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Resolving DUNE oscillation parameter ambiguities in the 3+1 sterile neutrino scenario using SBN

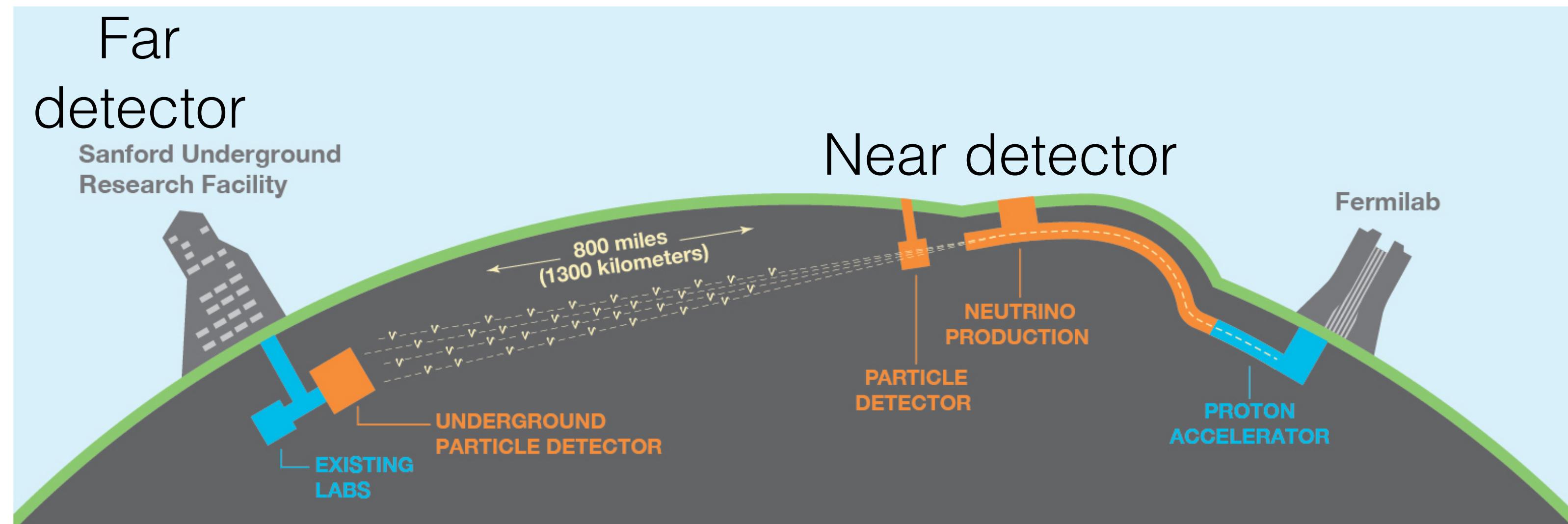
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Contents

- **Introduction**
 - DUNE aims to explore lepton sector CPV, mass ordering in 3 neutrinos
 - SBN aims to search for additional neutrinos (light sterile neutrinos)
- Parameter ambiguities between CP symmetry violation in 3 neutrino model and light sterile neutrino scenarios in DUNE
- Can SBN resolve these parameter ambiguities? Over current globally allowed 3+1 parameters?
- DUNE's sensitivities of CPV and mass ordering for 3 neutrino model, 3+1 neutrino models with and without SBN constraint
- Conclusion

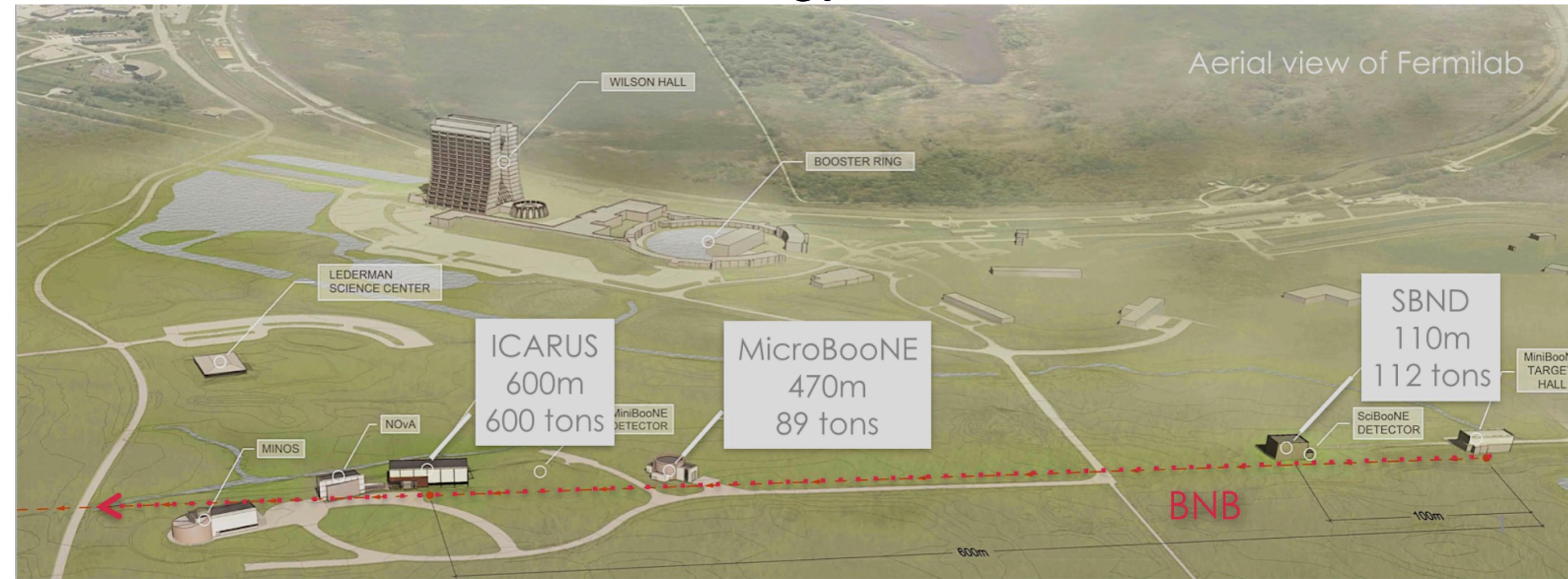
DUNE: Deep Underground Neutrino Experiment



- Long baseline neutrino experiment consisting near detector @ Fermi lab, far detector @ South Dakota, with the mean neutrino energy around 2~3 GeV.
- Primary goals : testing CPV in lepton sector, determining the order of neutrino masses, θ_{23} octant
- Far detector of 40 kton fiducial volume LArTPC will be located 1300 km from the neutrino production to maximally observe the $P(\nu_\mu \rightarrow \nu_e)$ and $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$ oscillation effects;
- Anticipating data collection from 2026 for 7 years (3.5 years of neutrino/anti-neutrino beam mode)

