

# Probing the second oscillation maximum at DUNE



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# What is Second Oscillation Maximum (SOM)?

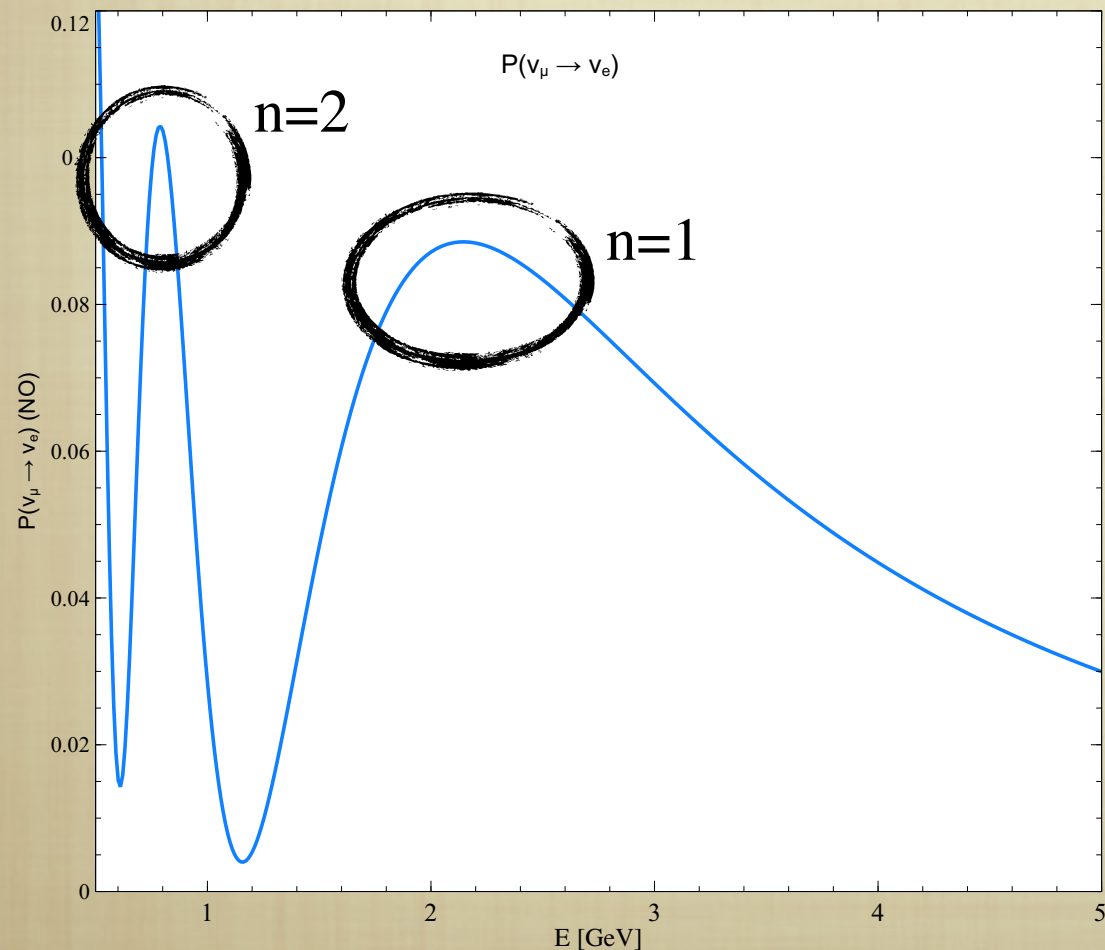
$$P_{\mu e} = \sin^2 2\theta_{13} \sin^2 \theta_{23} \sin^2 \Delta + \alpha \Delta \sin 2\theta_{13} \sin 2\theta_{12} \sin 2\theta_{23} \sin \Delta \cos(\delta + \Delta)$$

$$\Delta = \frac{\Delta m_{31}^2 L}{4E} = 1.27 \frac{\Delta m_{31}^2 [\text{eV}^2] L [\text{km}]}{E [\text{GeV}]}$$

$$\alpha = \frac{\Delta m_{21}^2}{\Delta m_{31}^2} \sim 10^{-2}$$

Maximum when  $\sin^2 \Delta \approx 1$   
or  $\Delta = (2n - 1)\pi/2$   
where  $n=1,2,\dots$

