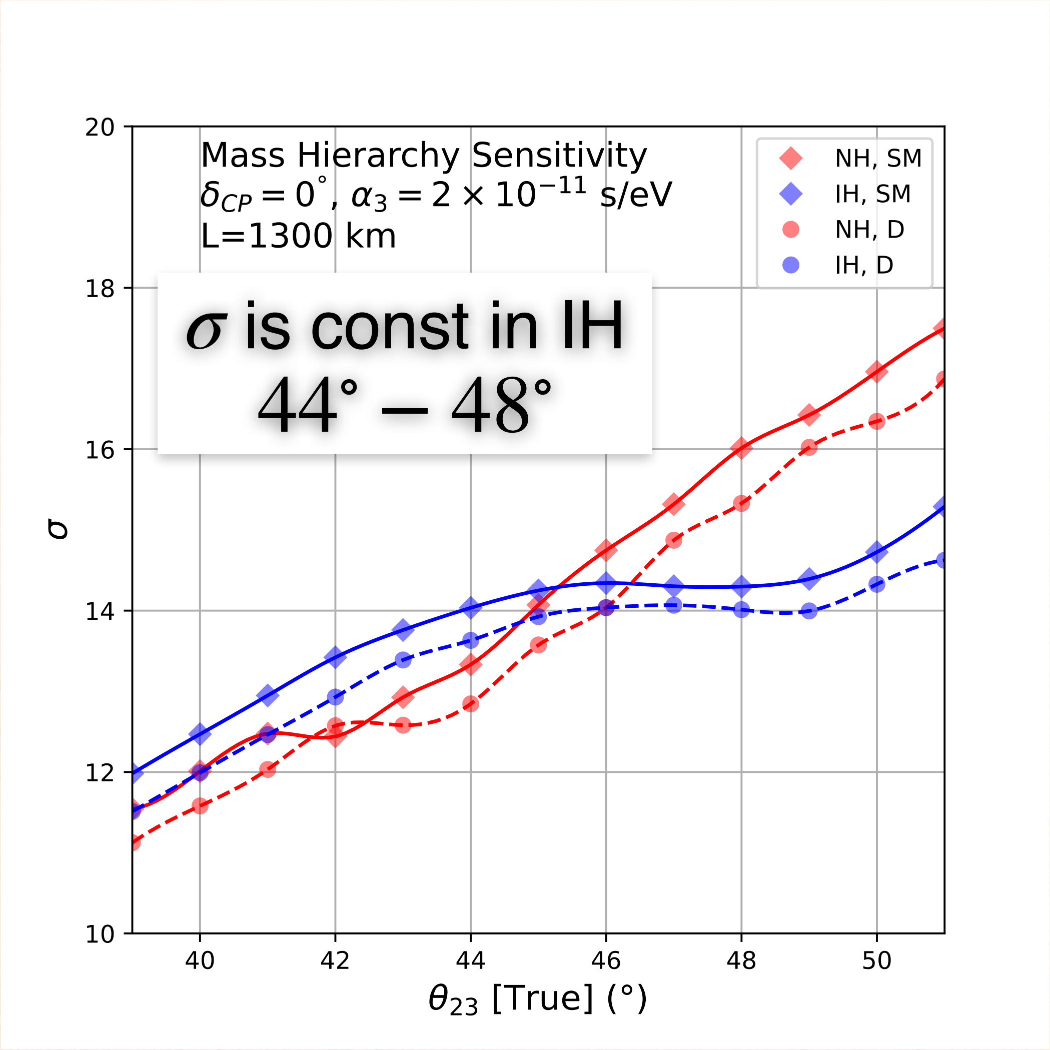




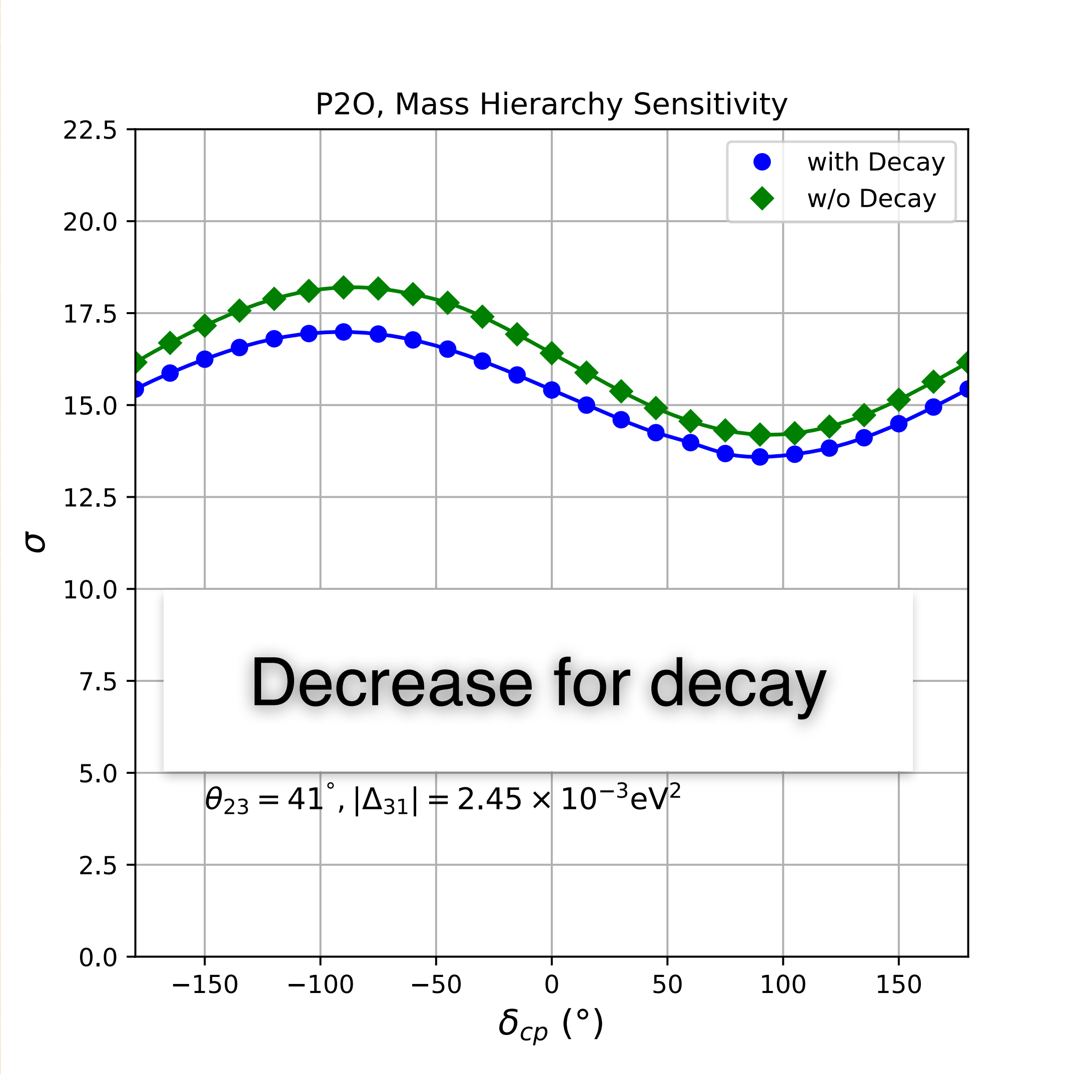


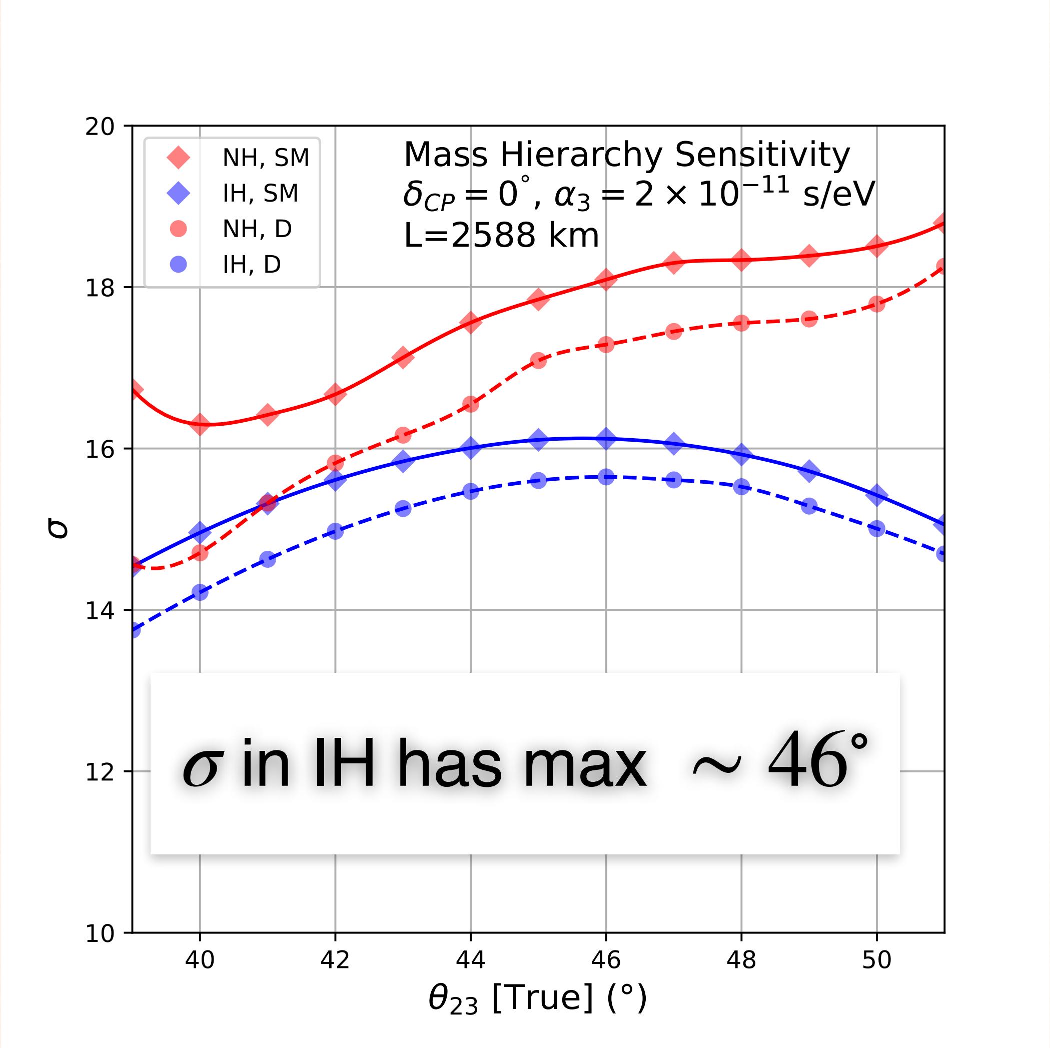


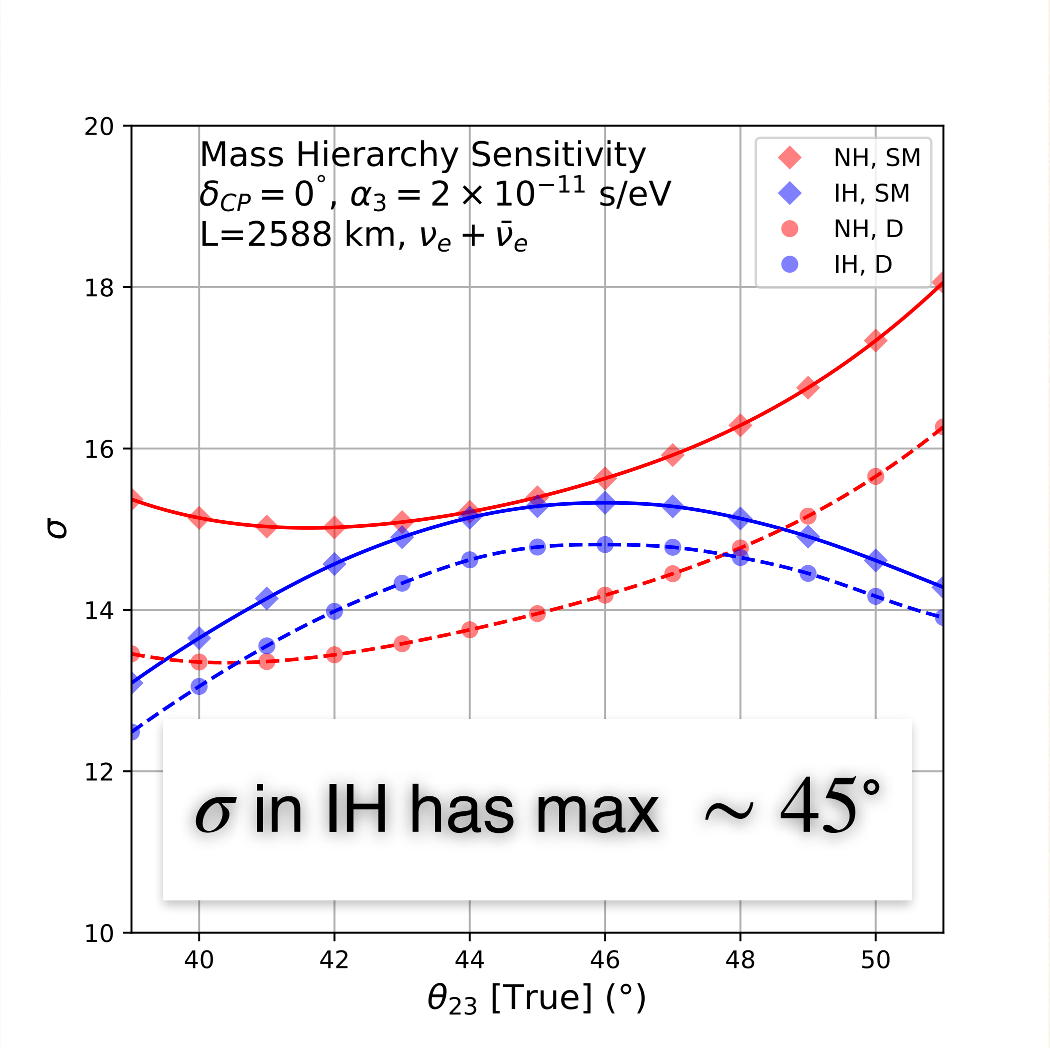


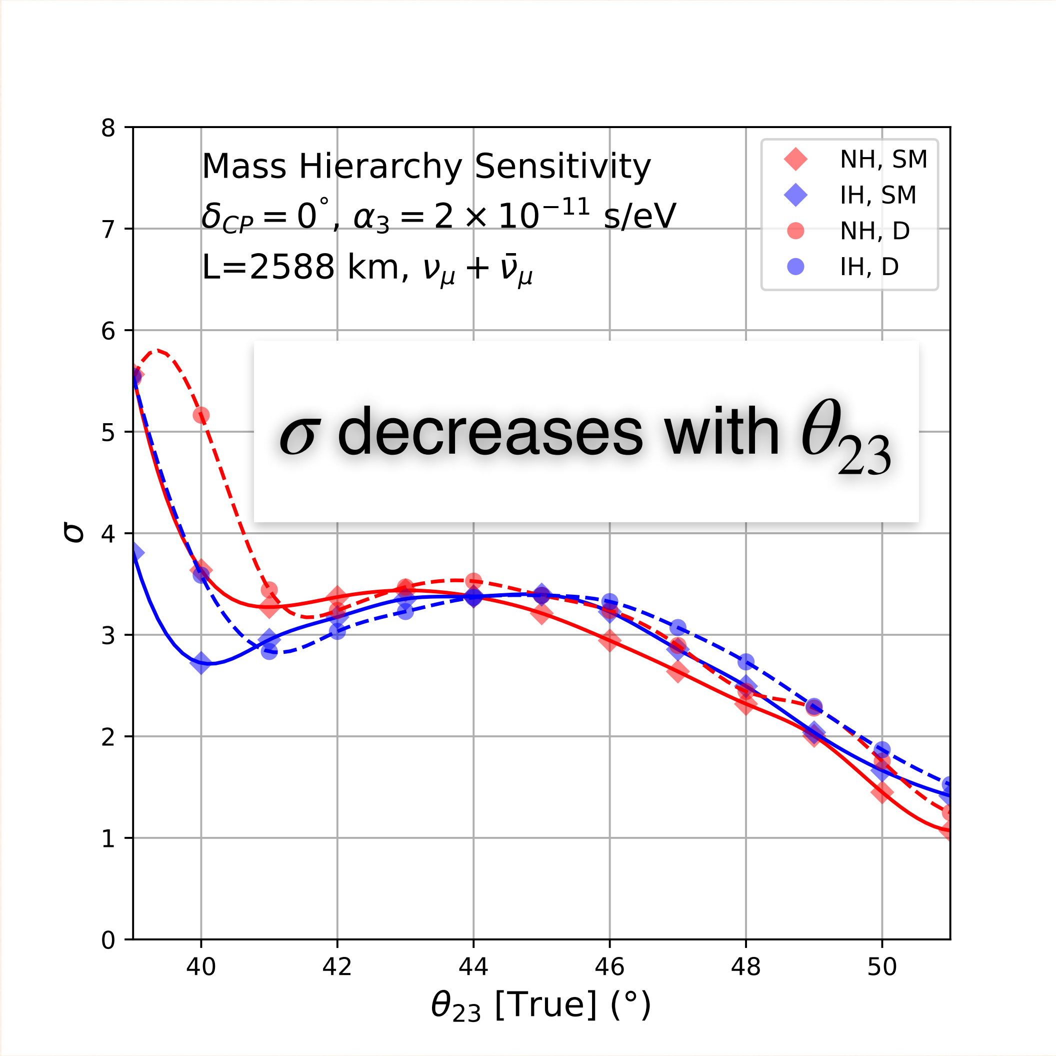


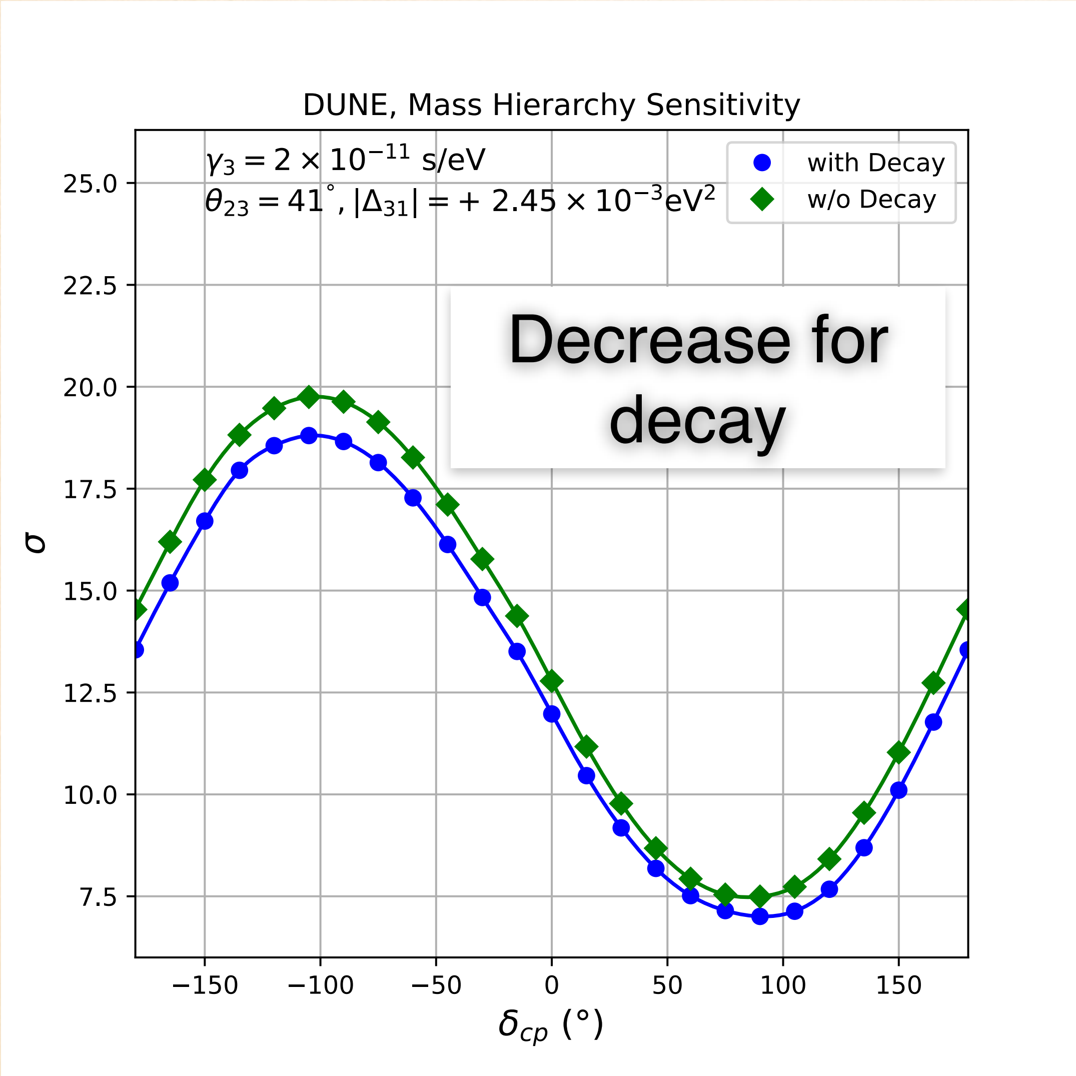
MASS ORDERING SENSITIVITY

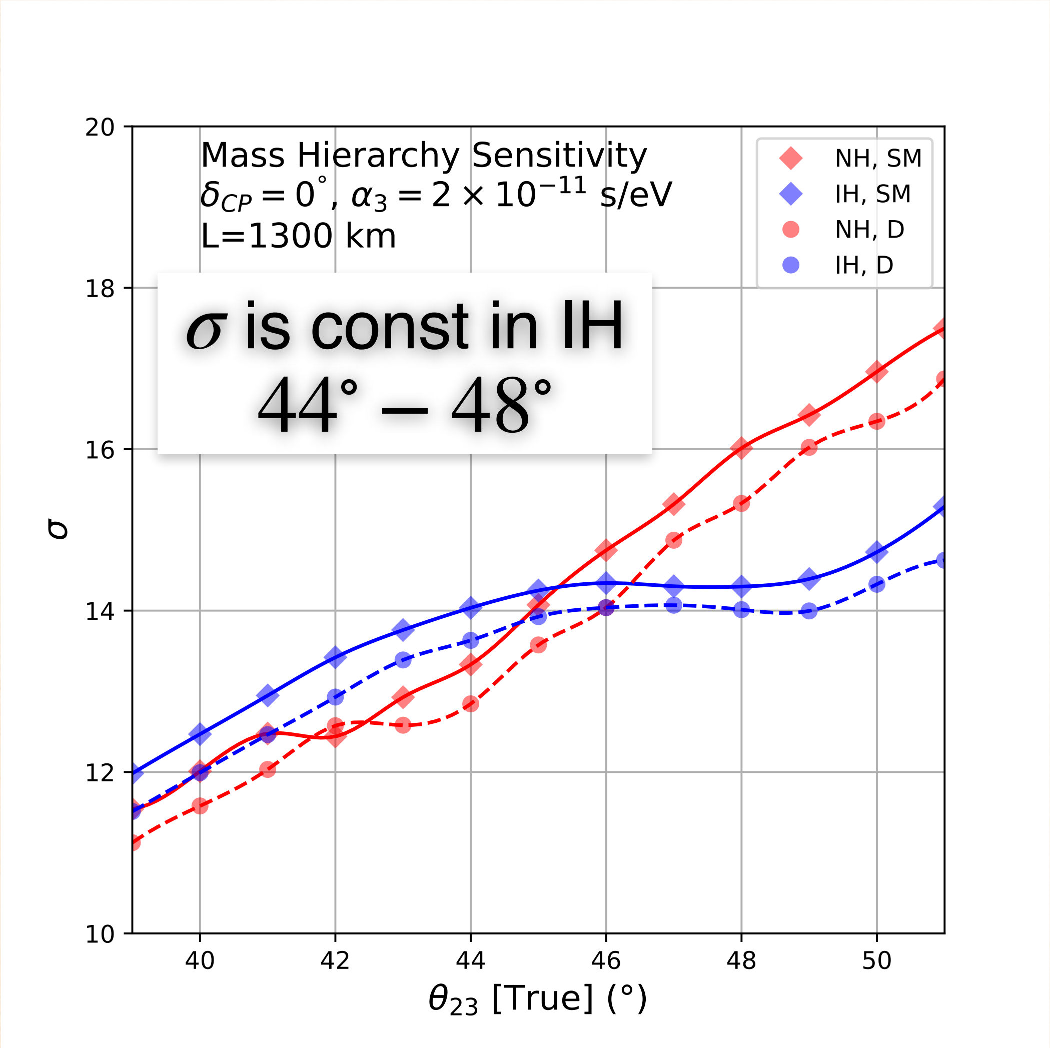