SBN: Short-Baseline Neutrino Program

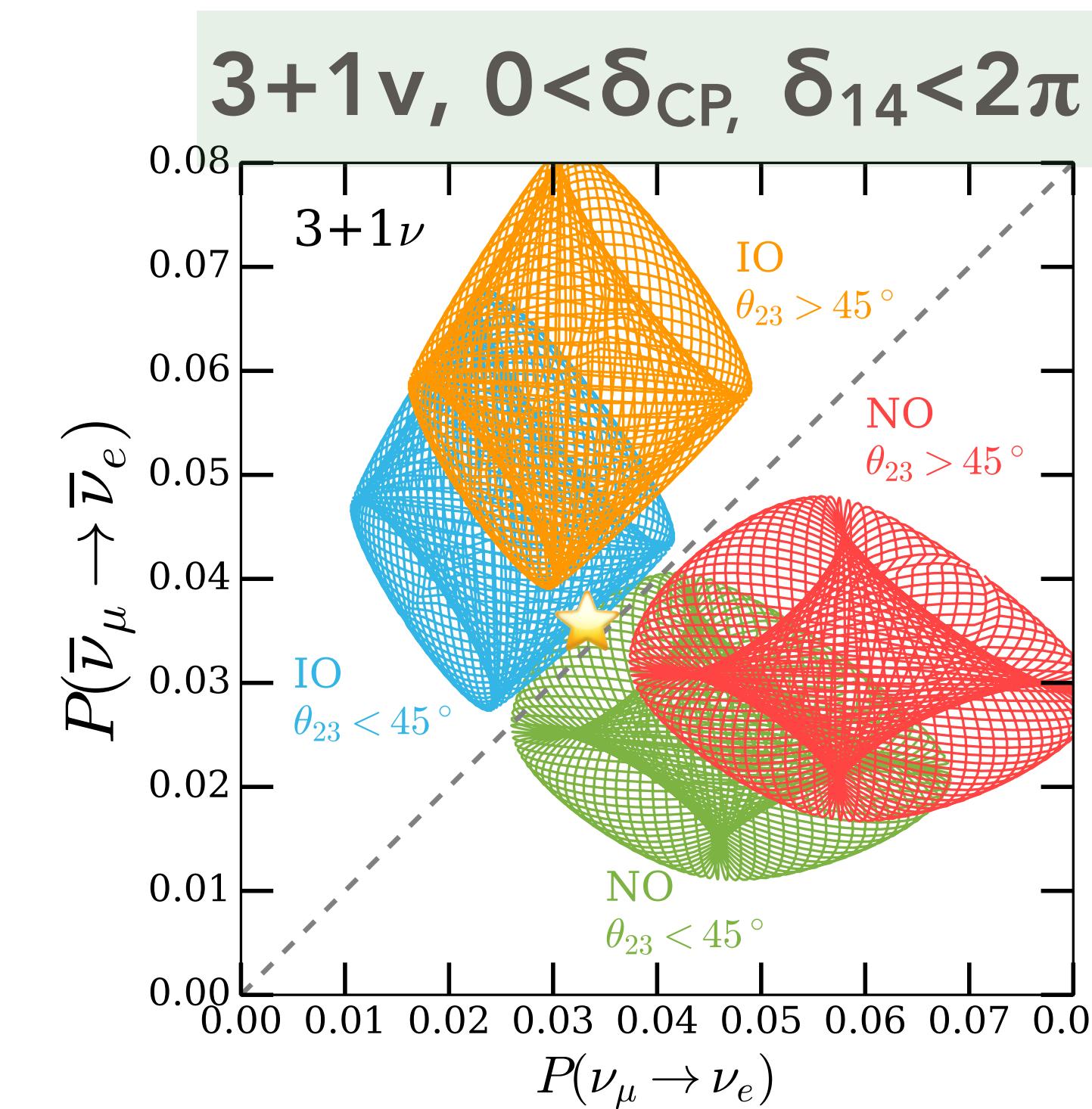
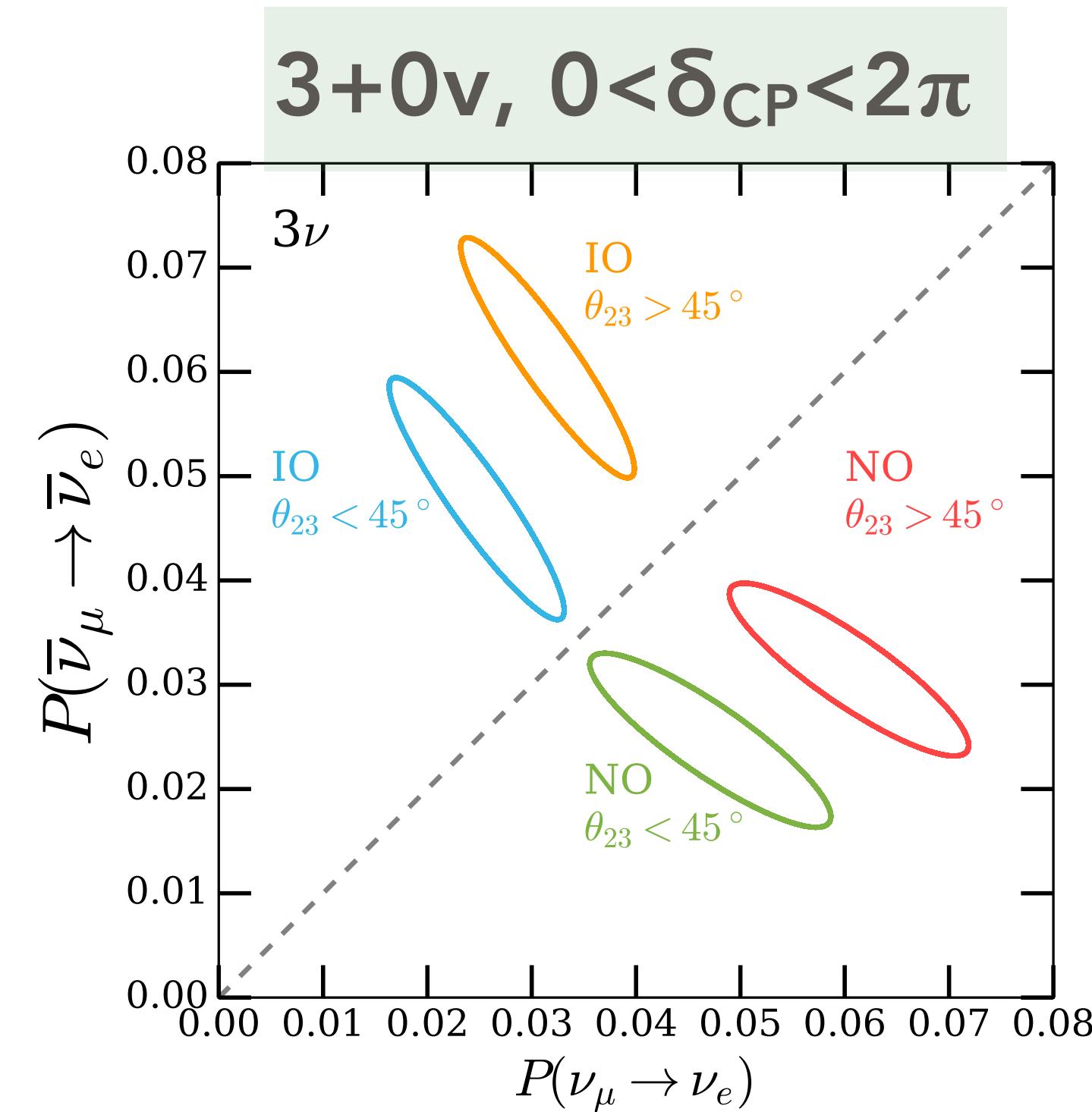
- A series of three **LArTPC** detectors (SBND, MicroBooNE, ICARUS) along the Booster Neutrino Beam at Fermilab with the mean neutrino energy around 600 MeV.



- SBN has much smaller L/E than DUNE uniquely sensitive to higher Δm^2 , aims to search for sterile neutrinos in $\sim \text{eV}^2$ mass splitting regime with a high sensitivity measurement.
- Short baseline approximation for 3+1 :
$$P(\nu_\alpha \rightarrow \nu_\beta) = 4|U_{\alpha 4}|^2 |U_{\beta 4}|^2 \sin^2 x_{41}$$
 $x_{ij} \equiv 1.27 \Delta m_{ij}^2 L/E$
- LSND, MiniBooNE anomalies (see yesterday's talk by A. Diaz)

Parameter ambiguities @ DUNE with sterile neutrinos

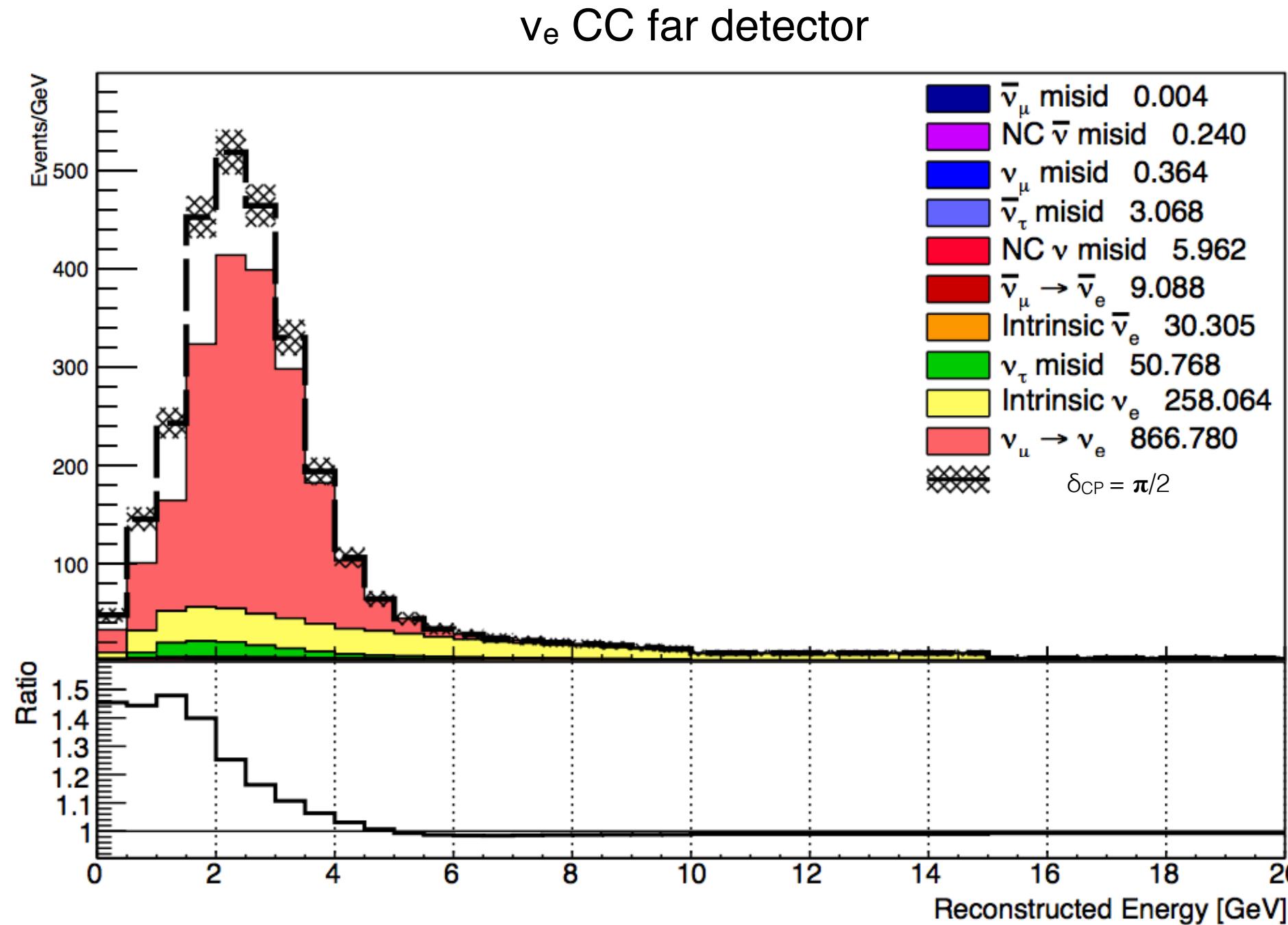
- Bi-probability plot of oscillation probability; $P(\text{anti-}\nu_\mu \rightarrow \text{anti-}\nu_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$