In matter,  $\Delta \rightarrow (1 - A)\Delta$  where  $A = \frac{2\sqrt{2}G_F N_e E}{\Delta m_{31}^2}$



$$n=1 \implies E_1^{max} \approx 2.5 \text{ GeV}$$

$$n=2 \implies E_2^{max} = E_1^{max} / 3 \approx 0.8 \text{ GeV}$$

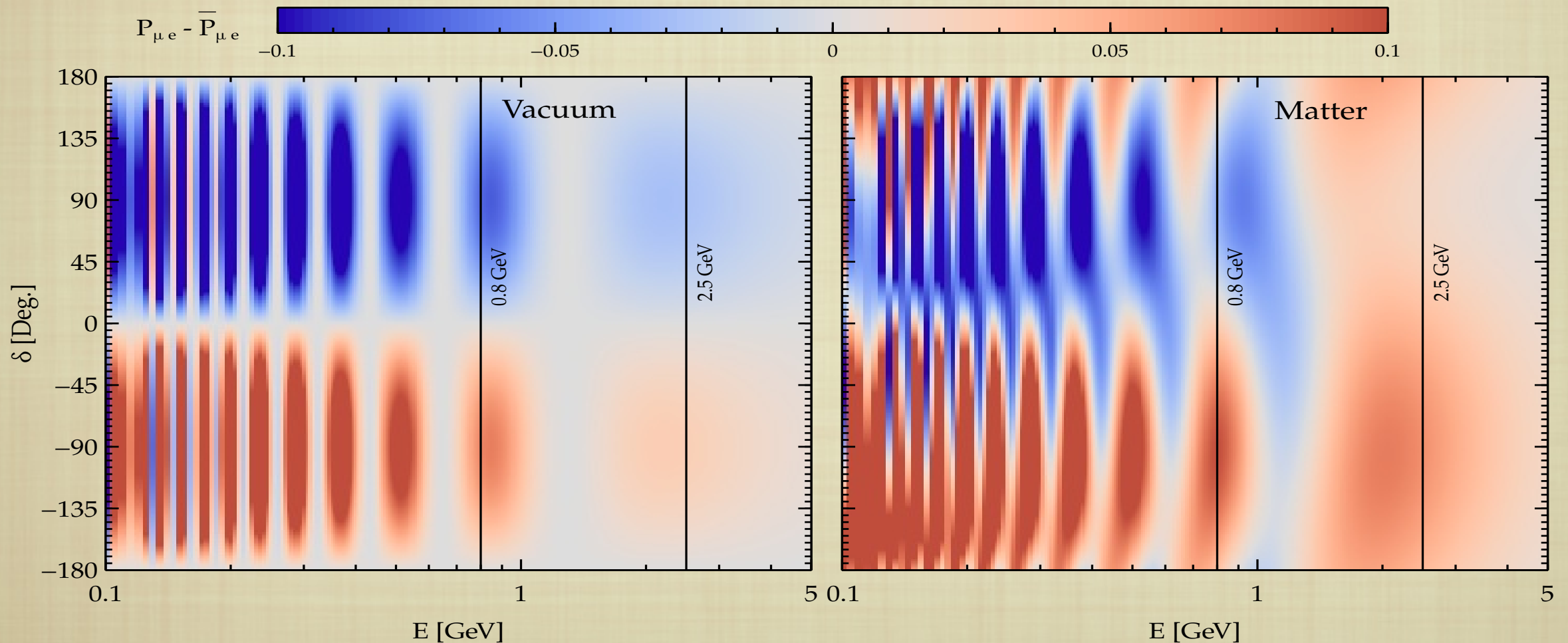
# Importance of Second oscillation maximum (SOM)

1.

$$\Delta P_{\mu e} = P_{\mu e} - \bar{P}_{\mu e} \approx -2\alpha \Delta \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\theta_{12} \sin^2 \Delta \sin \delta$$