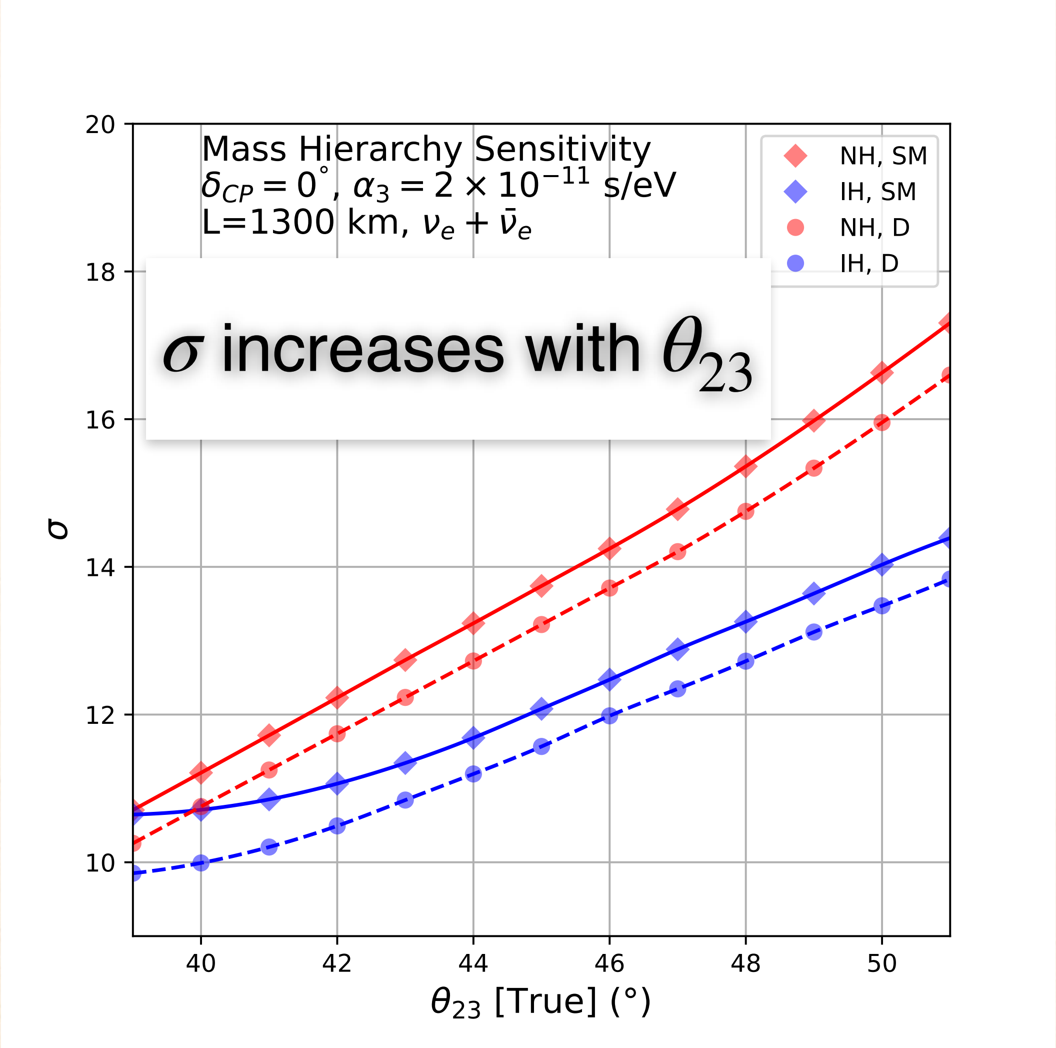


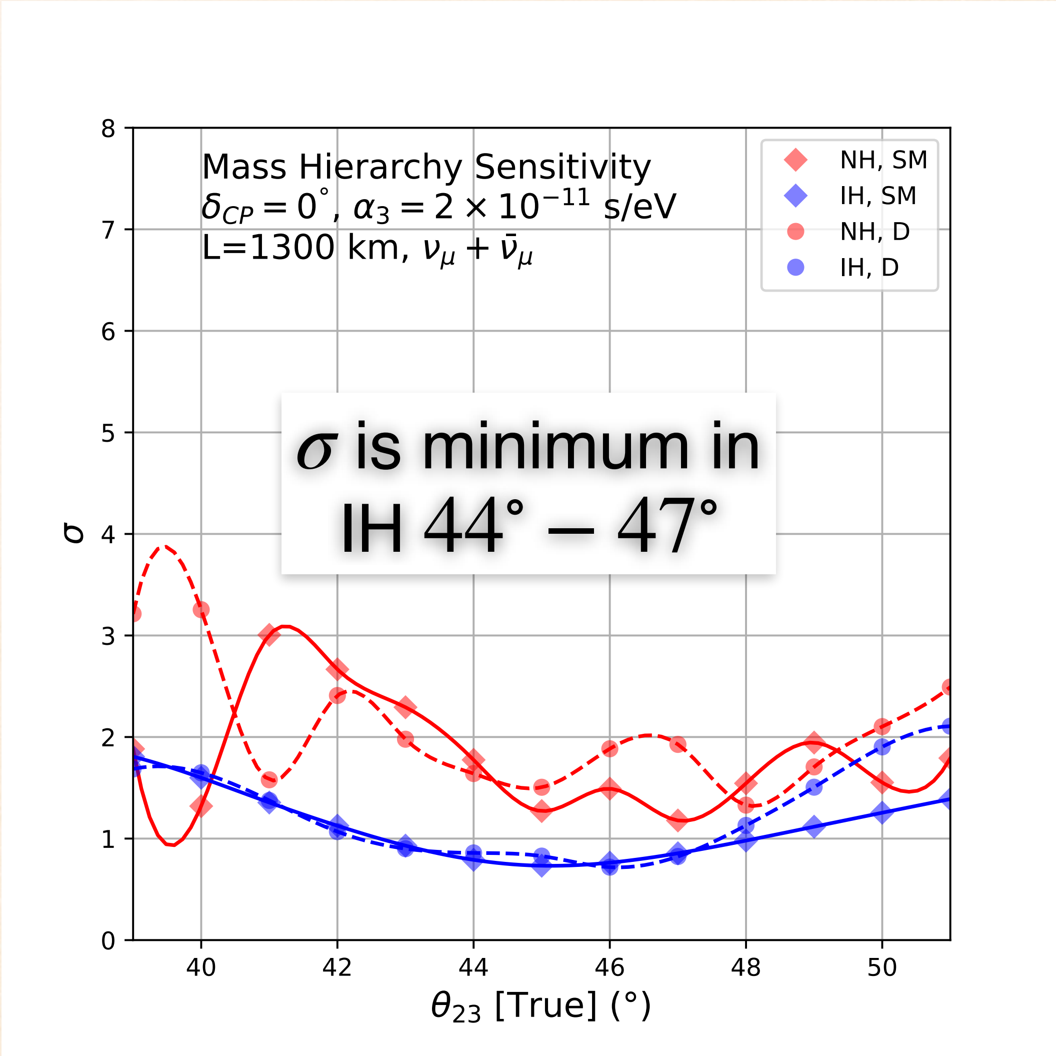




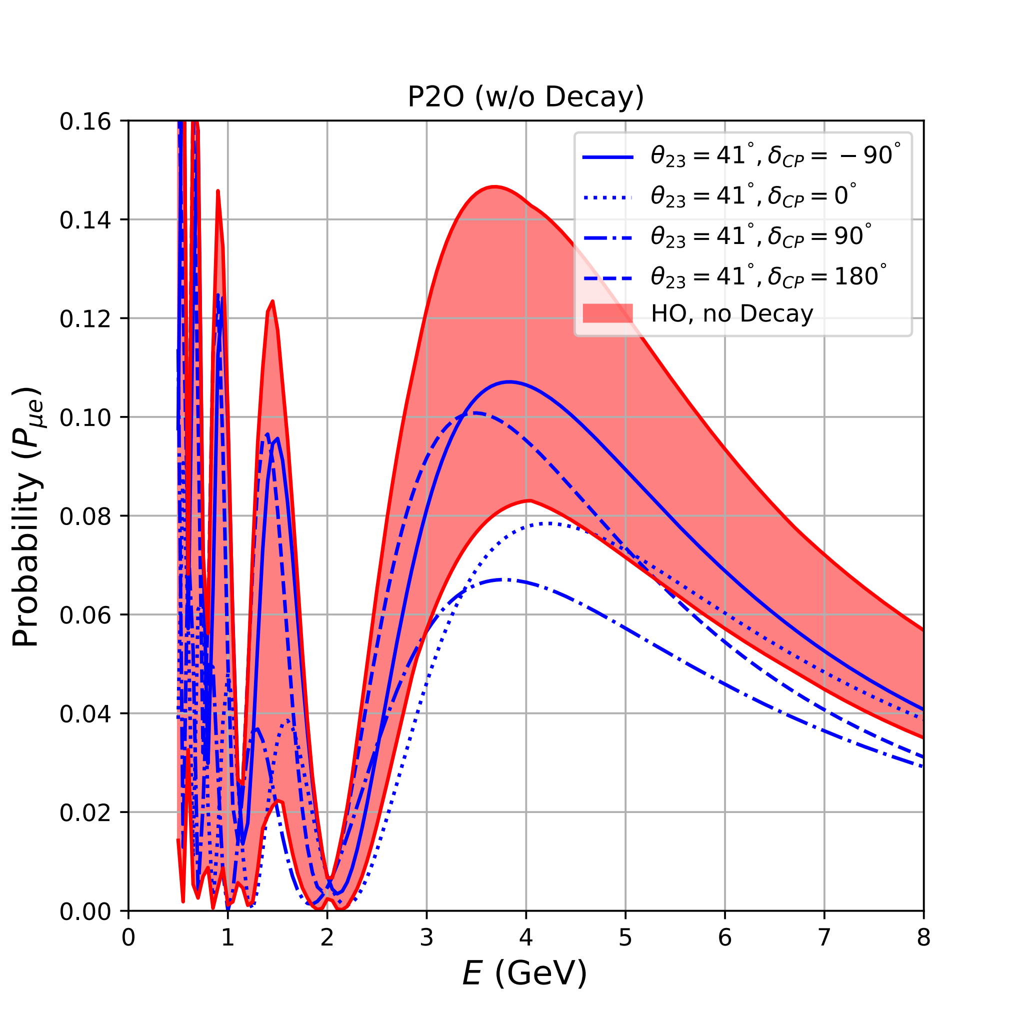


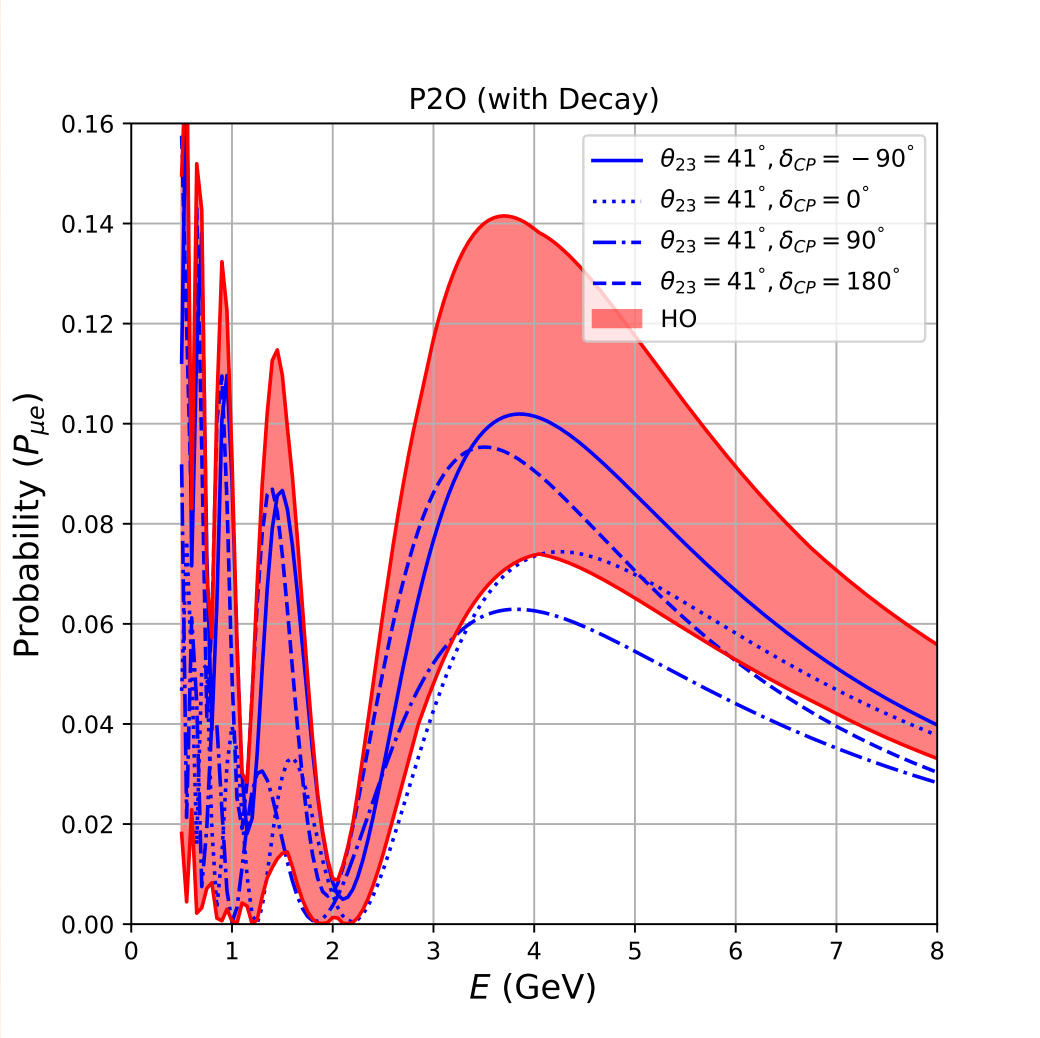


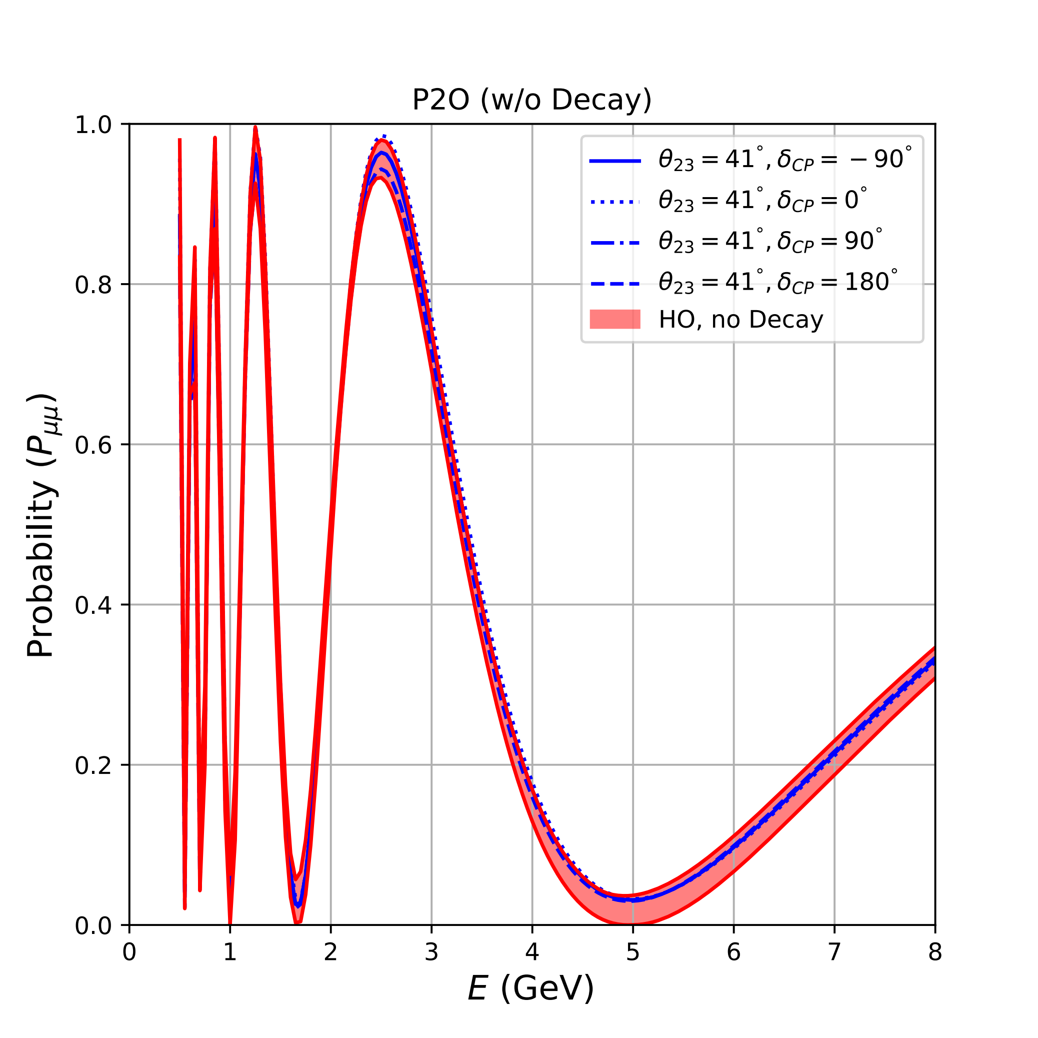


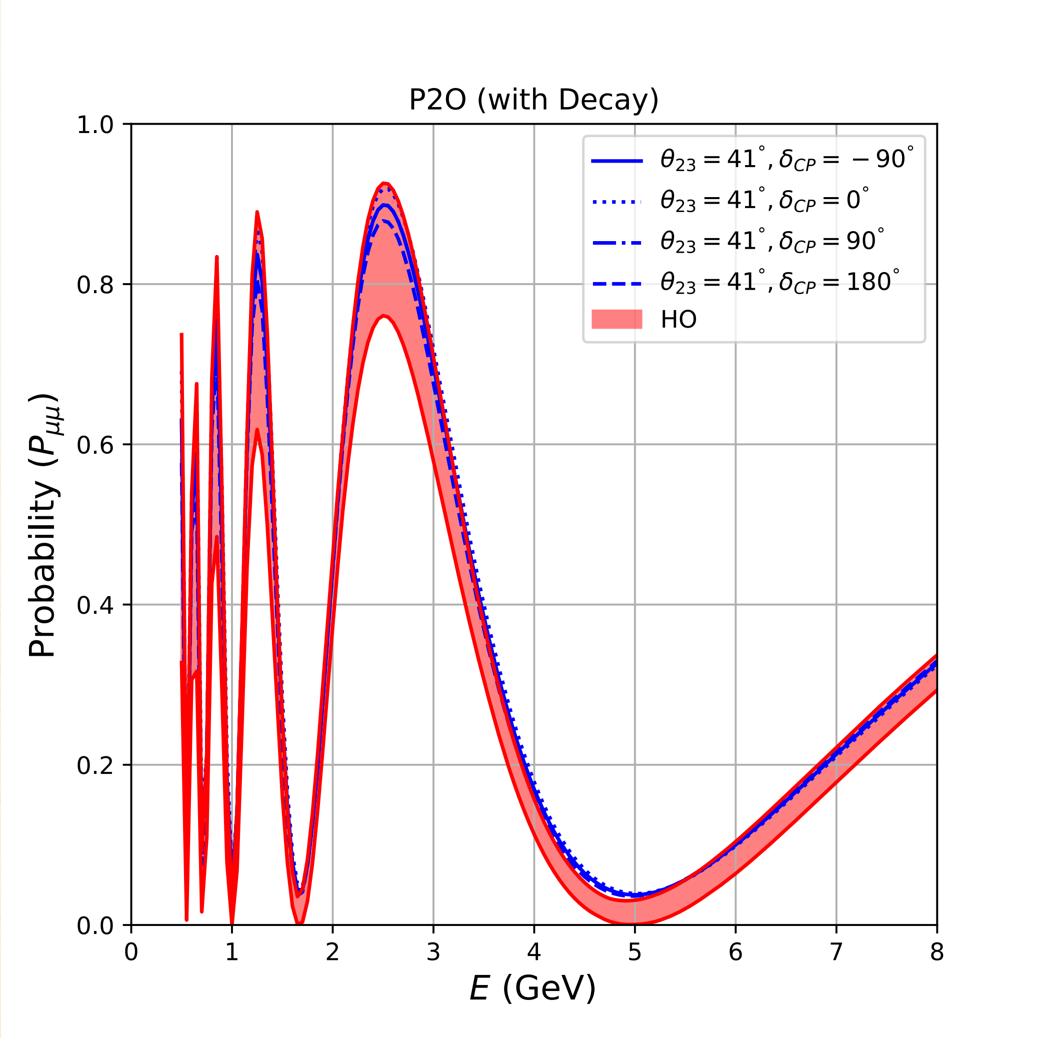


DEGENERACY RELATED TO OCTANT OF θ_{23}