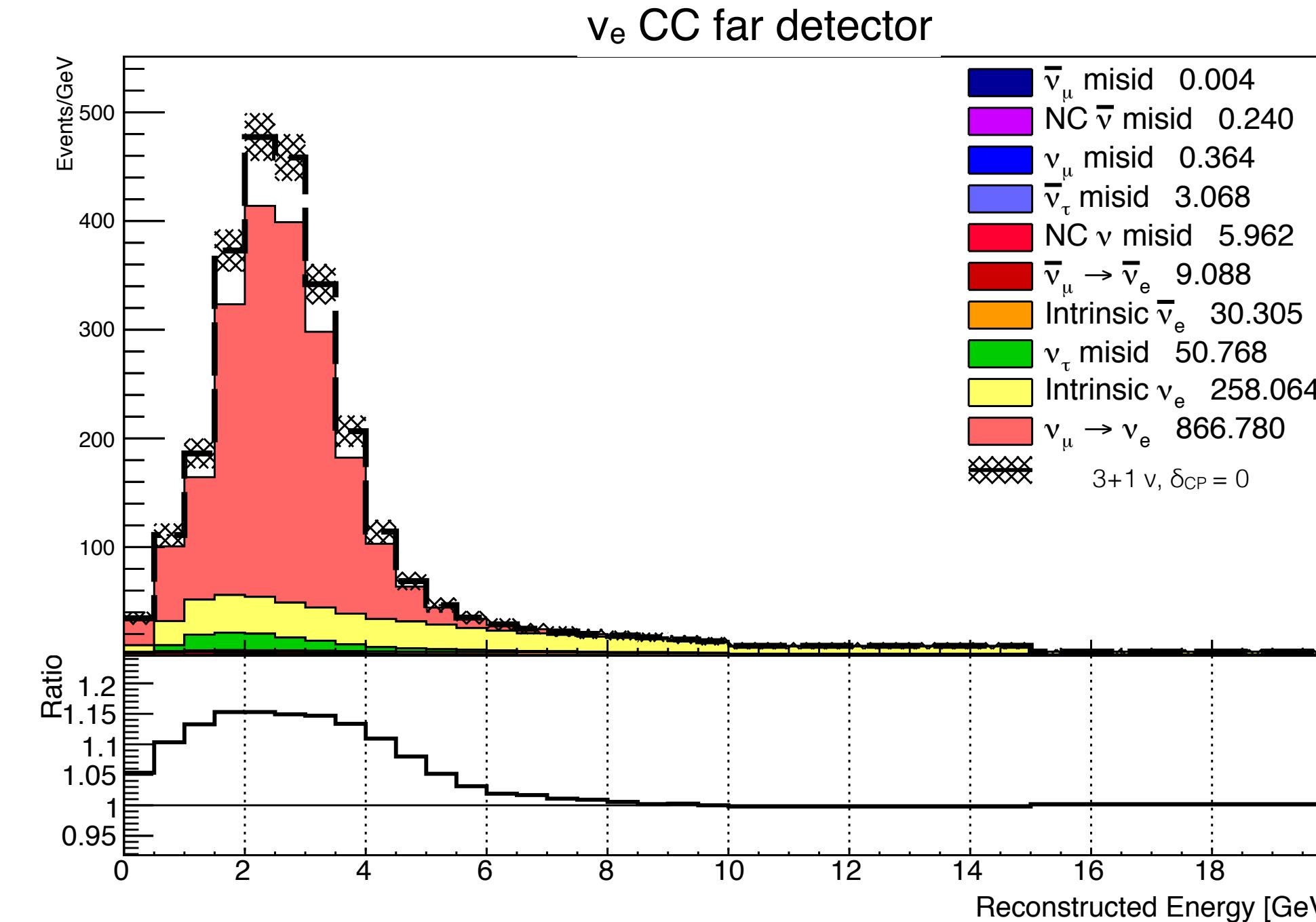
Even one light sterile neutrino can invite severe overlaps in oscillation probabilities, thus ambiguities in oscillation parameters

Parameter ambiguities @ DUNE with sterile neutrinos; Signal histograms at far detector

3+0ν, $\delta_{CP} = \pi/2$



3+1ν, $\delta_{CP} = 0$

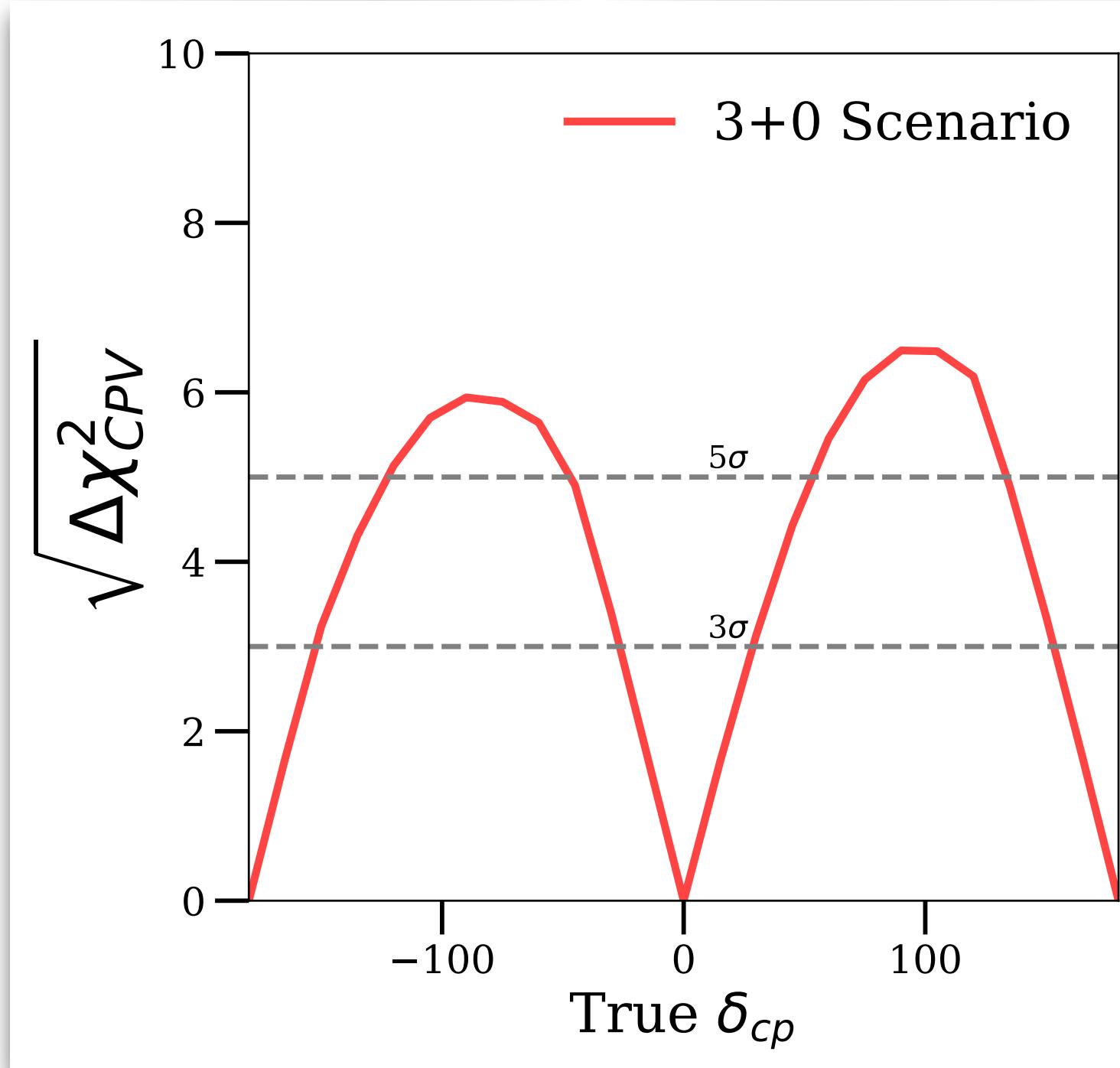


As a result of the parameter ambiguity, different physics scenarios may give similar observations