Magnitude increases 3 times at SOM

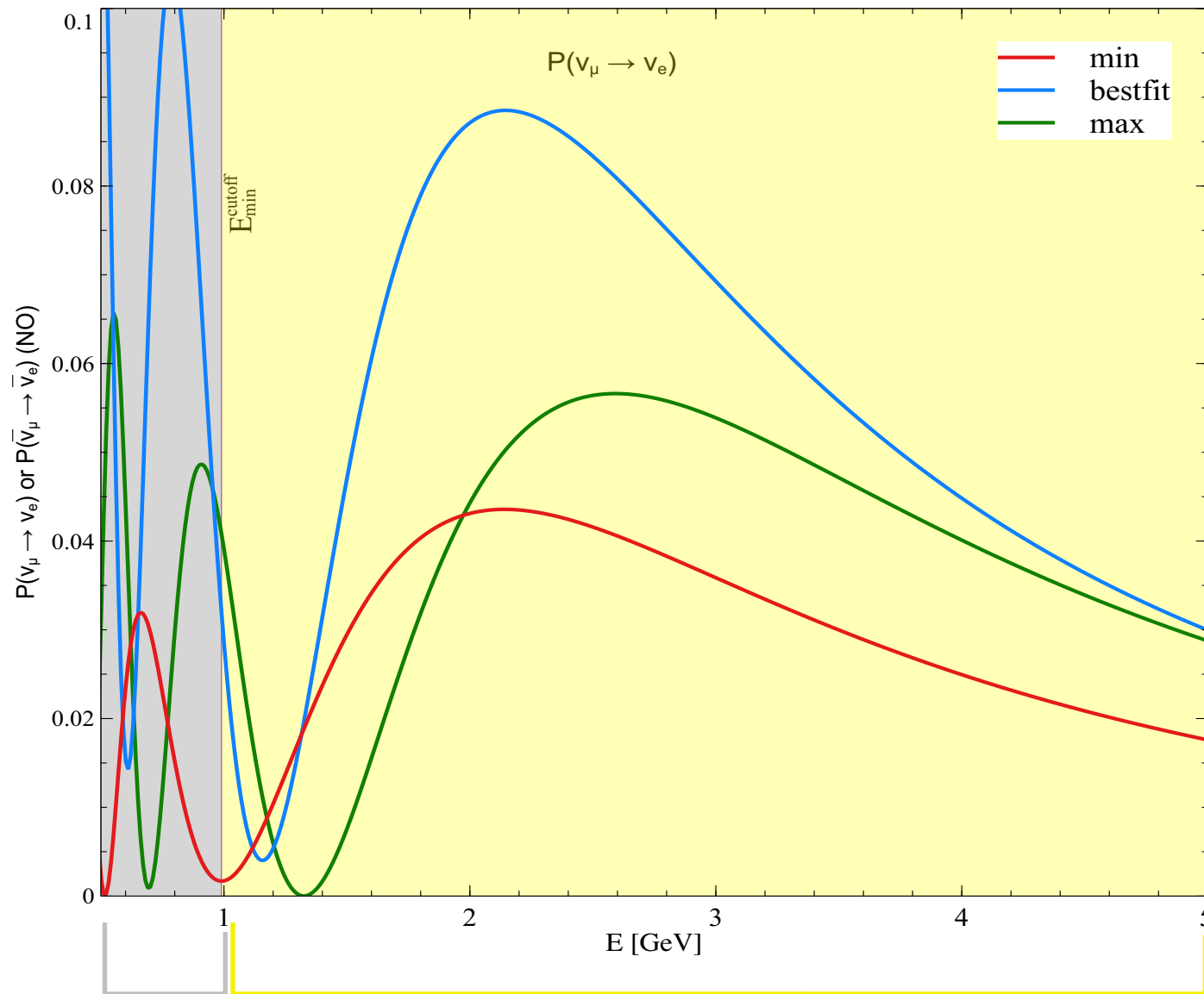
2.