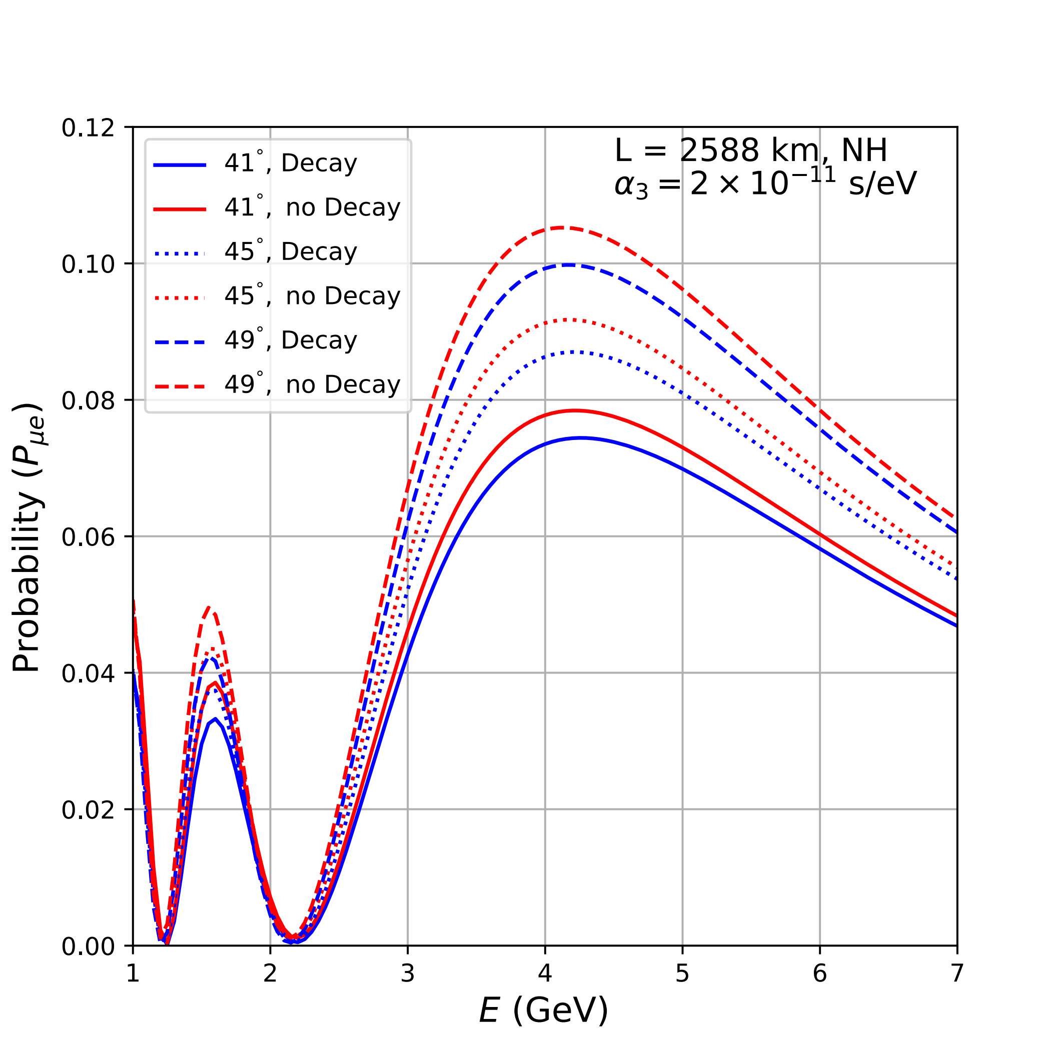


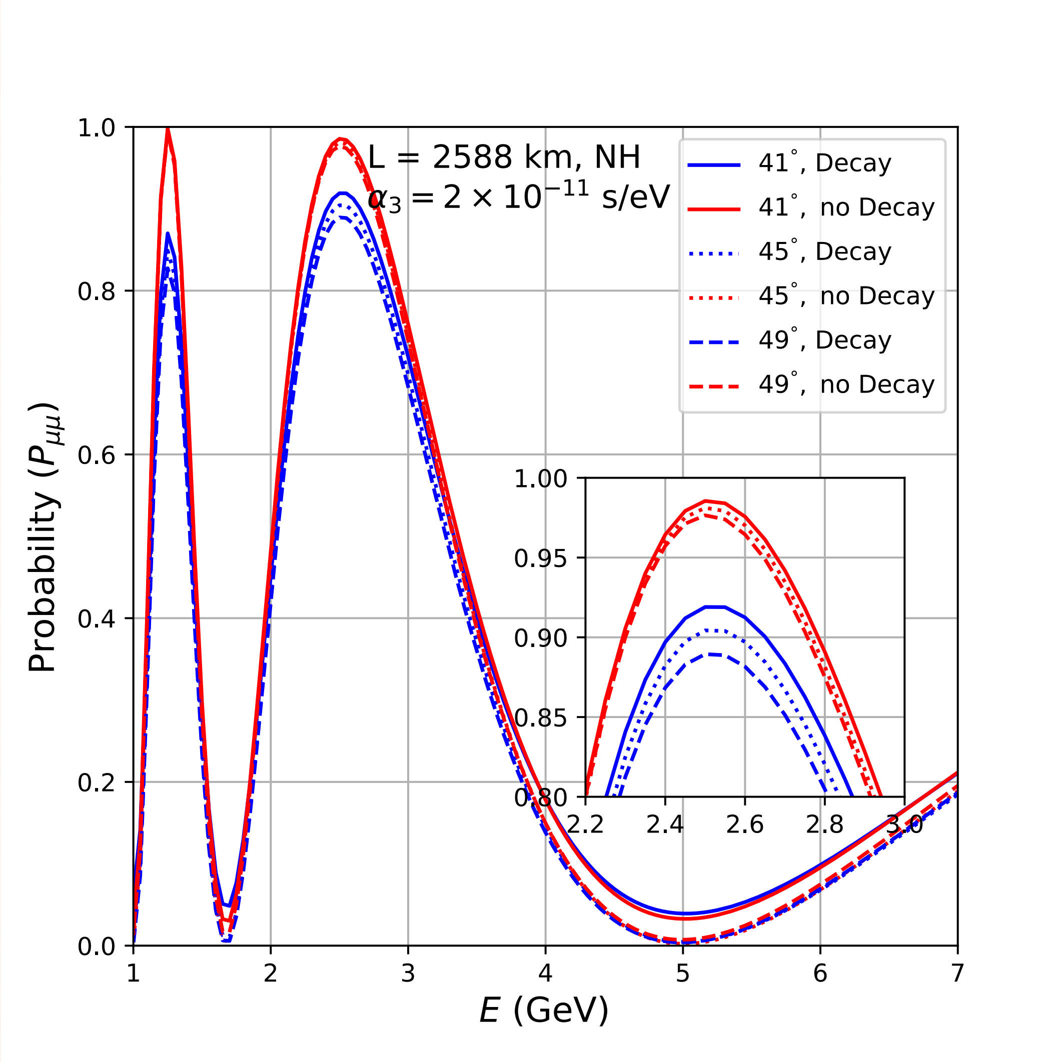




- Separation b/w HO band and 41° curve around 4 GeV smaller in $P_{\mu e}$$\Rightarrow$decreased sensitivity
- Separation between in $P_{\mu\mu}$ is higher for decay around 4 GeV $\Rightarrow$increased sensitivity