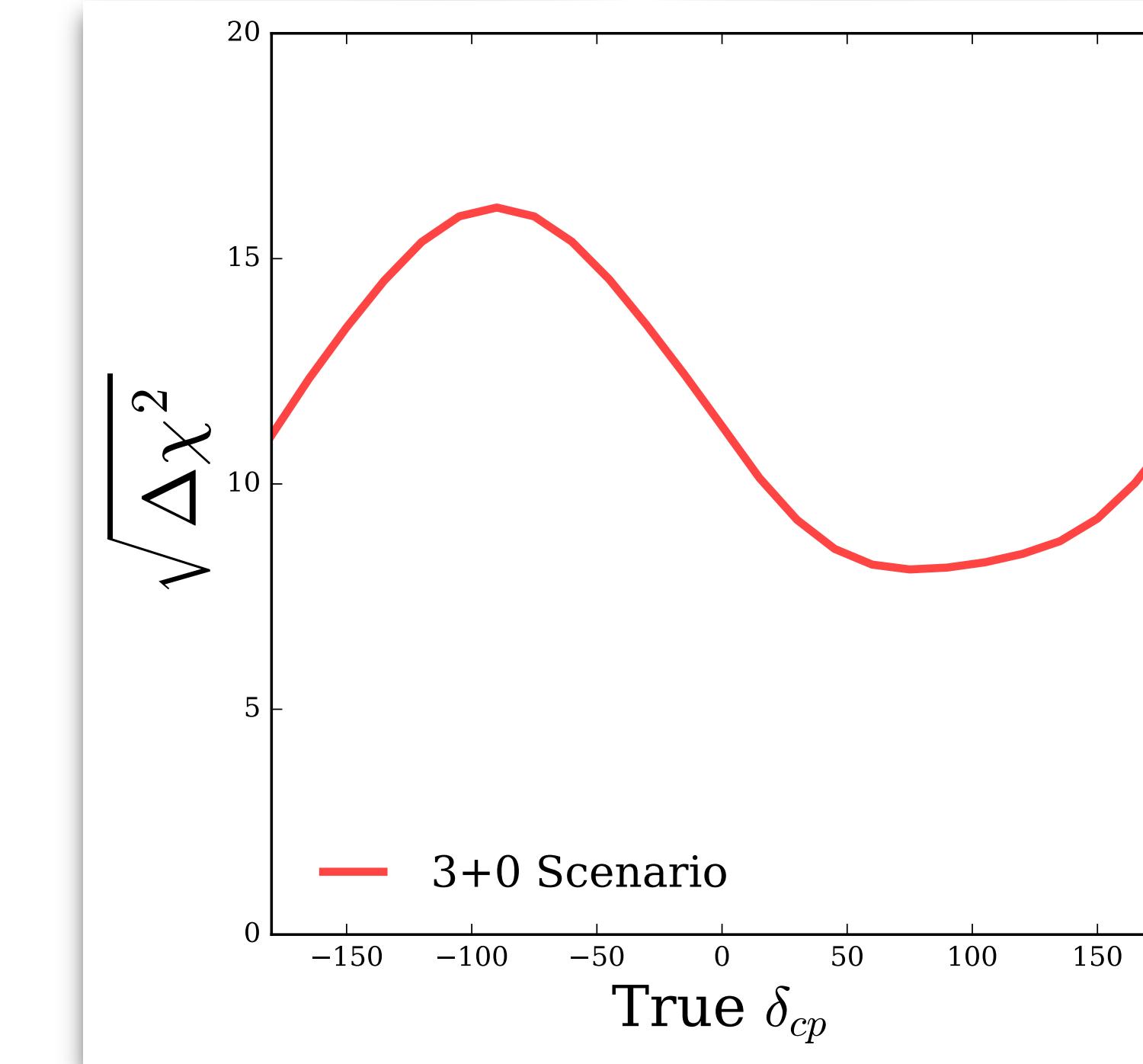
DUNE's sensitivities

(Normal ordering, 3+0 neutrino)

CPV Sensitivity



Mass Ordering Sensitivity

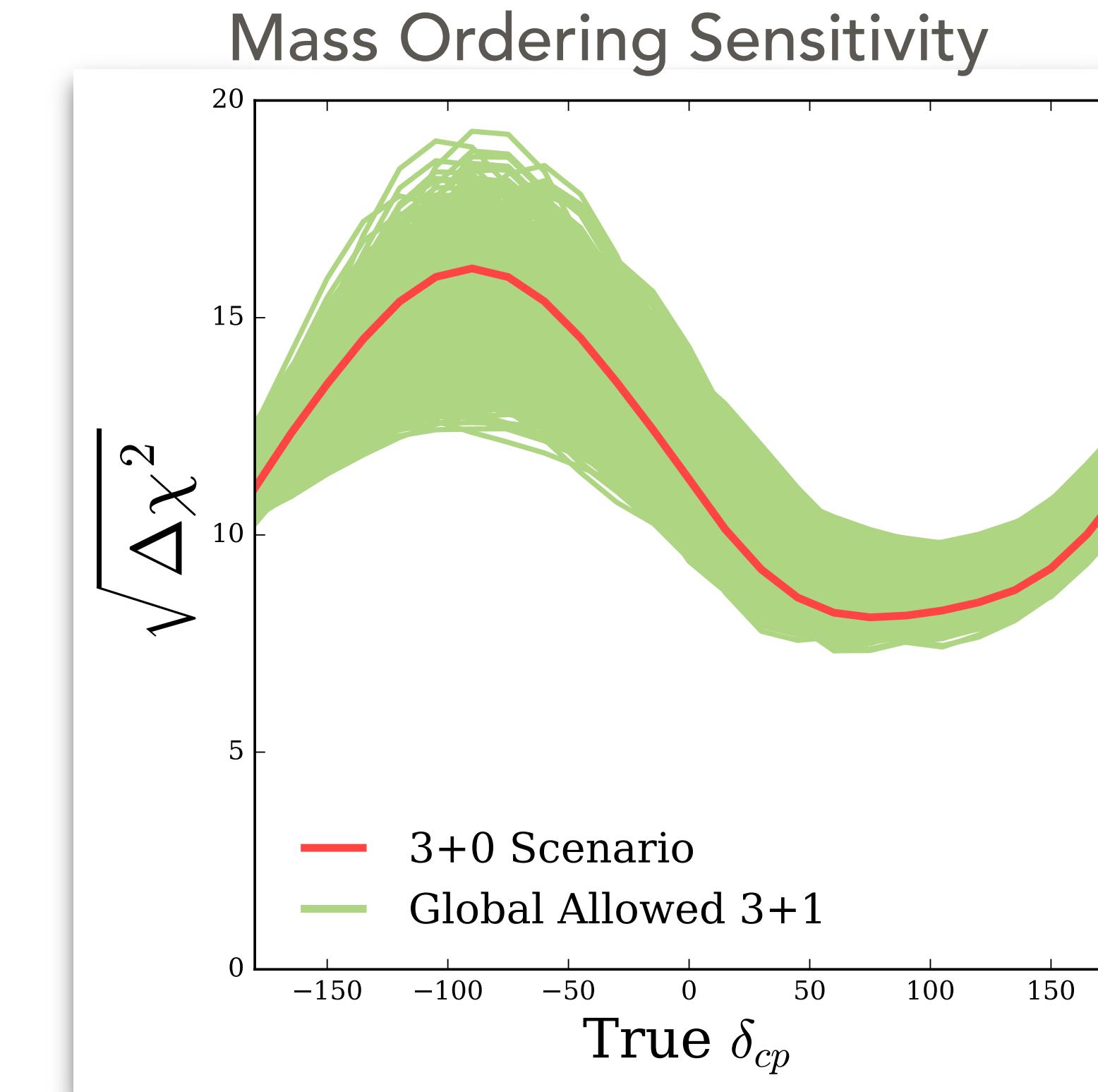
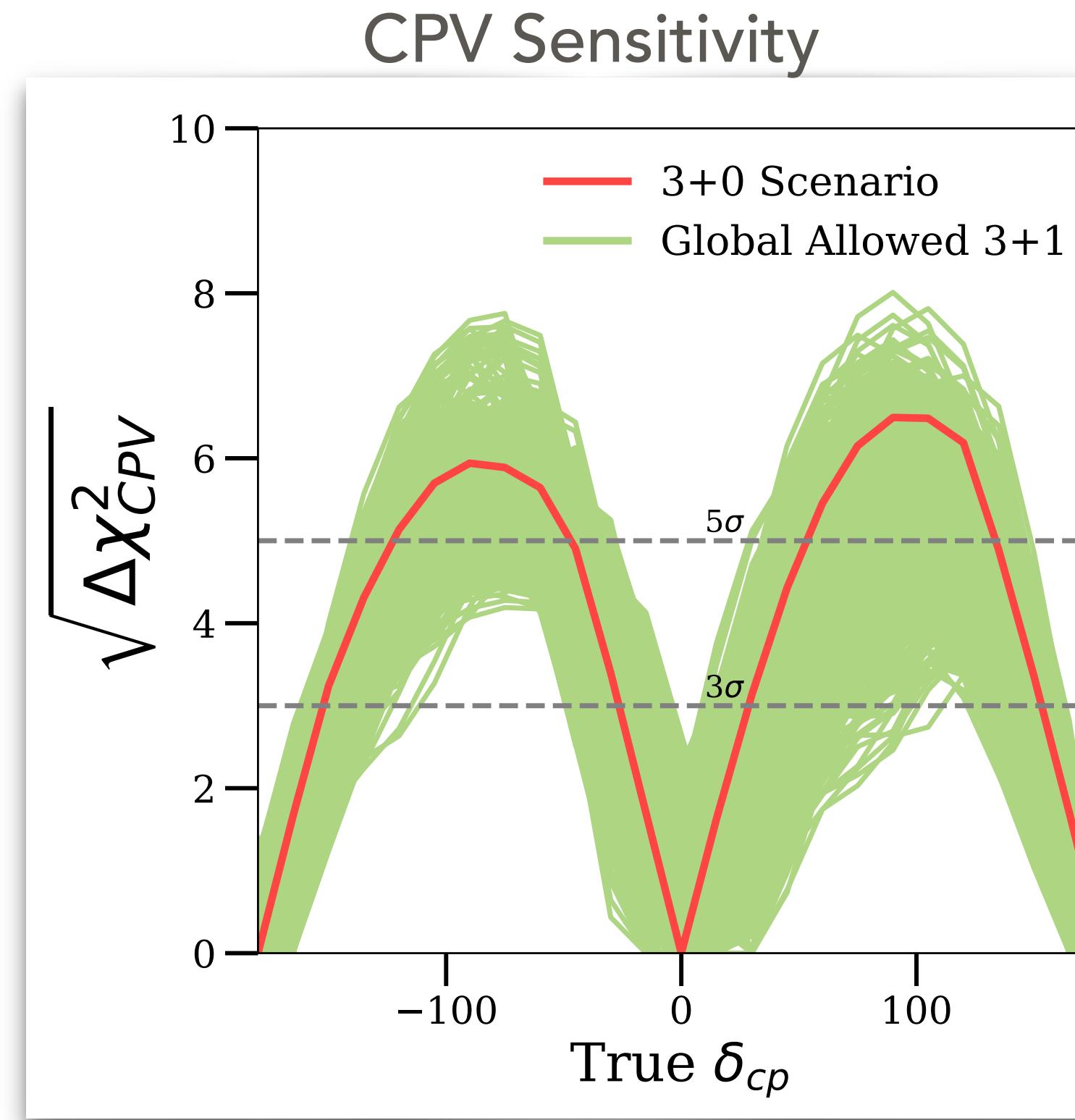