Less distortion of CPV effects by matter at SOM



# Dependence of second oscillation maximum (SOM) on parameters



- Parameters varied:  $\theta_{23}, \Delta m_{31}^2, \delta_{13}$



- Shift of oscillation maxima zones
- We analyse the narrowest SOM zone

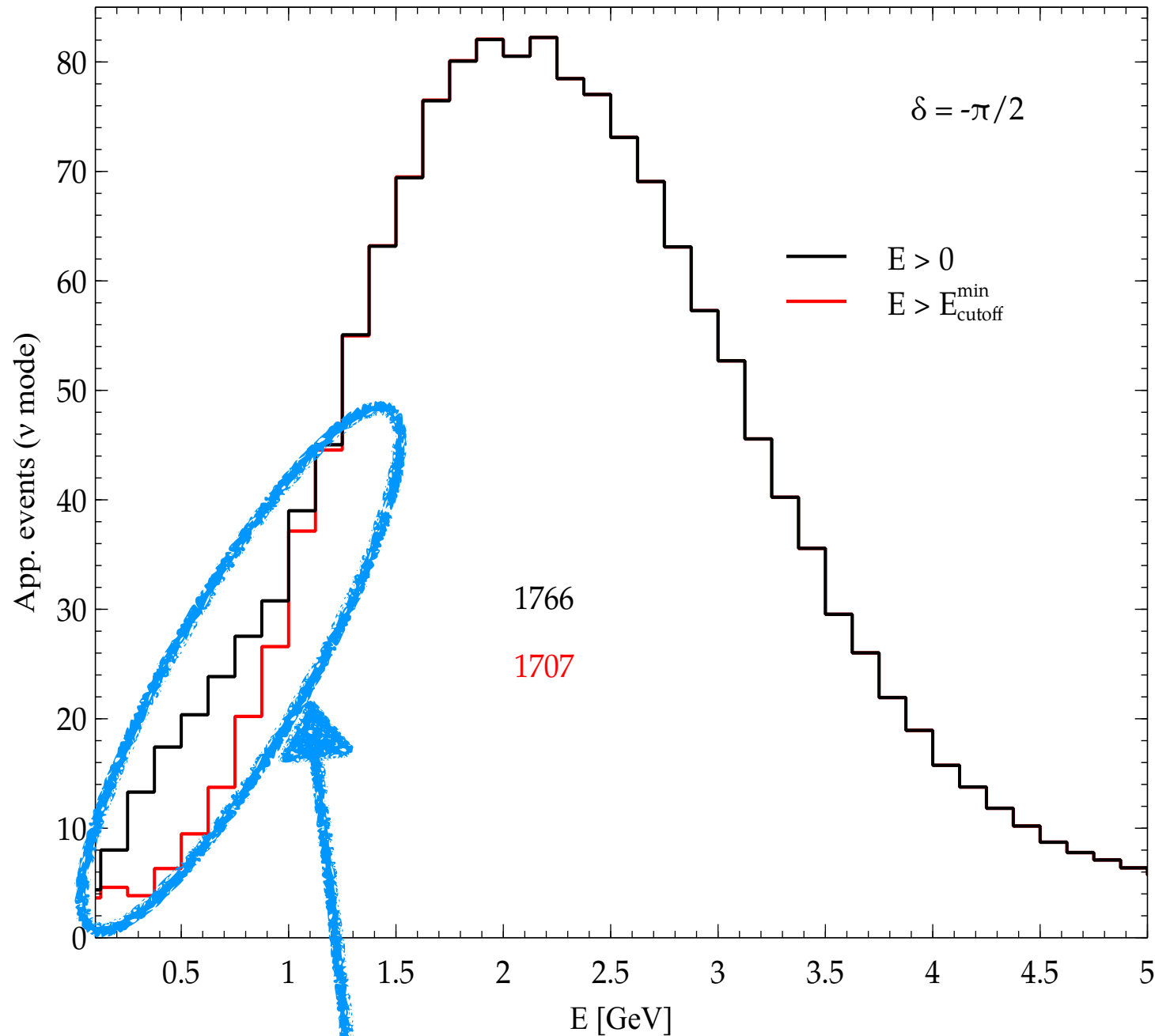
$$E_{\min}^{\text{cutoff}} \approx 0.99 \text{ GeV}$$