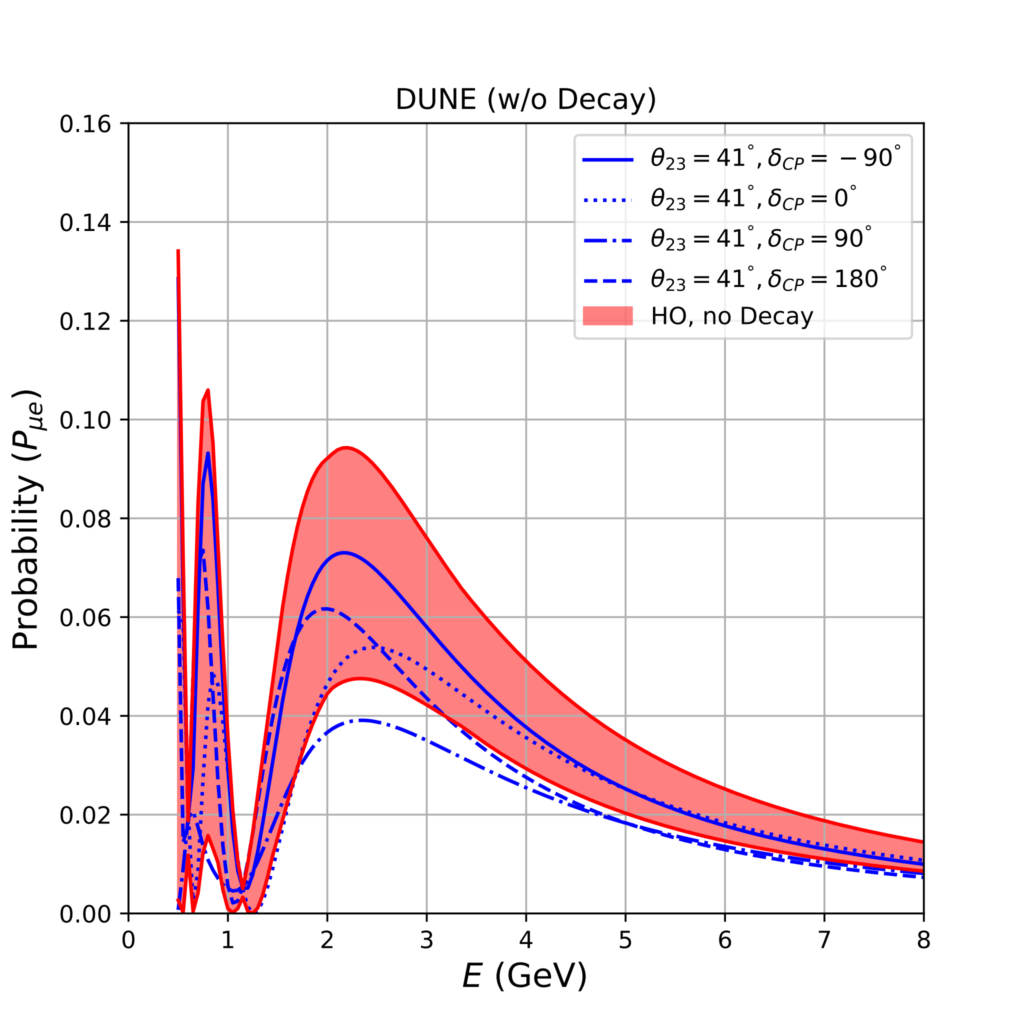
DEGENERACY RELATED TO OCTANT OF θ_{23}

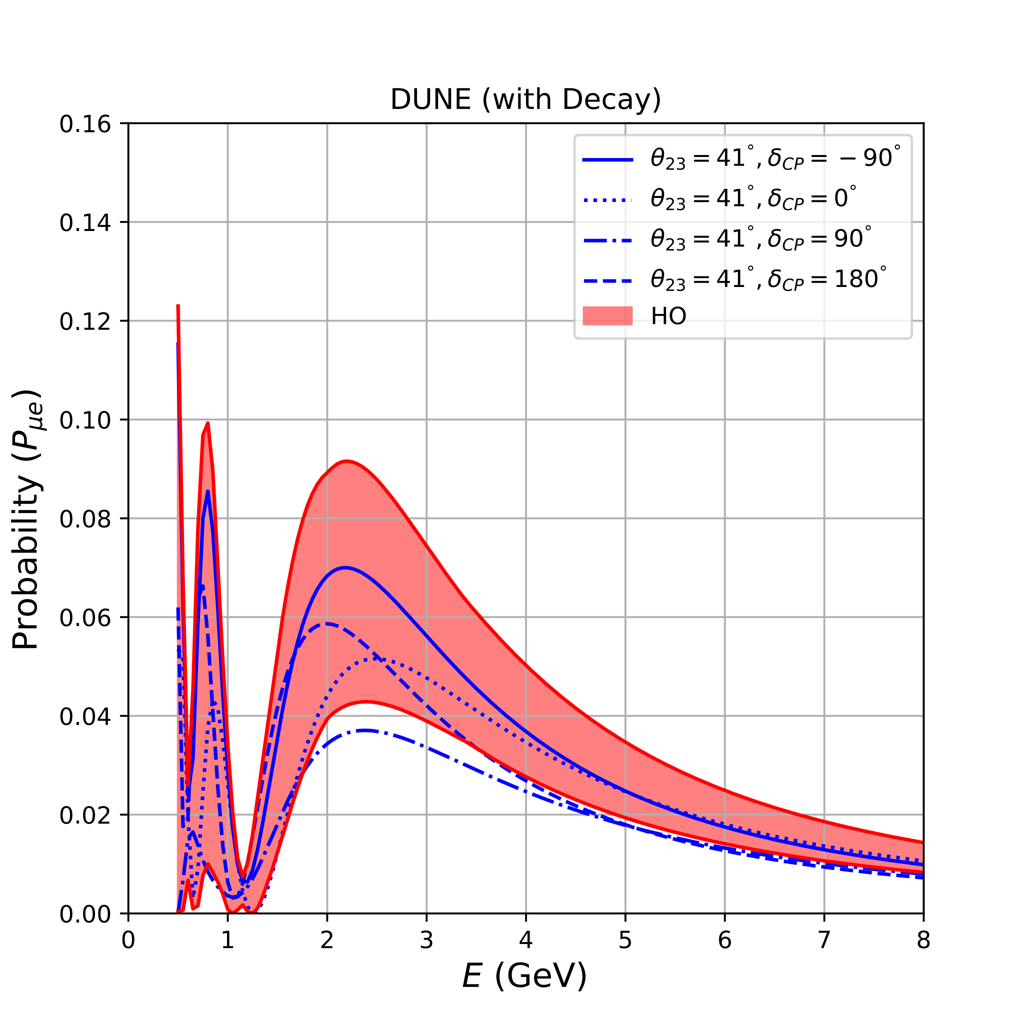




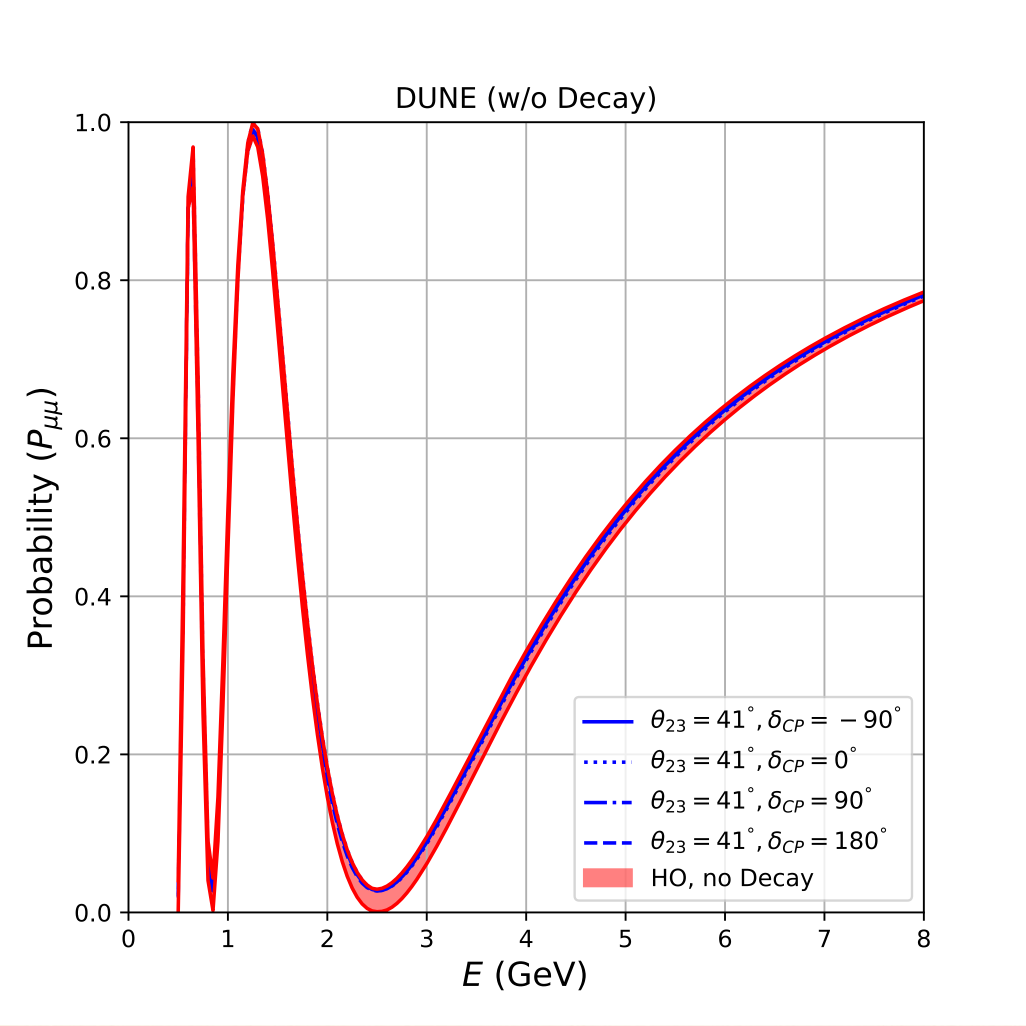
- Decrease in $P_{\mu e}, P_{\mu\mu}$ for lowering θ_{23} and higher value of decay $\Rightarrow$ New degeneracy b/w $\theta_{23} - \alpha_3$