Our simulated results of 3 neutrino model in DUNE shows CPV sensitivity over 5 sigma for maximally violating phases, sensitivity of mass ordering over 5 sigma over all δ_{CP} .

DUNE's sensitivities

(Normal ordering, **3+1 globally allowed**)

→ See yesterday's talk by A. Diaz

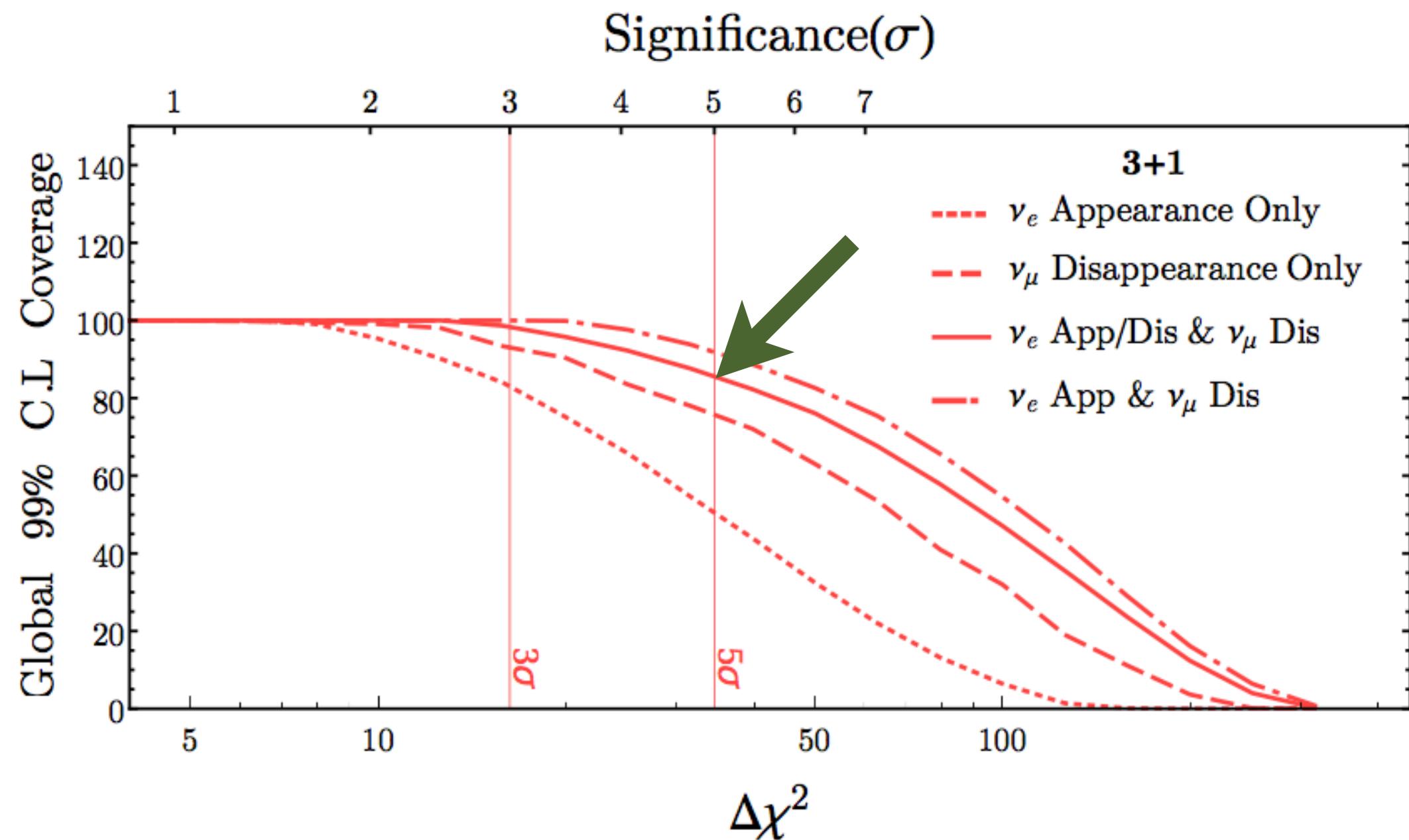


$\Delta m_{41}^2 = 1.7 \text{ eV}^2$,
 $\delta_{14} = [-\pi, \pi]$,
 $\delta_{34} = 0$,
 $\theta_{23} = [38^\circ, 53^\circ]$,
 $\theta_{14} = [5.7^\circ, 12.3^\circ]$,
 $\theta_{24} = [3.65^\circ, 12.93^\circ]$,
 $\theta_{34} = [0^\circ, 25^\circ]$
3+0 fit

Within globally allowed 3+1 region, DUNE's sensitivities in CPV and mass ordering can be ranging with a large uncertainty.