$$\bar{E}_{\min}^{\text{cutoff}} \approx 1.21 \text{ GeV}$$

Second oscillation maximum zone

First oscillation maximum zone

# Second oscillation maximum (SOM) & Event spectra



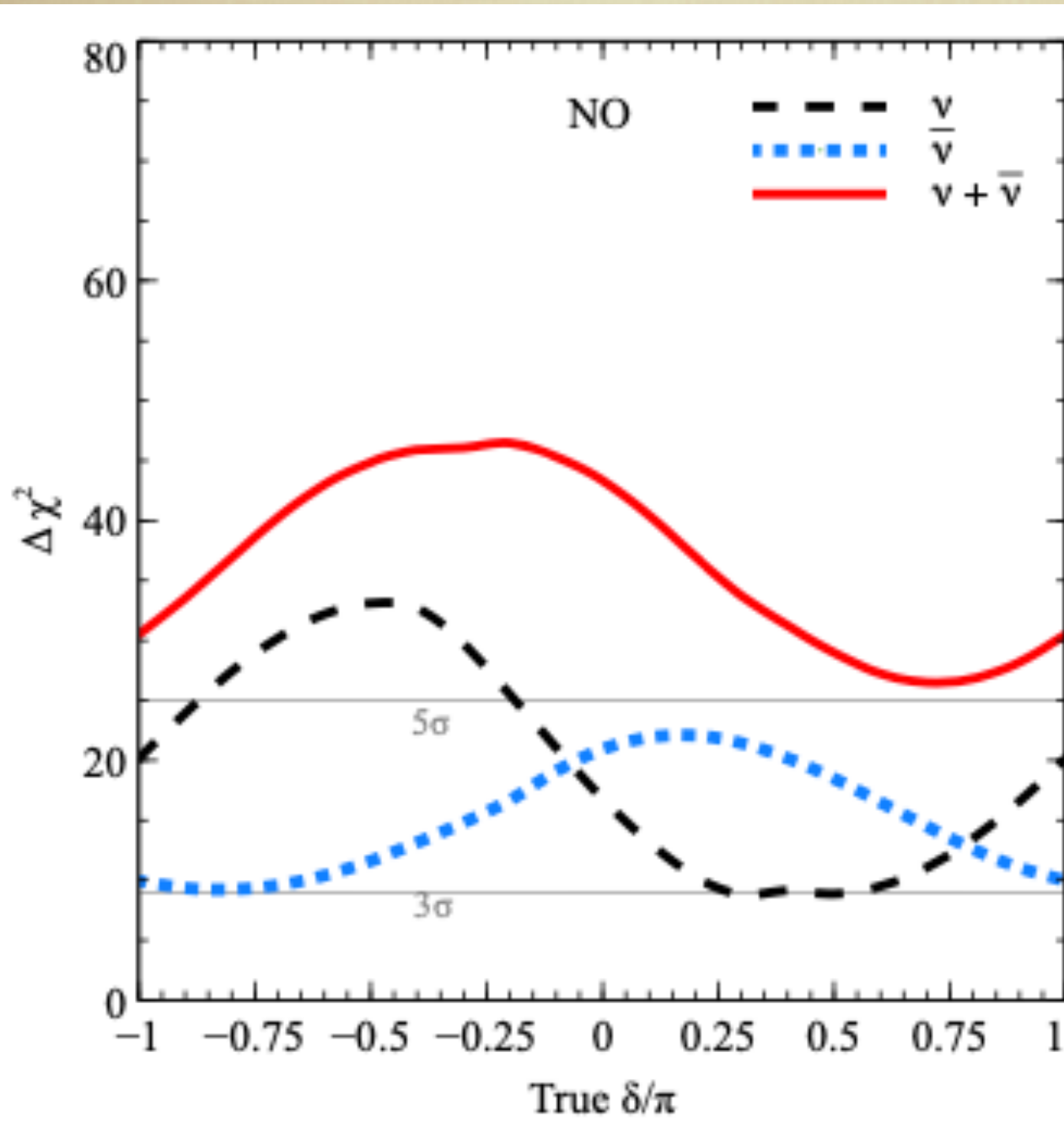
Spectra generated for two fluxes:

1. Covering entire energy range upto 20 GeV
2. Only covering the first osc. max. zone

Can DUNE probe SOM by distinguishing two such spectra?

Spectral distortion

# $\Delta\chi^2$ for probing Second oscillation maximum (SOM)



A manual  $\Delta\chi^2$  analysis  
within GLoBES

- $\nu$ -mode &  $\bar{\nu}$ -mode give complementary results
- Combining both modes gives  $> 5\sigma$  sensitivity to probe SOM at DUNE

# Summary

- Second oscillation maximum (SOM) potentially allows us to be more sensitive to CPV effects with less interference from matter
- Low energy distortion of event spectra
- Novel method to probe SOM: New  $\Delta\chi^2$  implementation to calculate the sensitivity to SOM
- DUNE can probe SOM at  $\gtrsim 5\sigma$  irrespective of the value of  $\delta_{13}$

*Thank You!*