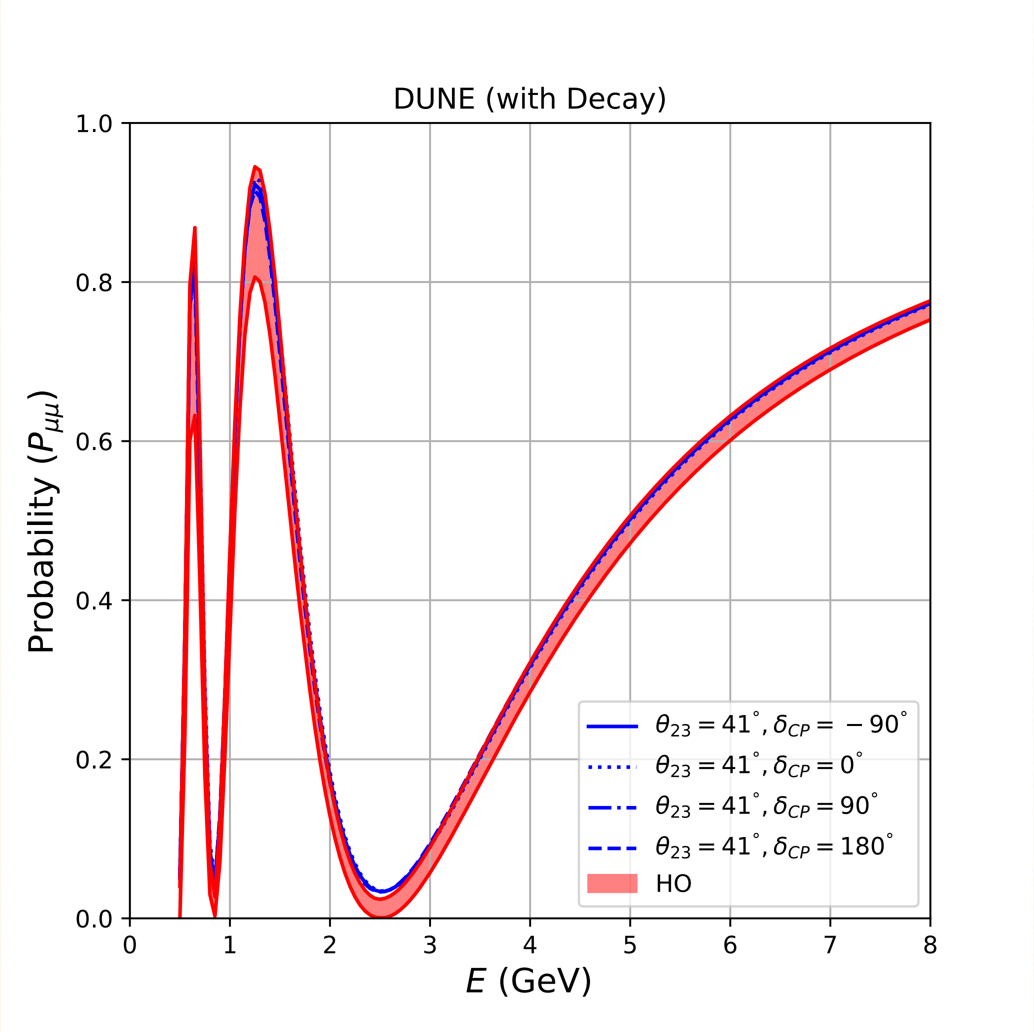
DEGENERACY RELATED TO OCTANT OF θ_{23}



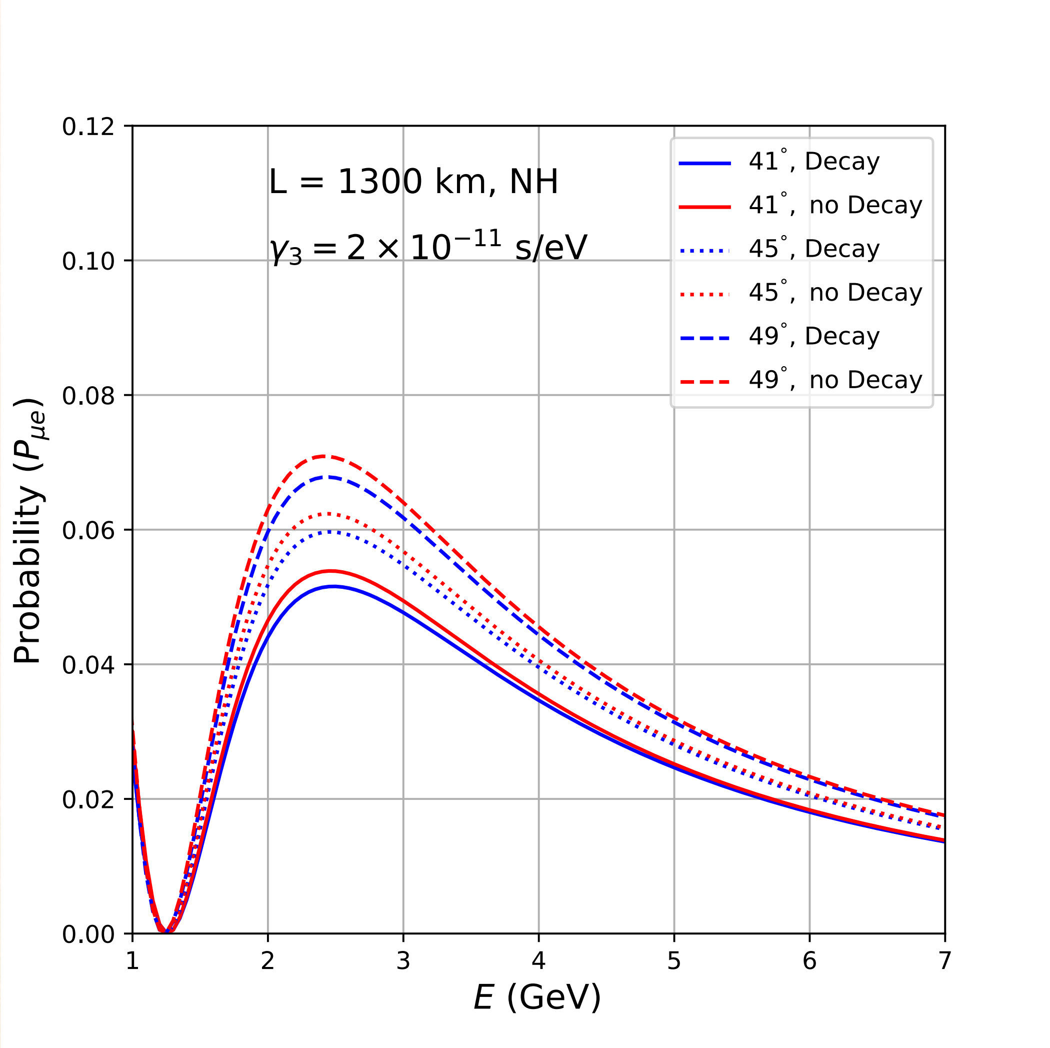


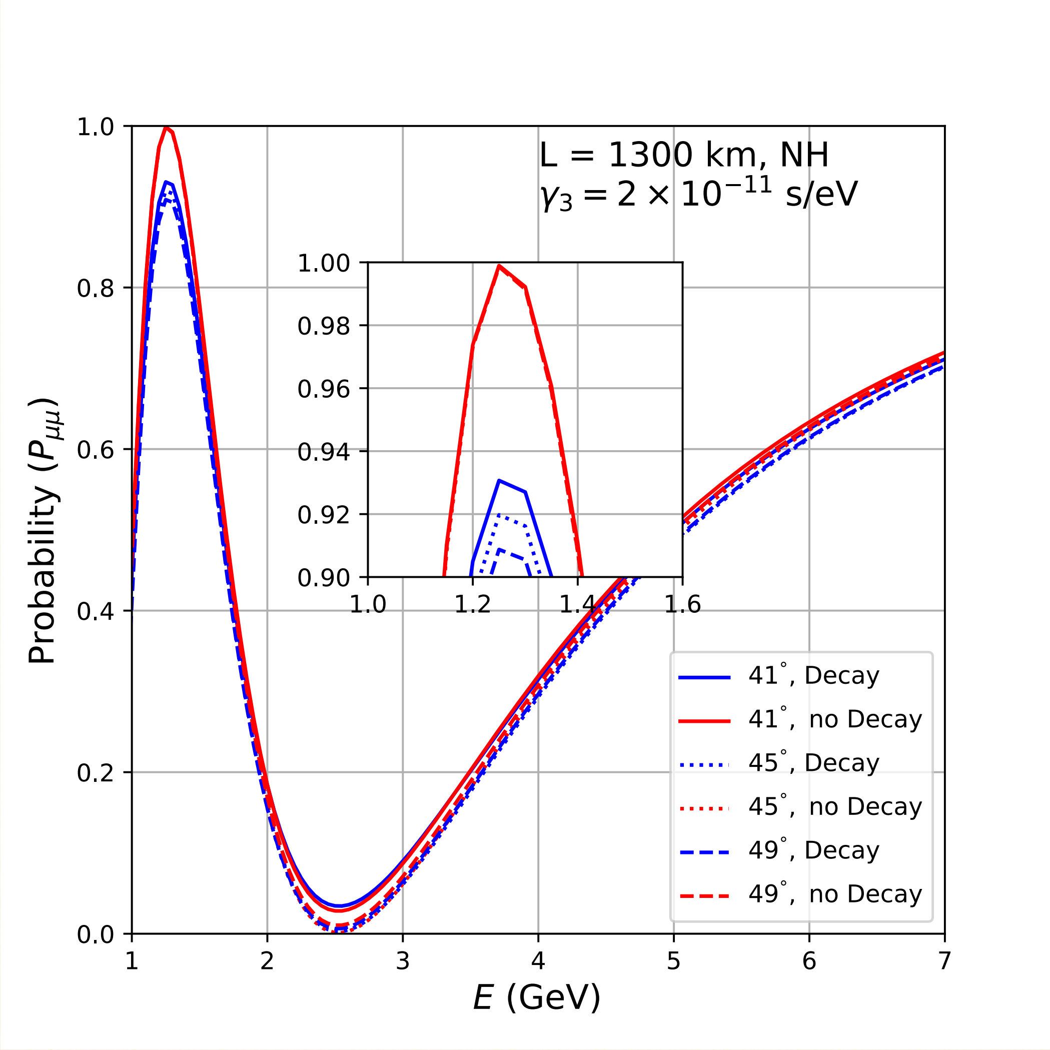
- Separation b/w HO band and 41° curve around 2.5 GeV smaller in $P_{\mu e}$ $\Rightarrow$ decreased sensitivity
- Separation between in $P_{\mu\mu}$ is higher for decay around 2.5 GeV $\Rightarrow$ increased sensitivity