SBN sensitivity on light sterile neutrinos

SBN SENSITIVITY COVERAGE IN (%) OVER 3+1 PARAMETER SPACE

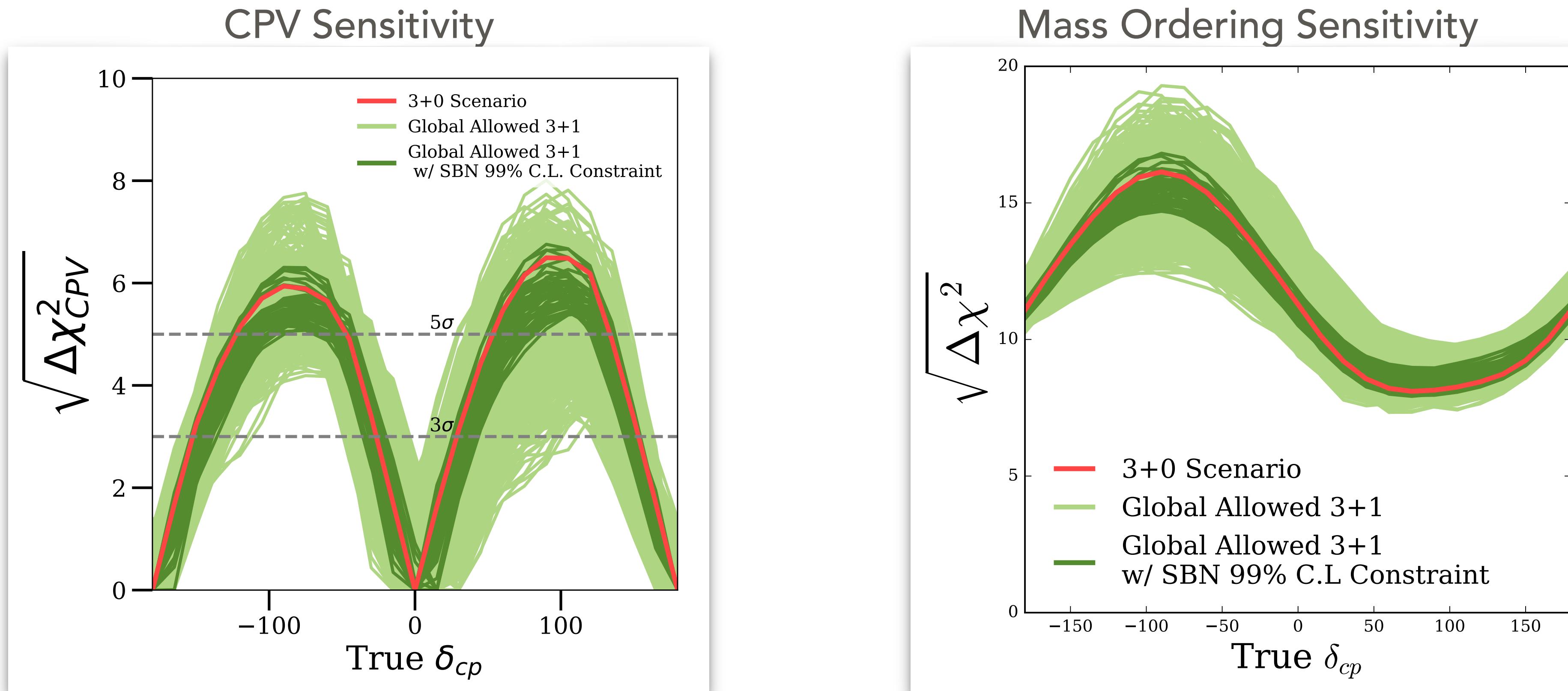


- SBN program is estimated to achieve 5 σ sensitivity over a large percentage of parameter spaces in 3+1 scenario.
- If SBN's result favors 3+0 neutrino model, it will rule out about 90% of 3+1 parameter space at 5 σ .

If SBN does not see sterile neutrinos

DUNE's sensitivities

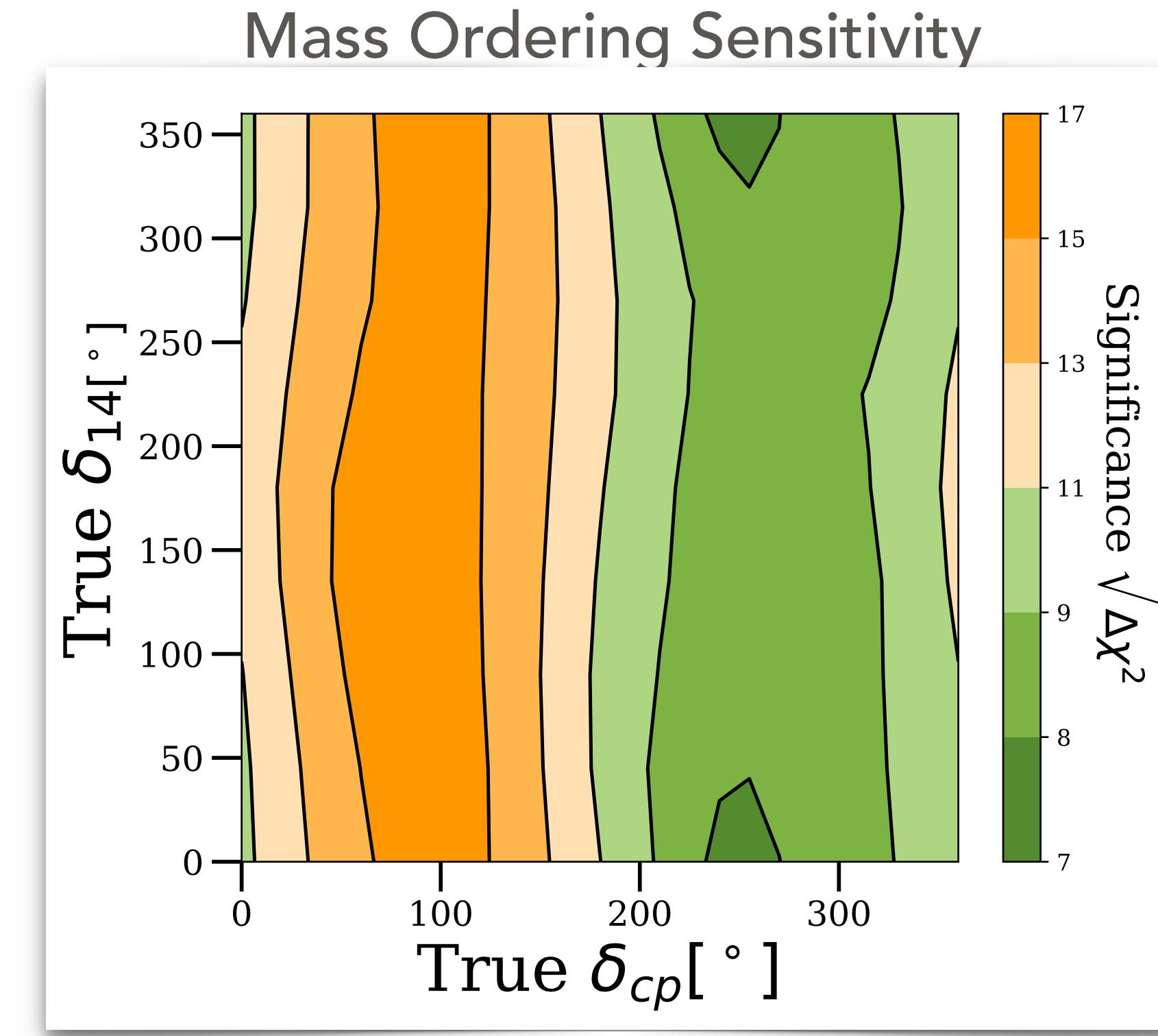
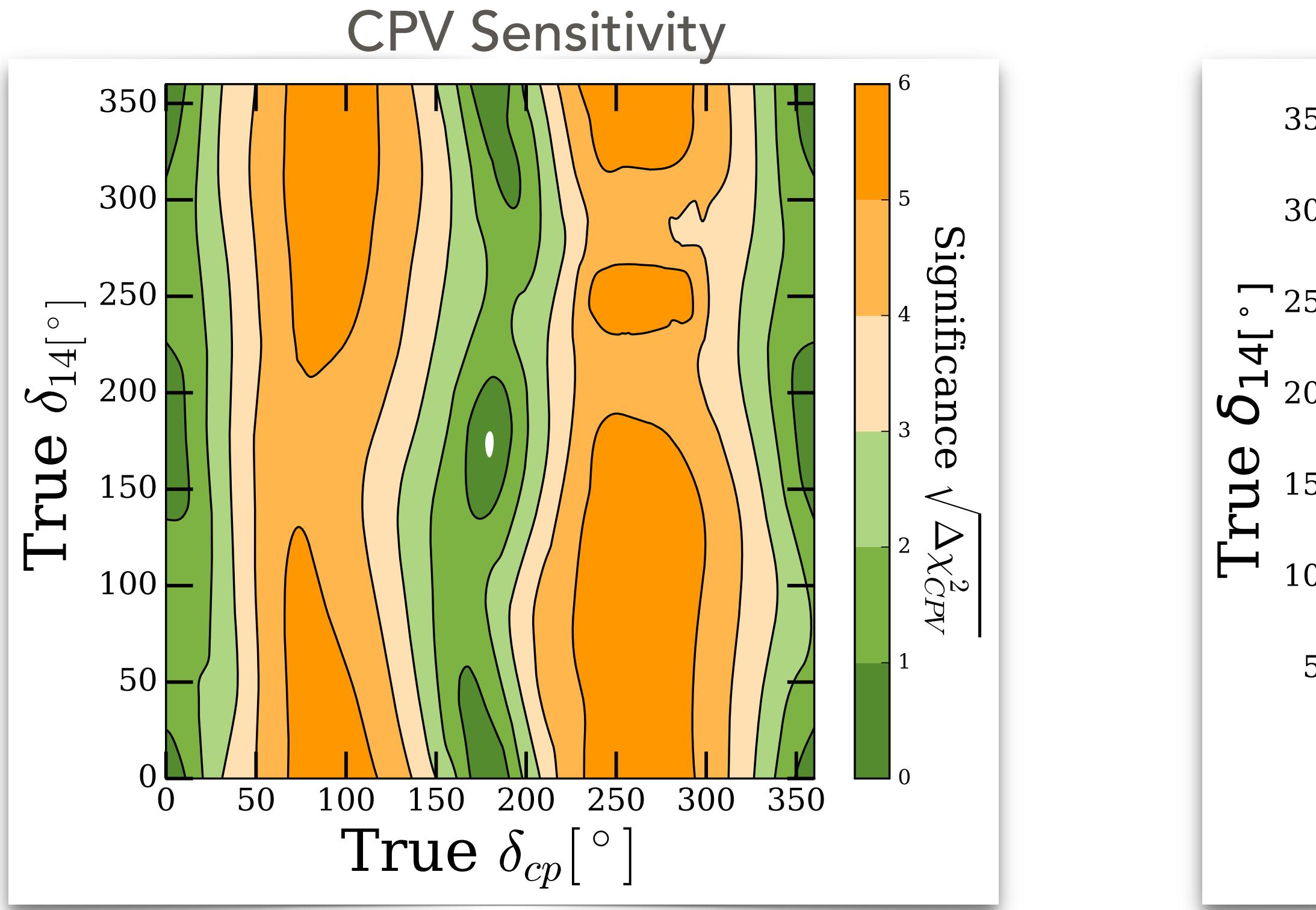
(Normal ordering, **3+1 globally allowed, w/ SBN constraint**)



With SBN, uncertainties in CPV and mass ordering sensitivity can be shrunk to the level of retainment of CPV sensitivity over 5 sigma significance at maximally violating δ_{CP} angles.

If SBN confirms current global best-fit,
What can we measure in DUNE?

If SBN result confirms a sterile neutrino at ($\theta_{14} = 8.3^\circ$, $\theta_{24} = 6.9^\circ$, $\Delta m_{41}^2 = 1.7 \text{ eV}^2$), can DUNE still achieve its physics goals?



$$\begin{aligned}\Delta m_{41}^2 &= 1.7 \text{ eV}^2, \\ \boldsymbol{\delta}_{14} &= [-\pi, \pi], \\ \boldsymbol{\delta}_{34} &= 0, \\ \theta_{23} &= [38^\circ, 53^\circ], \\ \theta_{14} &= 8.3^\circ, \\ \theta_{24} &= 6.9^\circ, \\ \theta_{34} &= 10^\circ\end{aligned}$$

In 3+1 model, DUNE's sensitivities in CPV and mass ordering can vary over δ_{14} as well as δ_{cp} phase.

At the best-fit point, the sensitivity for CPV is over 5 sigma significance for some subset of $(\delta_{cp}, \delta_{14})$ pairs.

Mass ordering sensitivity is over 5 significance throughout δ_{cp} - δ_{14} plane.

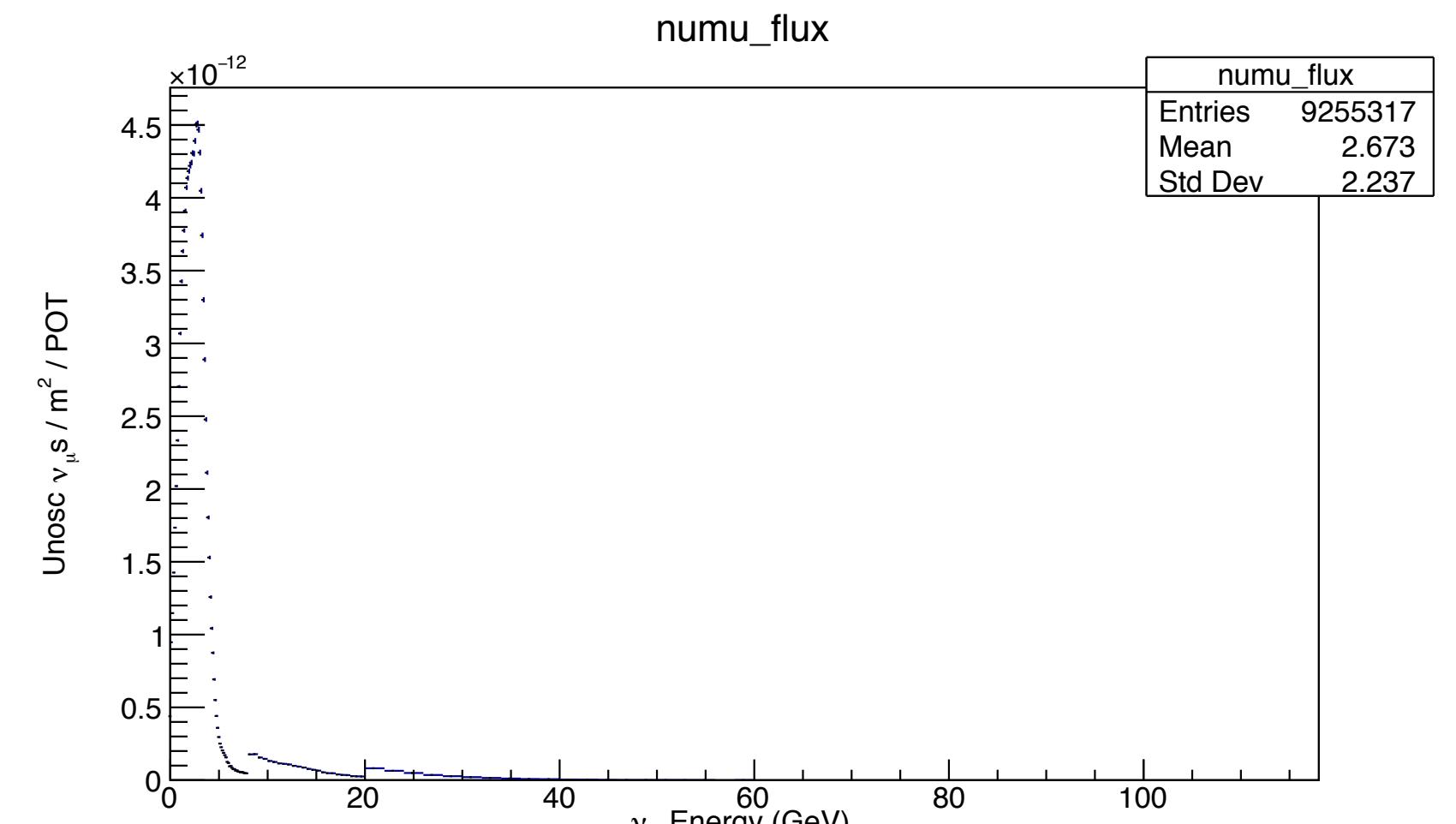
Summary

- While DUNE (Deep Underground Neutrino Experiment) aims to explore CPV in lepton sector, if there is a sterile neutrino, we will encounter ambiguities in oscillation parameters.
- Our past simulation on SBN program shows over 5σ sensitivity over a large percentage of parameter space in 3+1 light sterile neutrino models.
- Super-fast MC simulation for DUNE is performed, to estimate DUNE's sensitivities.
- If SBN's data rules out the the majority of current 3+1 global parameter space, DUNE retains the sensitivities in CPV and mass ordering.
- If SBN's data confirms the global 3+1 best fit, DUNE's sensitivities in mass ordering as well as CPV can vary over extra phases in 3+1 models, yet the sensitivities at the best-fit seem not to be largely affected.
- Next steps will be more rigorous exploration in 3+1 parameter space using the correlated χ^2 fit for SBN and DUNE.