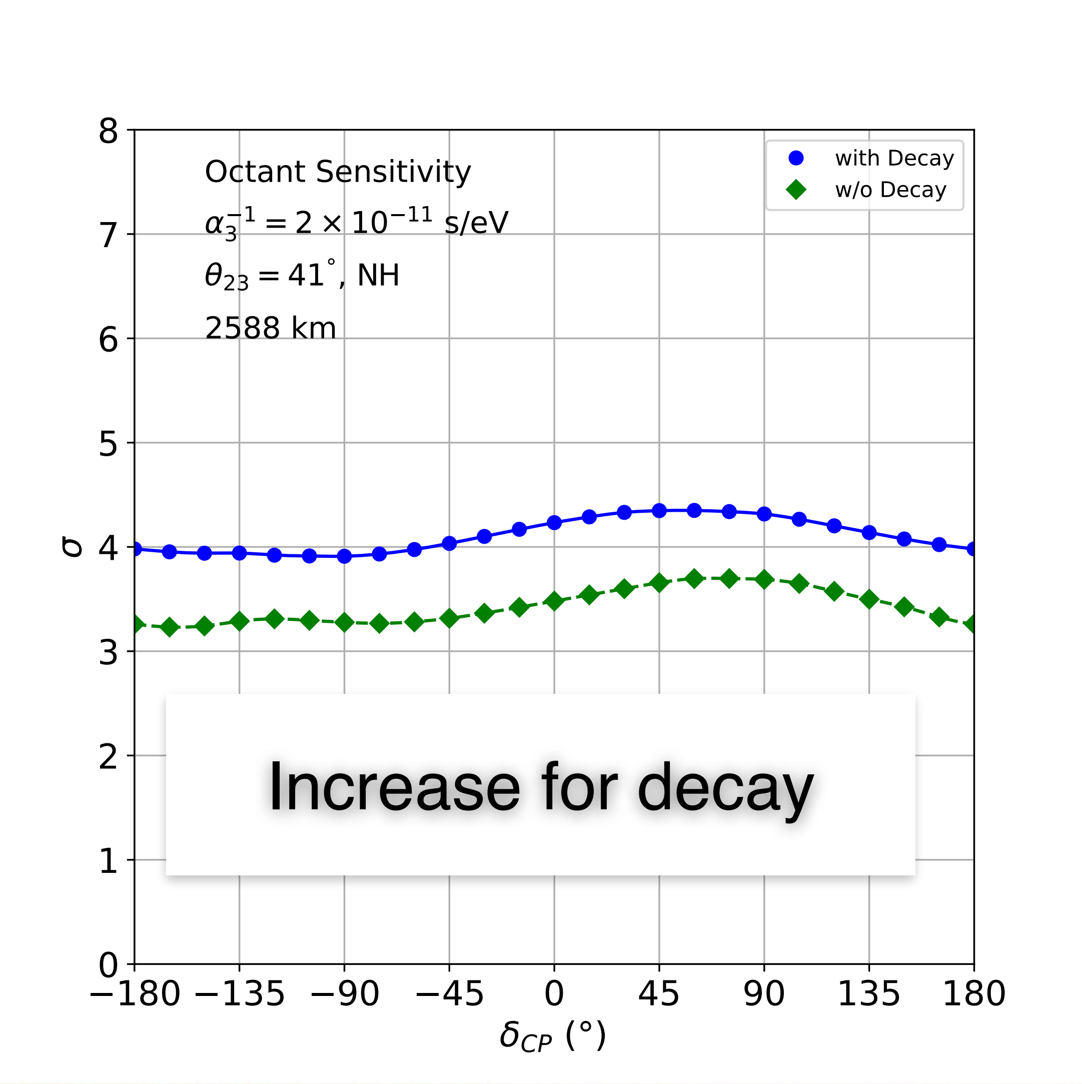
DEGENERACY RELATED TO OCTANT OF θ_{23}

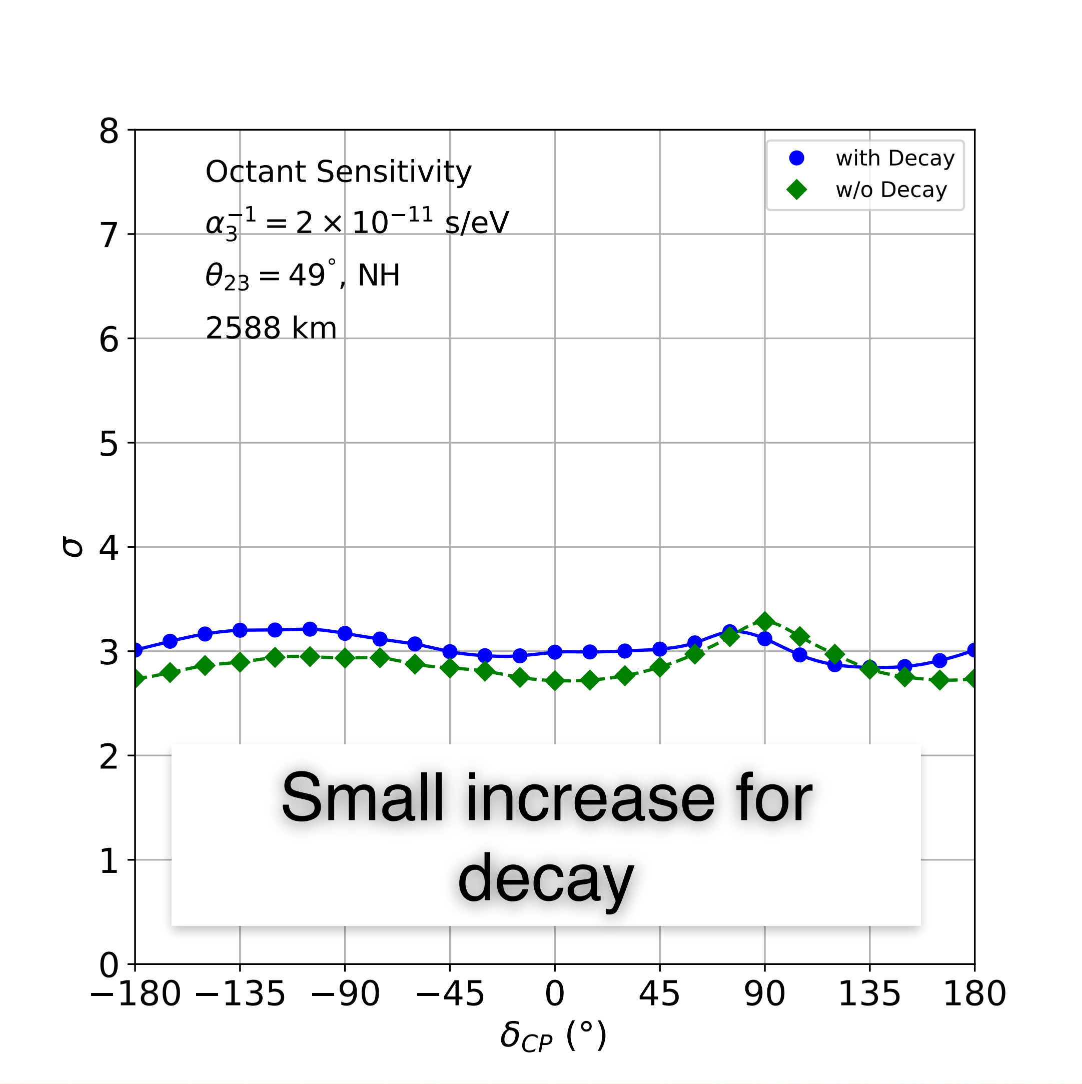


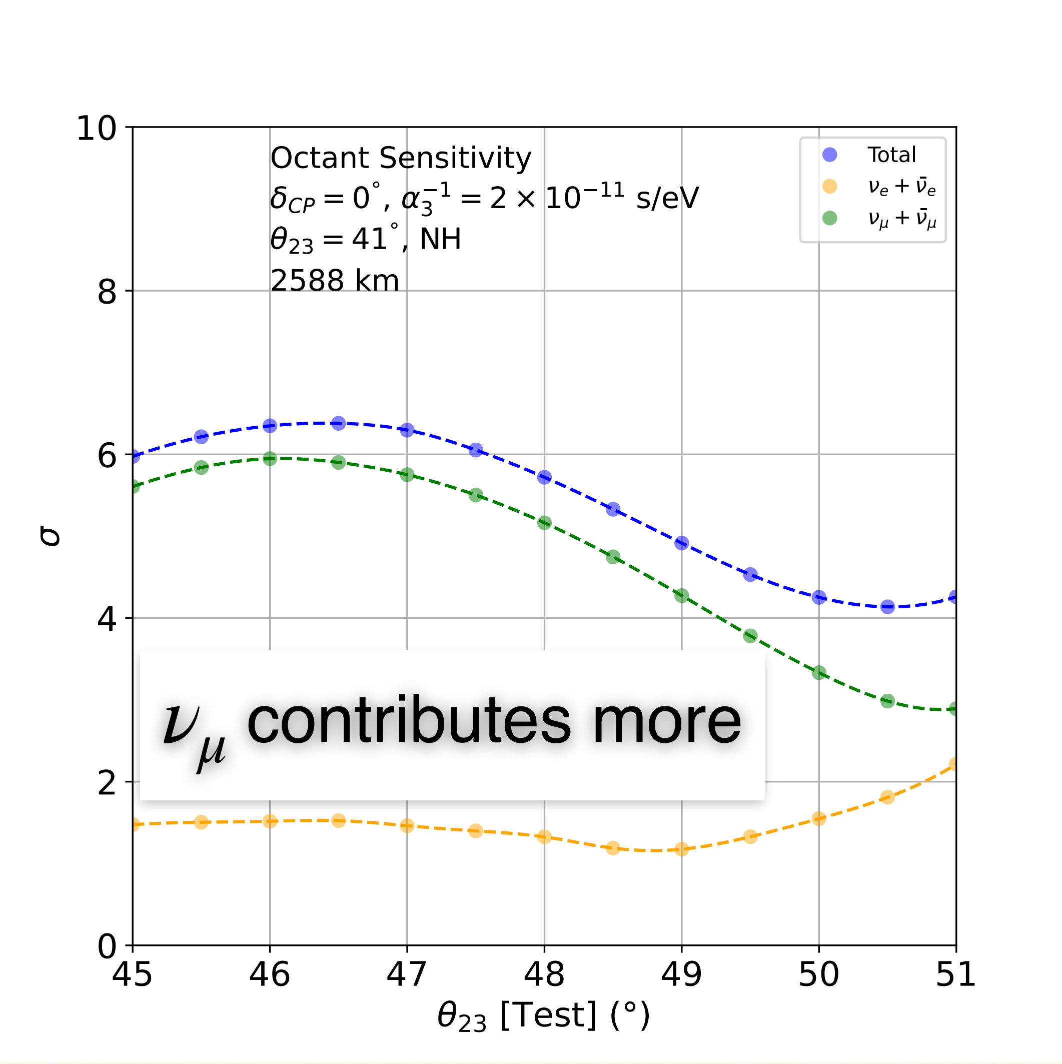


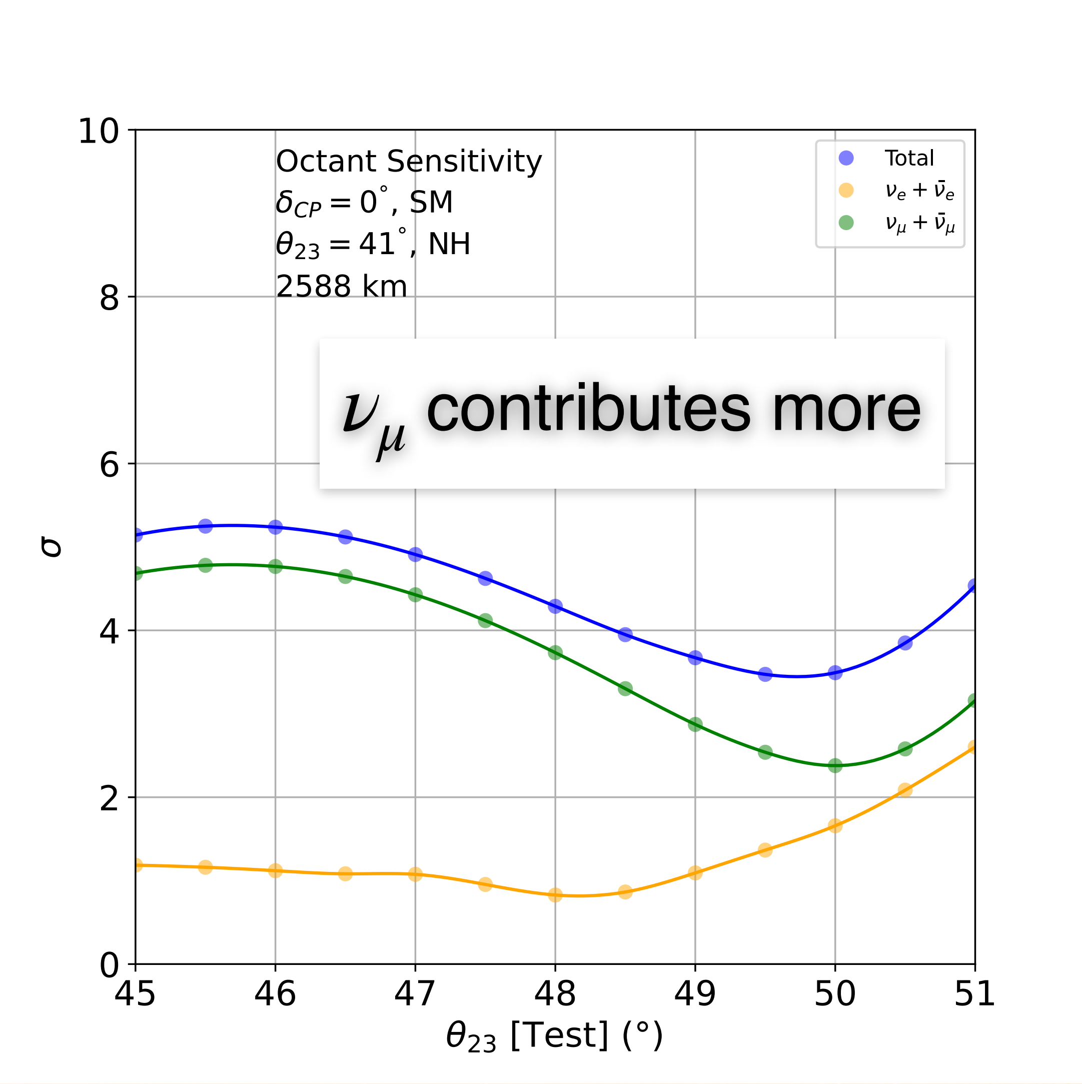
- Decrease in $P_{\mu e}, P_{\mu\mu}$ for lowering θ_{23} and higher value of decay $\Rightarrow$ New degeneracy b/w $\theta_{23} - \alpha_3$

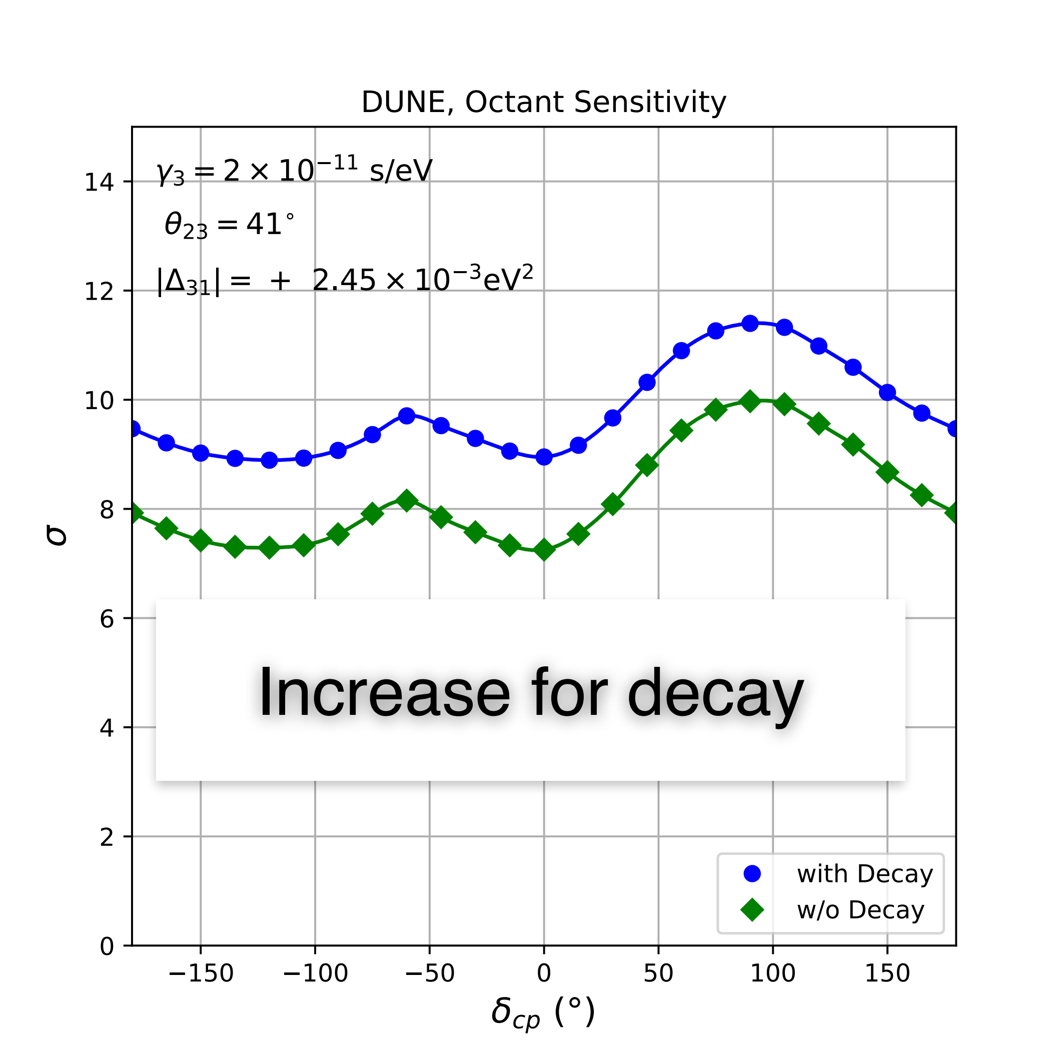
OCTANT SENSITIVITY

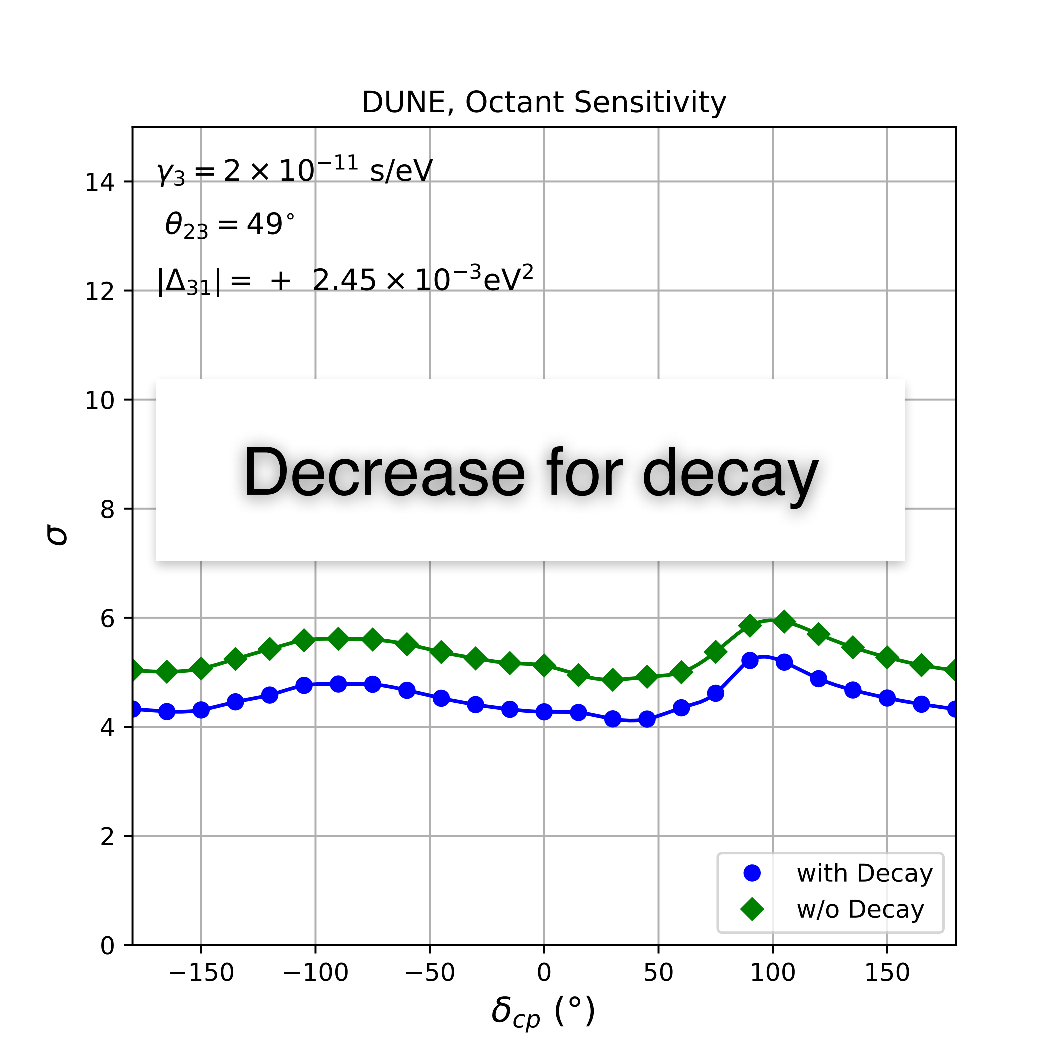


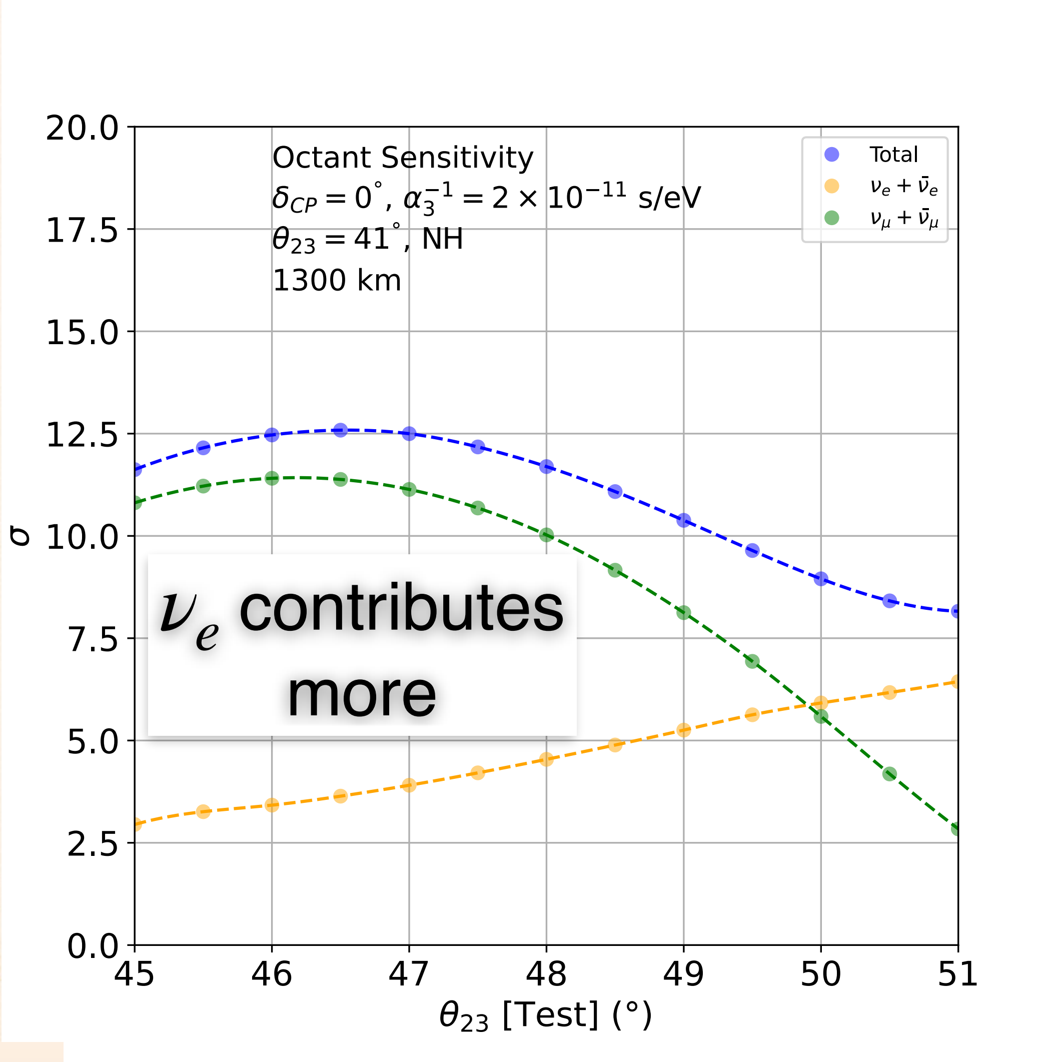


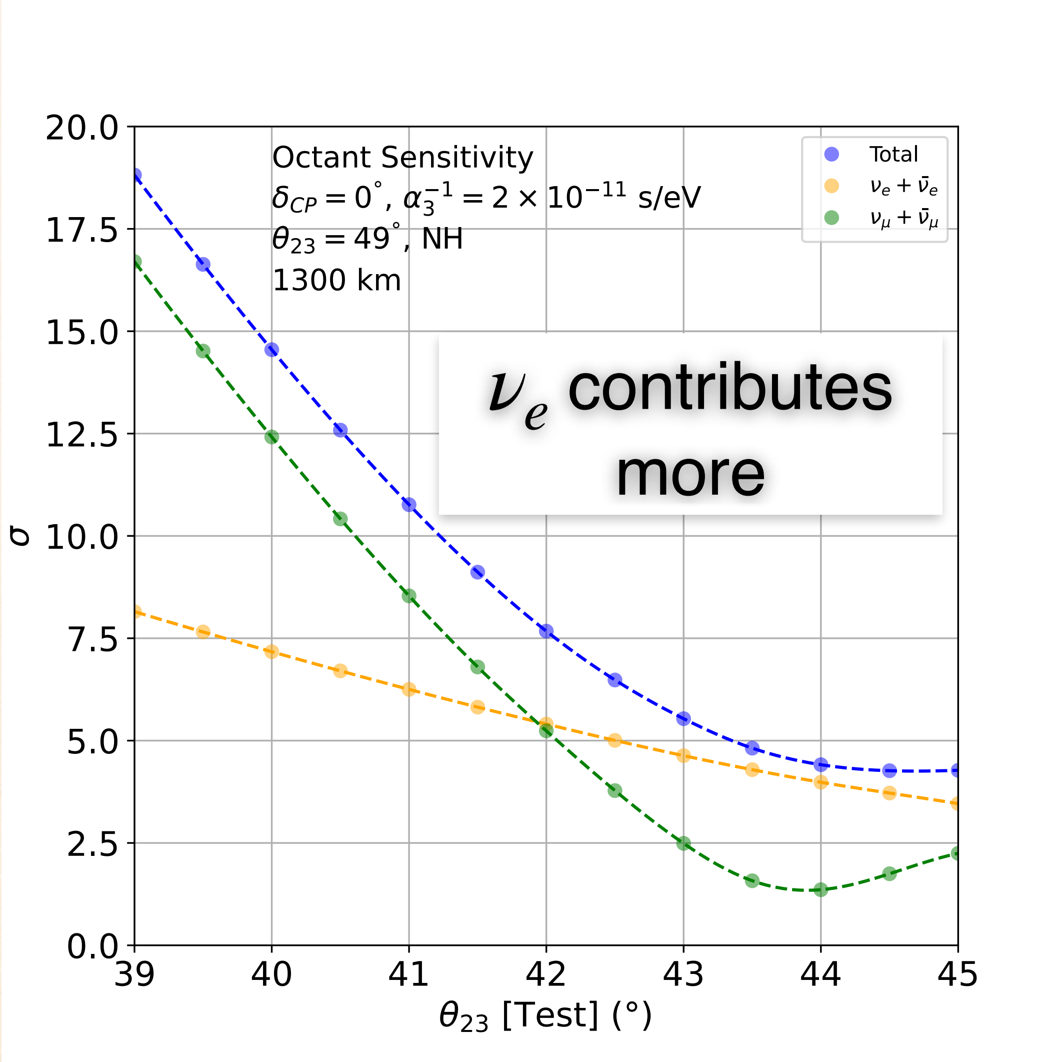




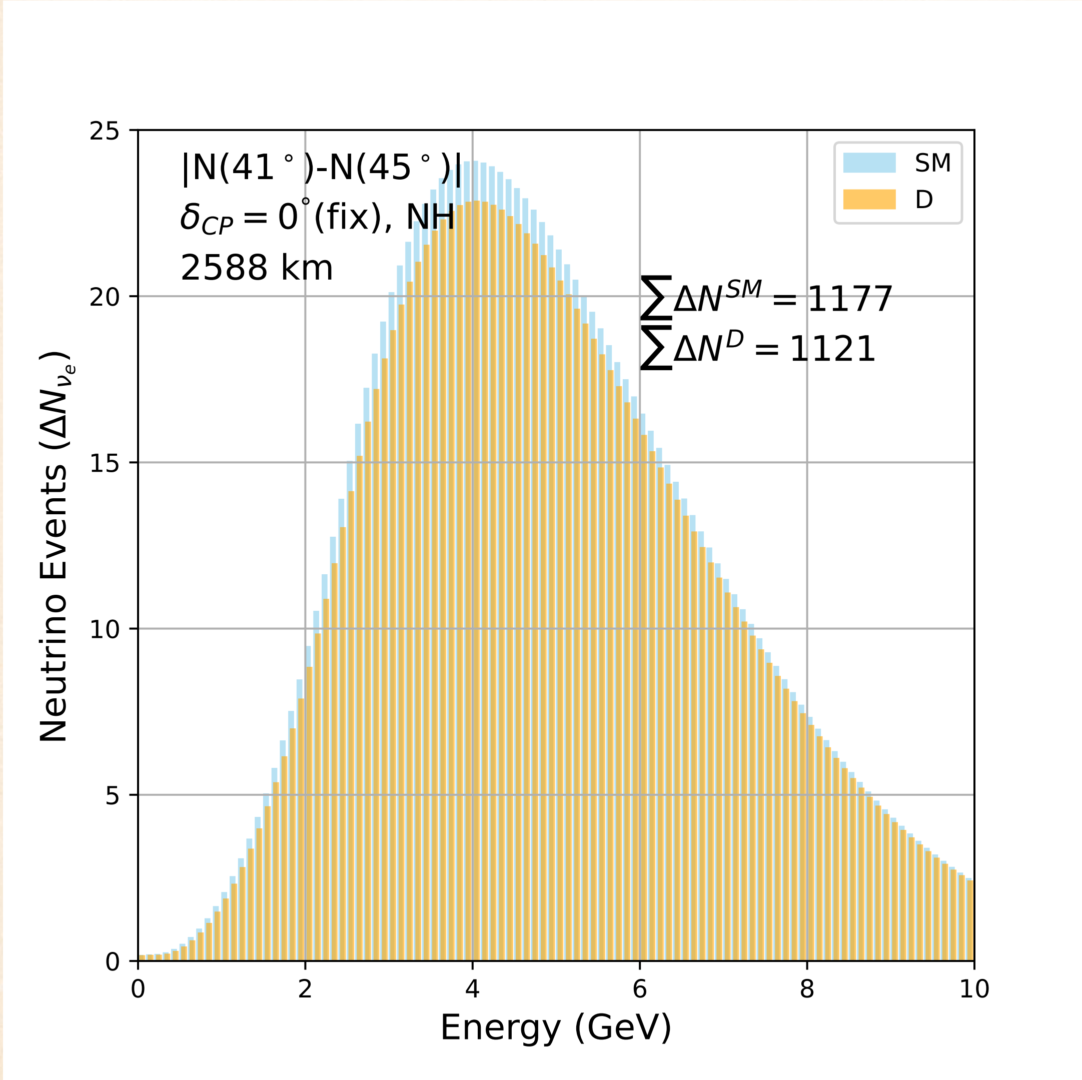


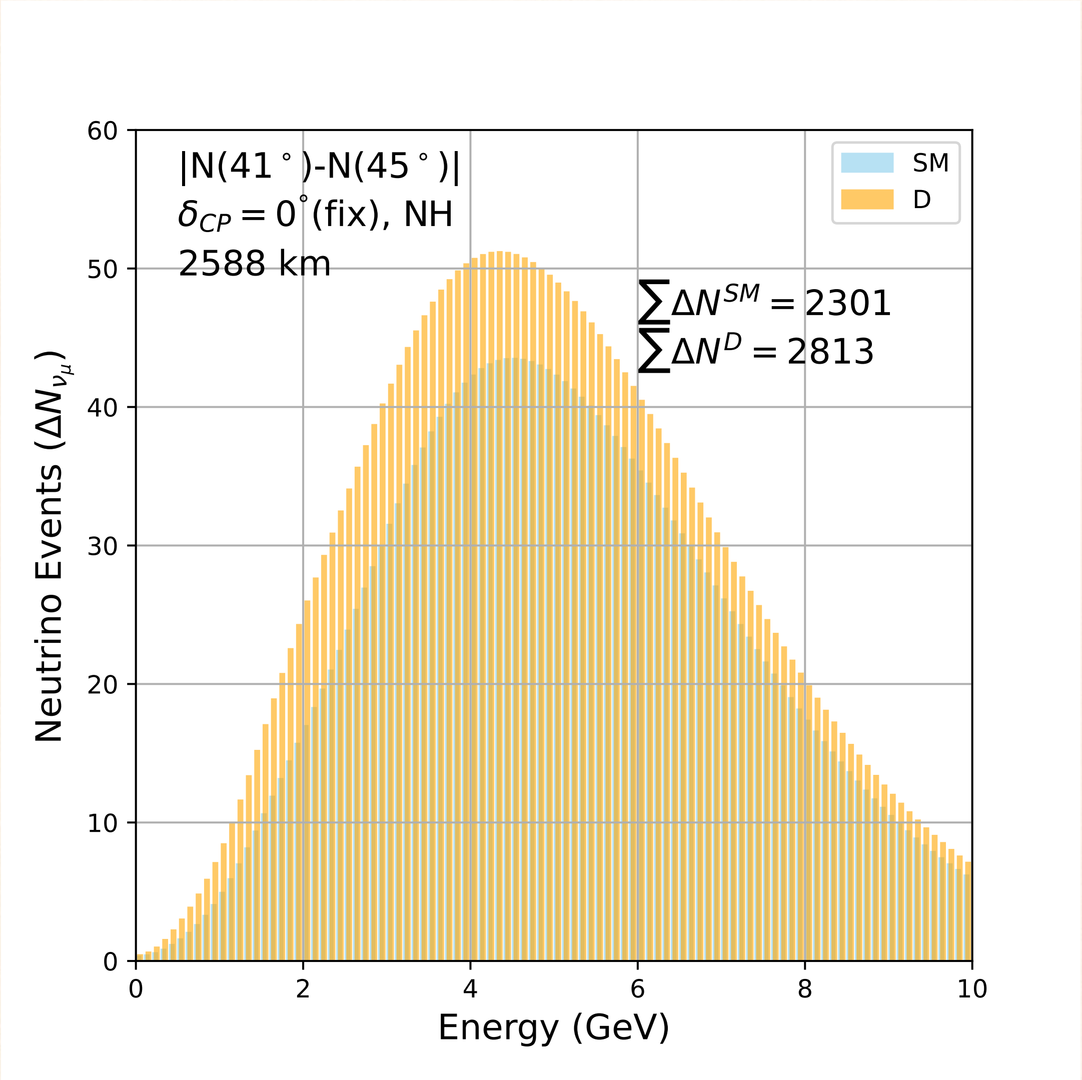


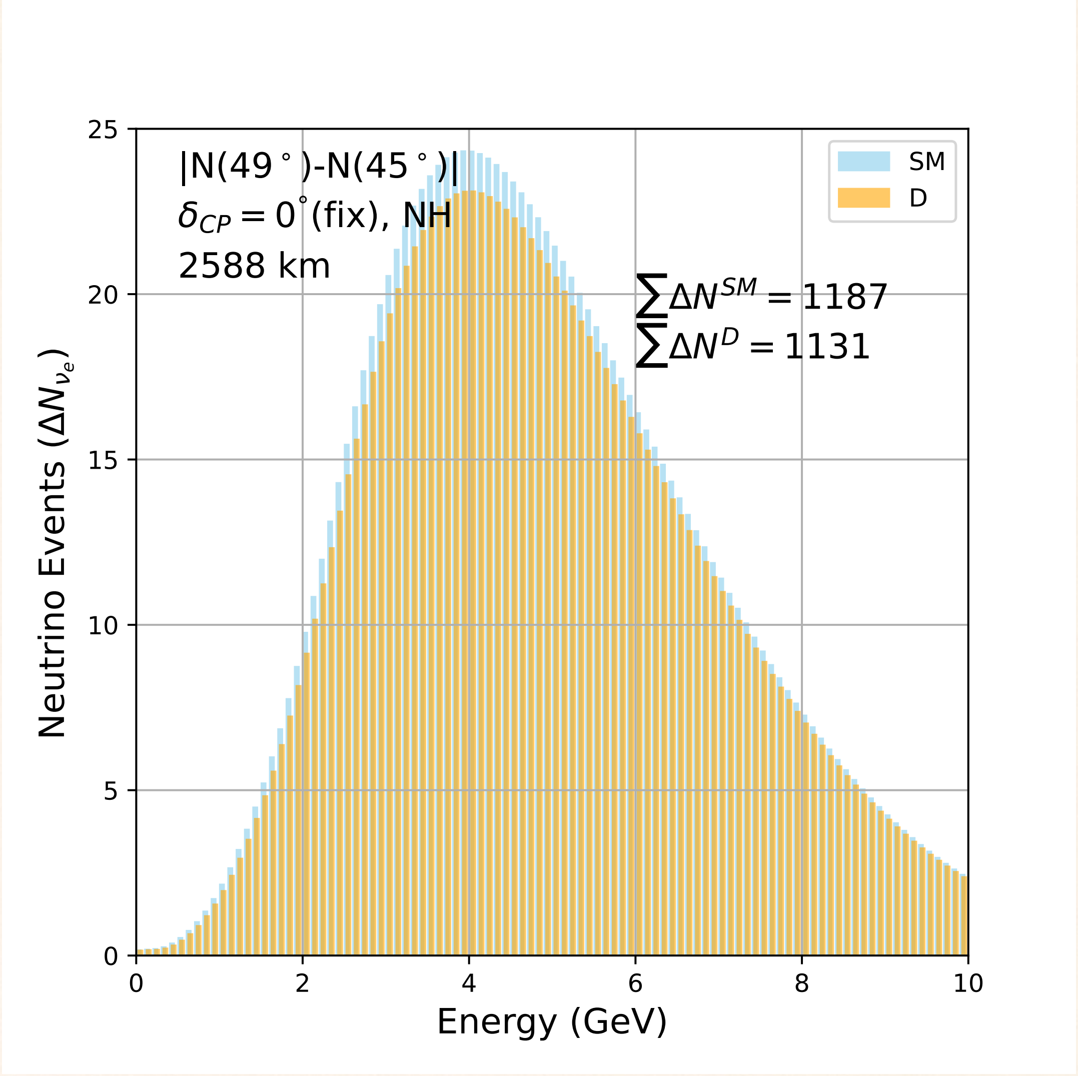


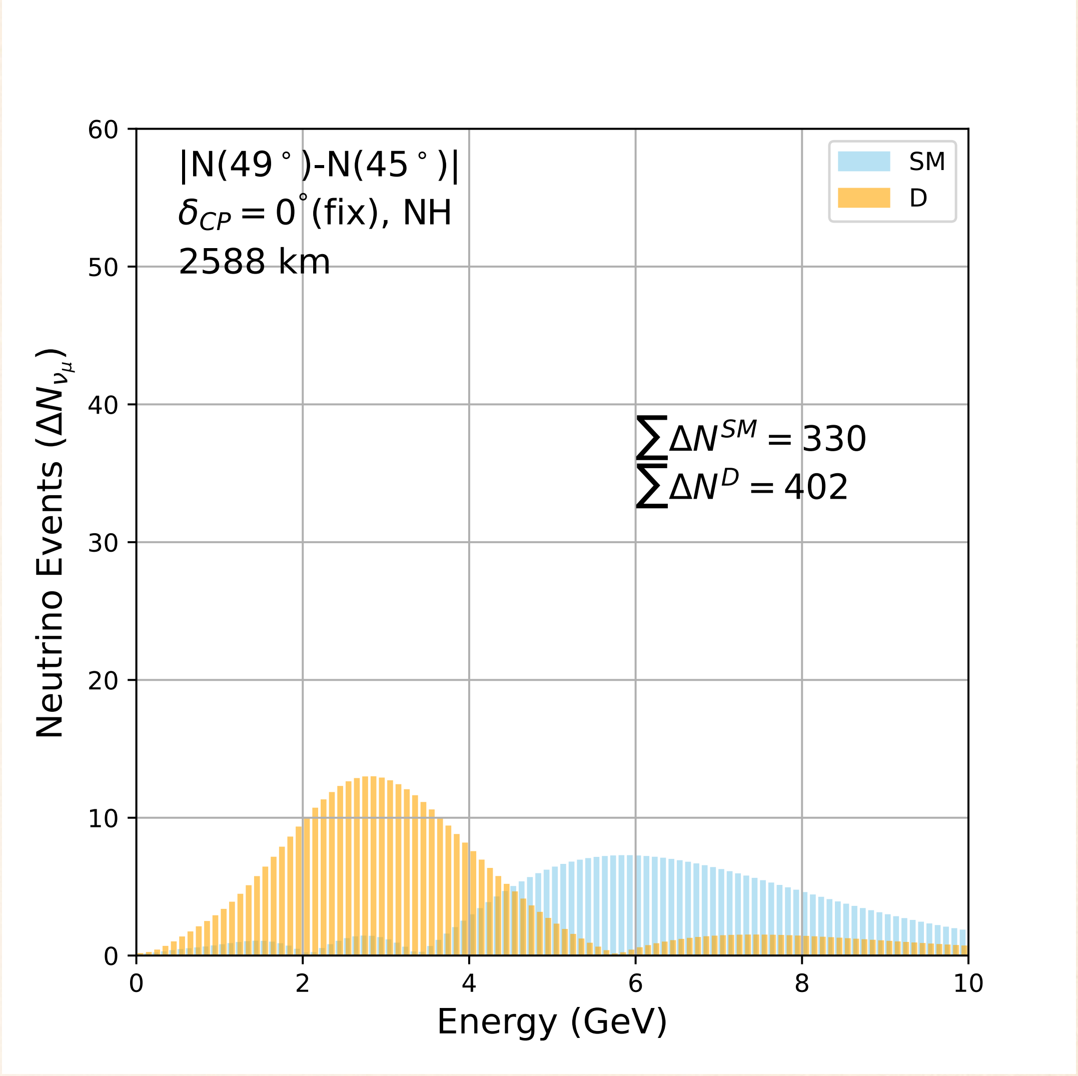


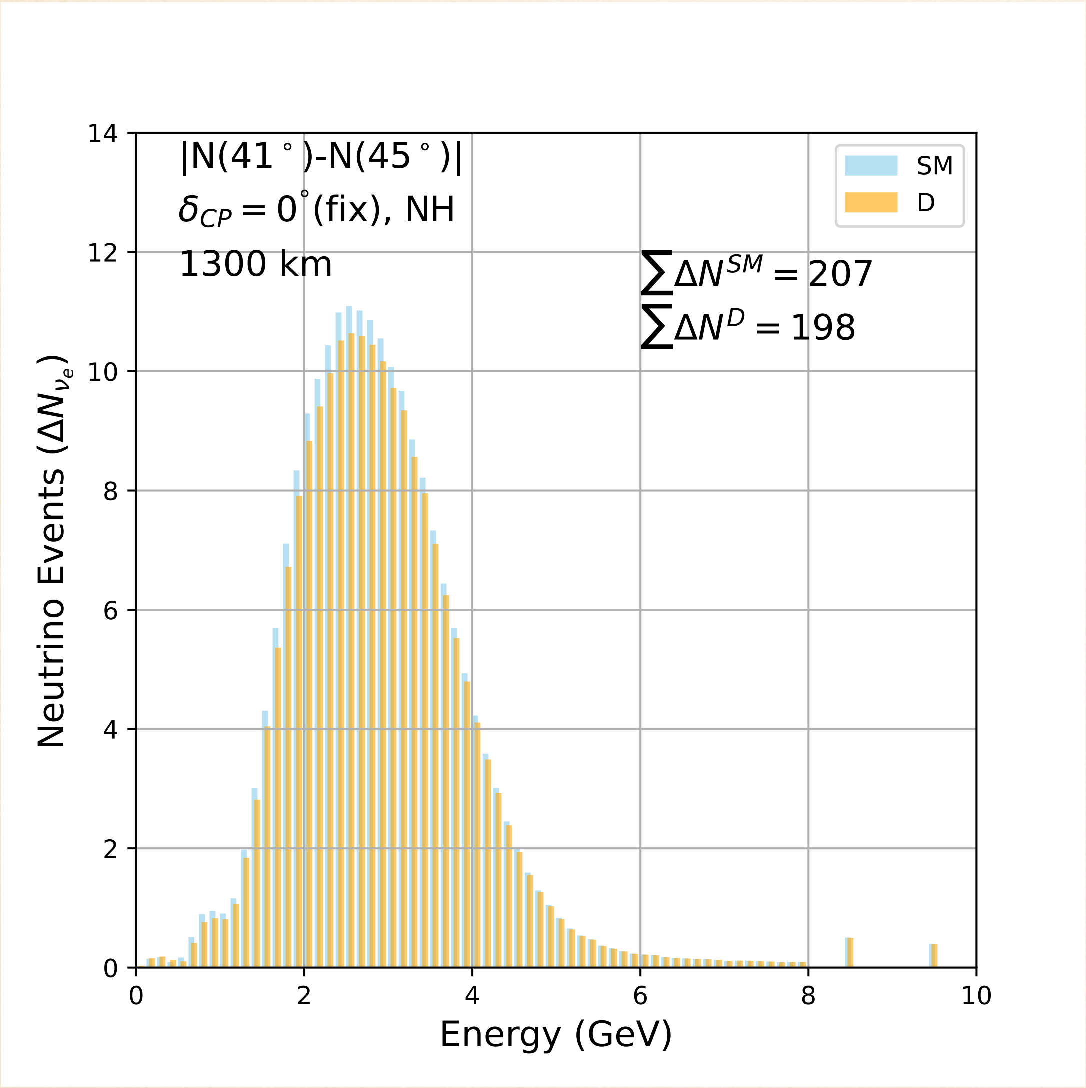
EVENTS SPECTRUM

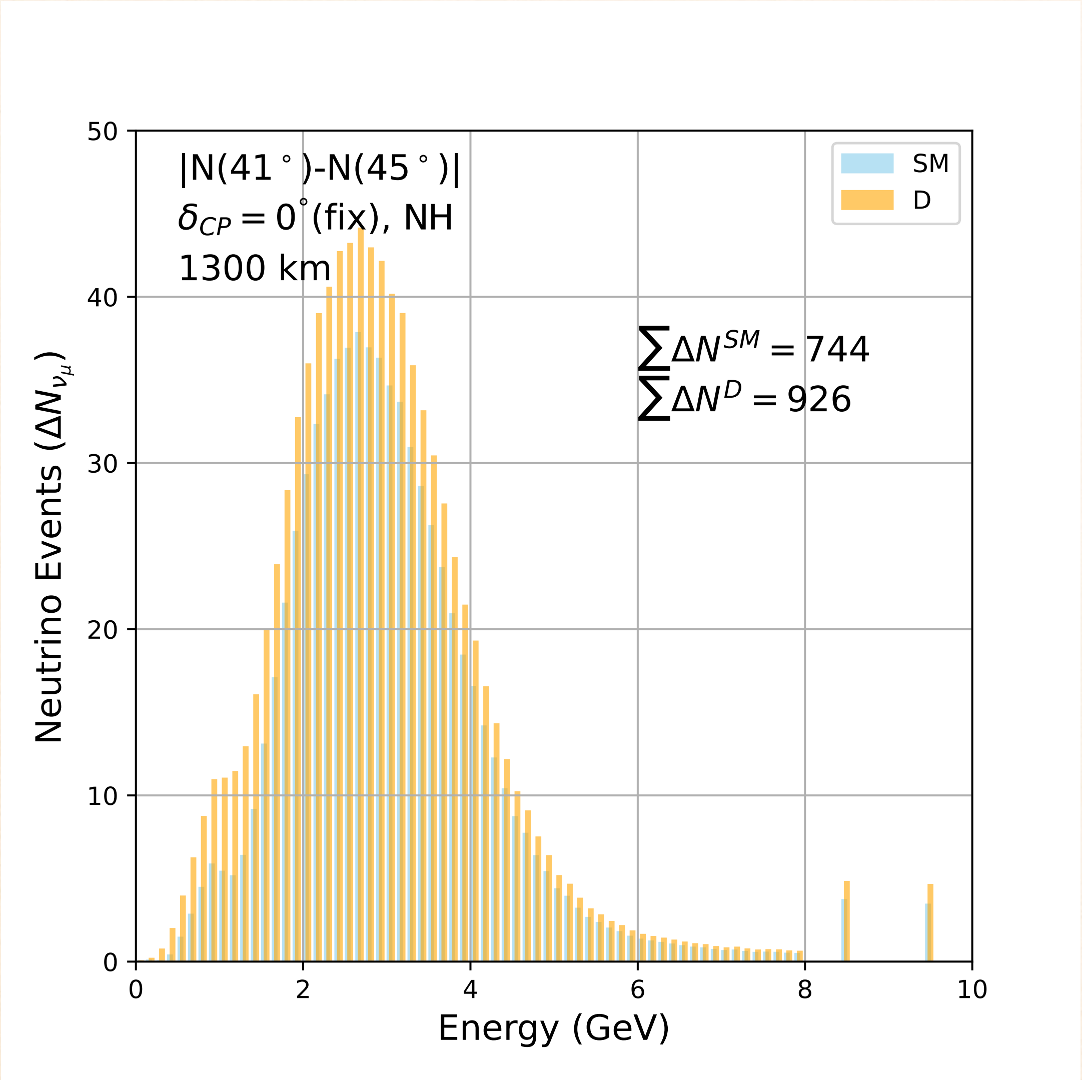


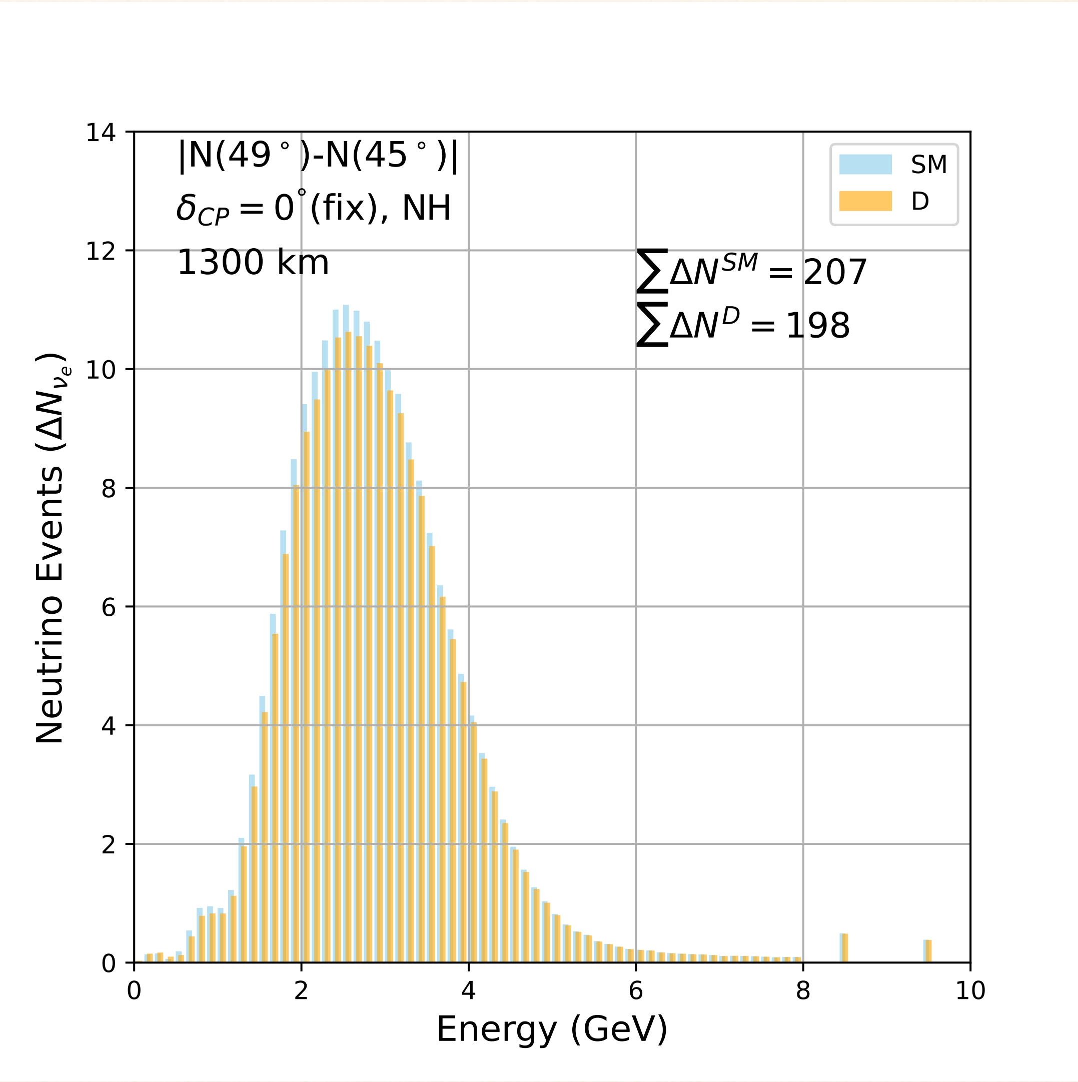


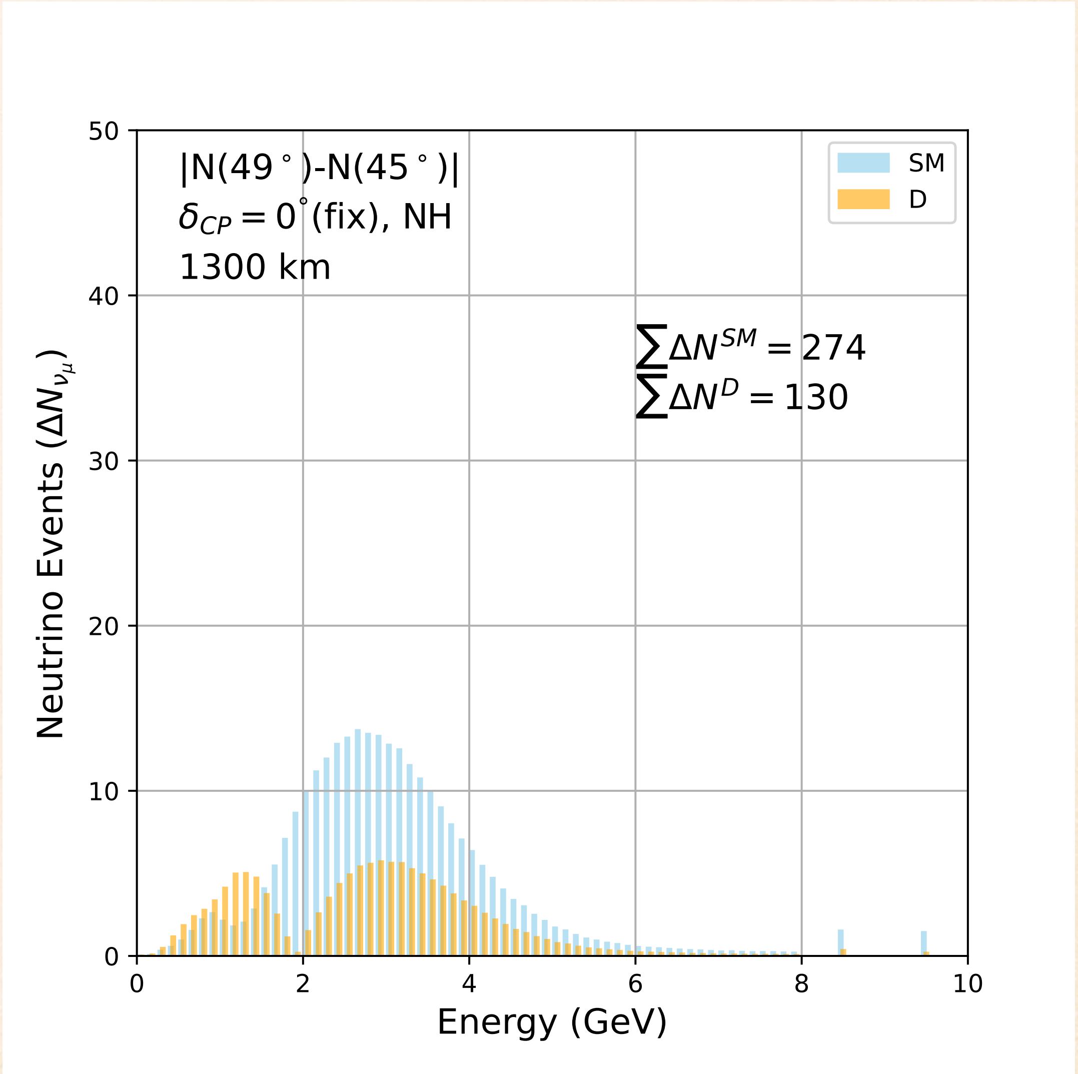




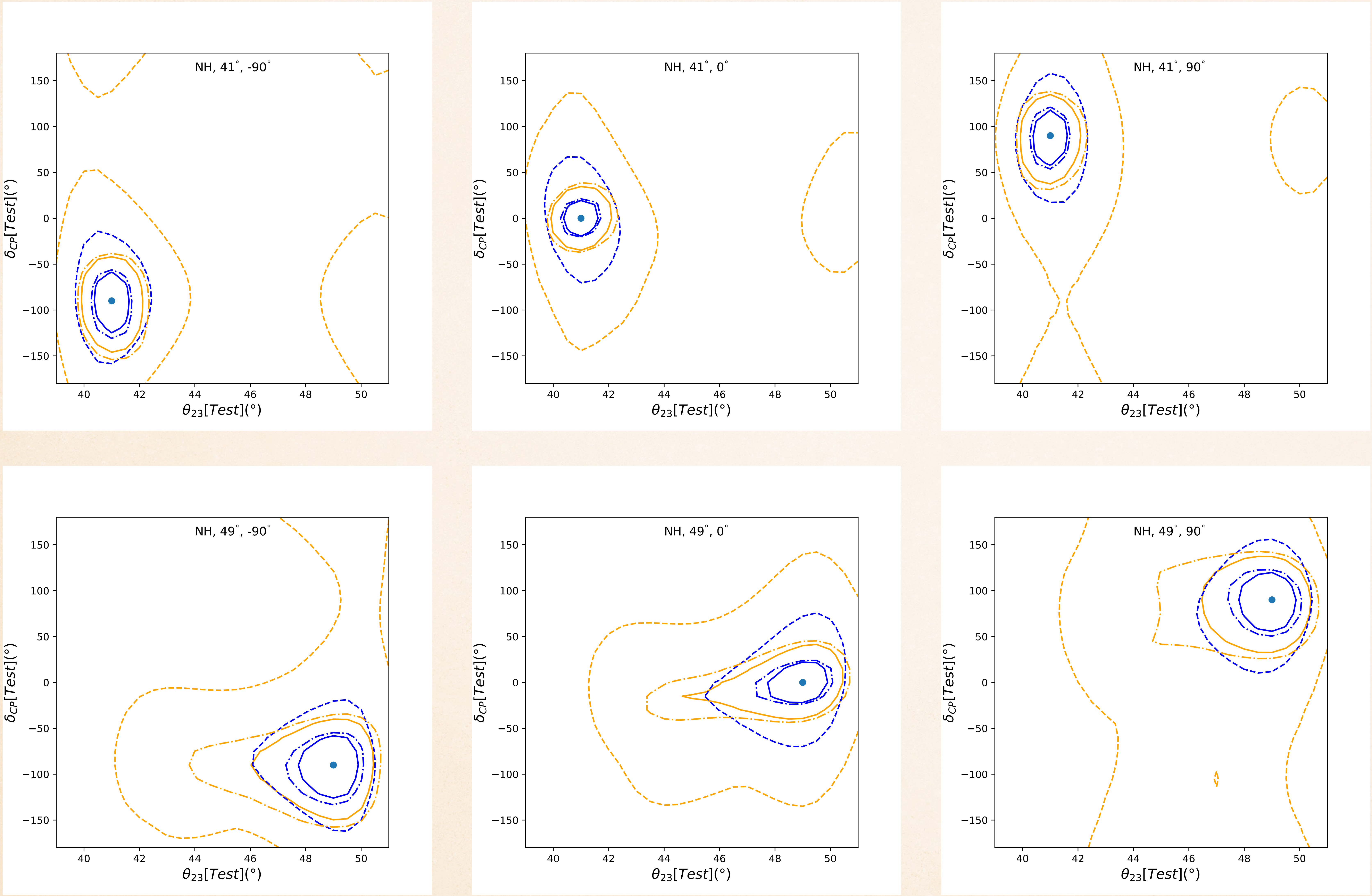








SENSITIVITY IN $\theta_{23} - \delta_{CP}$ PLANE



Dot-dashed, dashed, and solid lines correspond to P2O, DUNE and P2O+DUNE combined analysis. Orange and blue colours stand for 5σ, 3σ contours.

DUNE+P2O removes all the wrong octant, wrong δ_{CP} solutions

CONCLUSIONS

- Sensitivity to mass ordering reduces for decay in both baselines.
- MO sensitivity shows different dependance with θ_{23} in IH. In 2588 km it is due to ν_e channel
- Sensitivity to octant increases for decay in 2588 for θ_{23} in both HO and LO
- Octant sensitivity increases when θ_{23} in LO and decreases for θ_{23} in HO for decay
- Contribution of $\nu_\mu(\nu_e)$ channel in octant sensitivity is higher in 2588 km (1300 km).
- Joint analysis of DUNE, P2O removes wrong θ_{23}, wrong δ_{CP} solutions.

THANK YOU