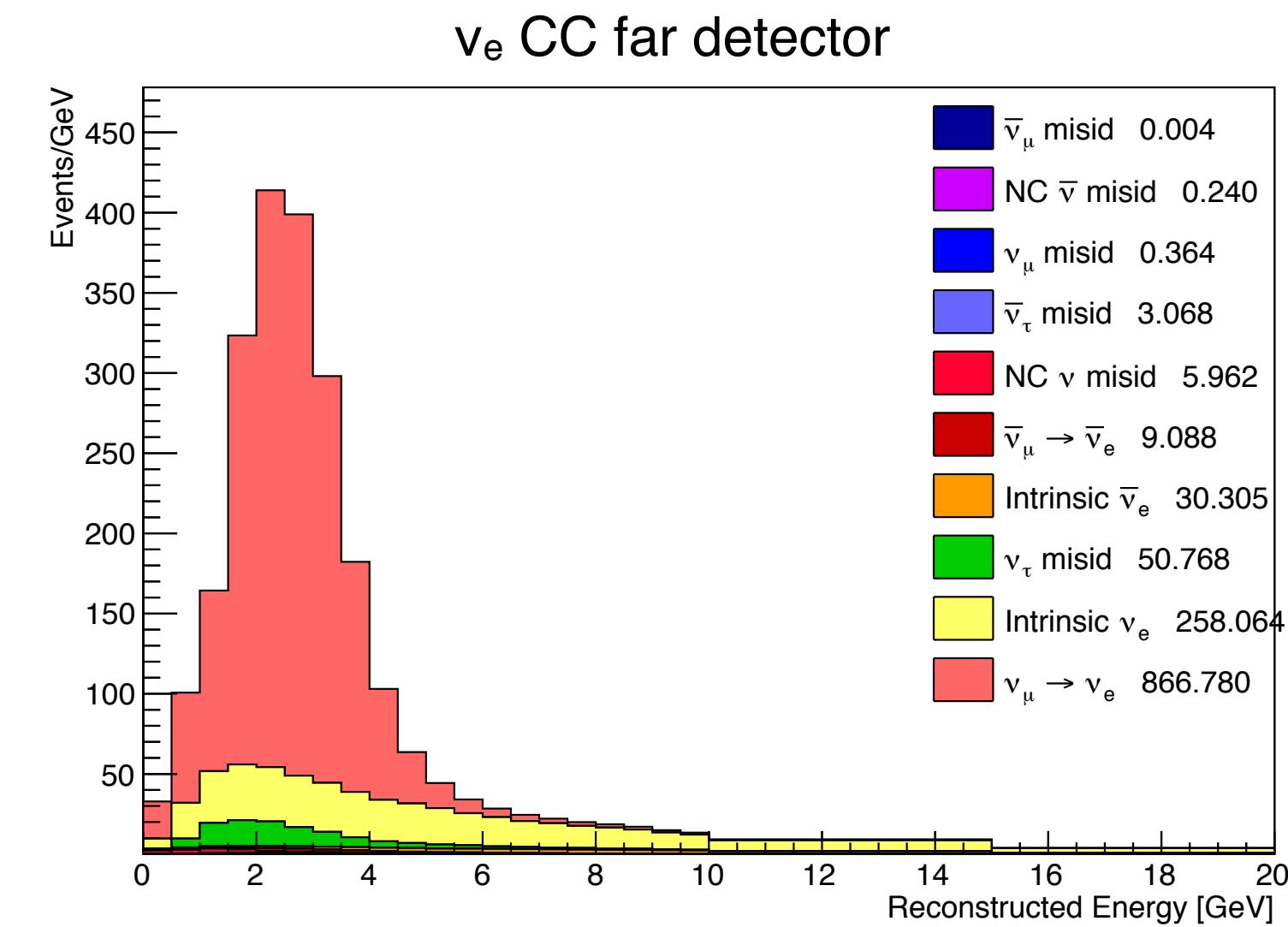
Back up

Super-fast MC simulation for DUNE

- Neutrino events for DUNE are generated by Genie MC generator for the given beam flux distribution ranging 0 to 40 GeV.
- Signatures of neutrino oscillation can be found in the appearance channel ($\nu_\mu \rightarrow \nu_e$), the disappearance channel ($\nu_\mu \rightarrow \nu_\mu$) in DUNE.
- For both channels, detector effects and event selections are applied.

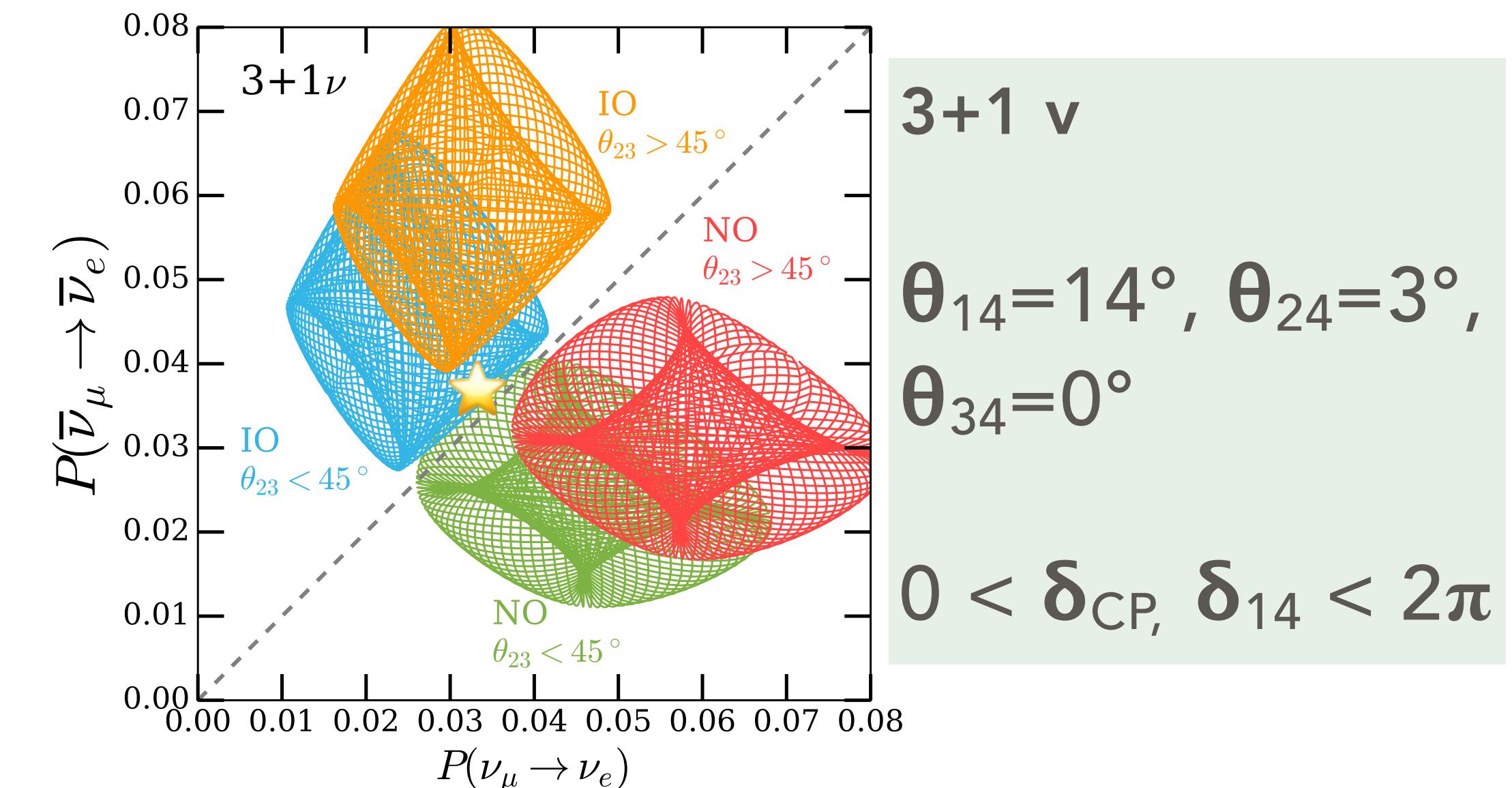
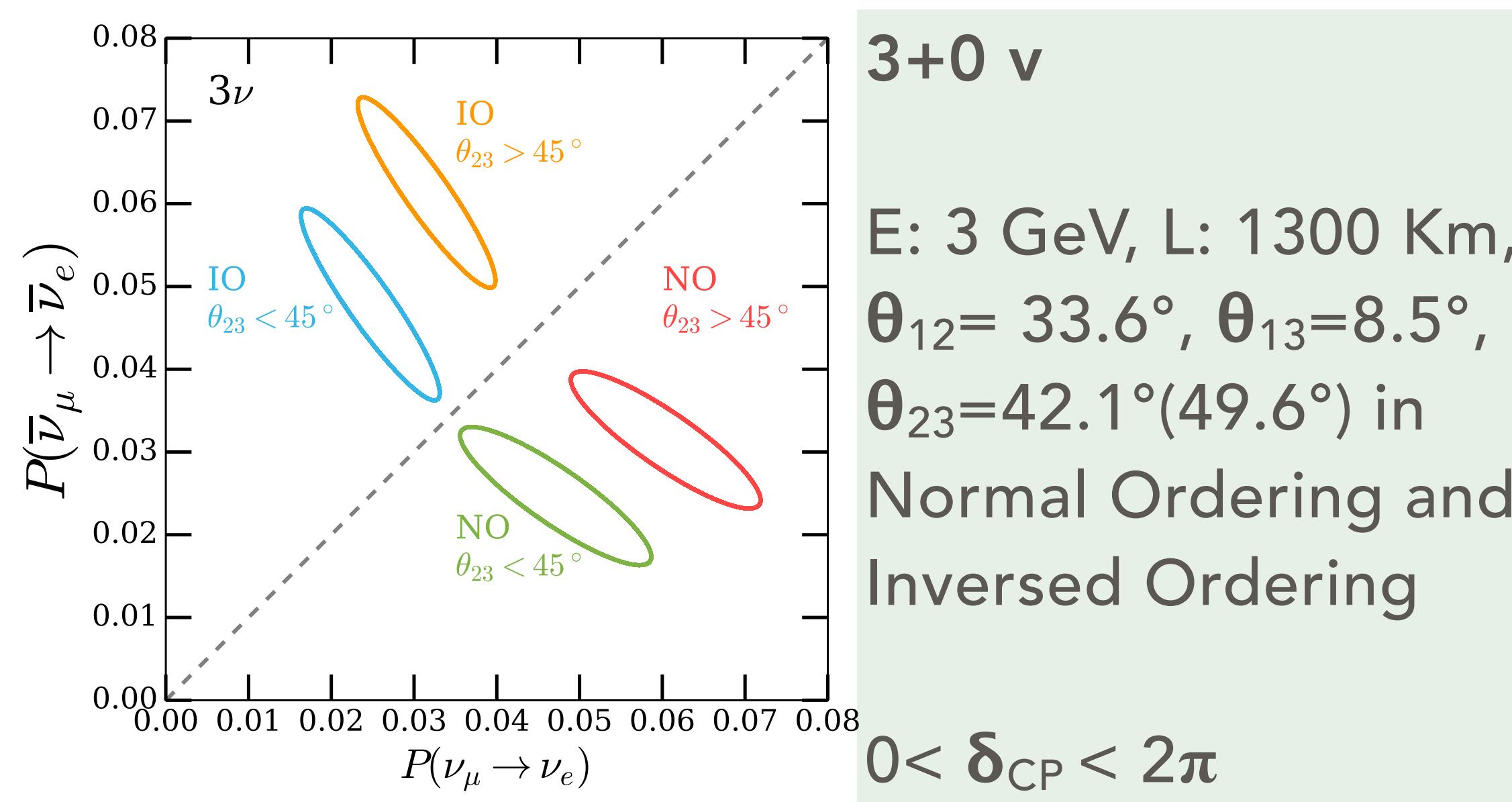


T. Alion, et al. arXiv:1606.09550



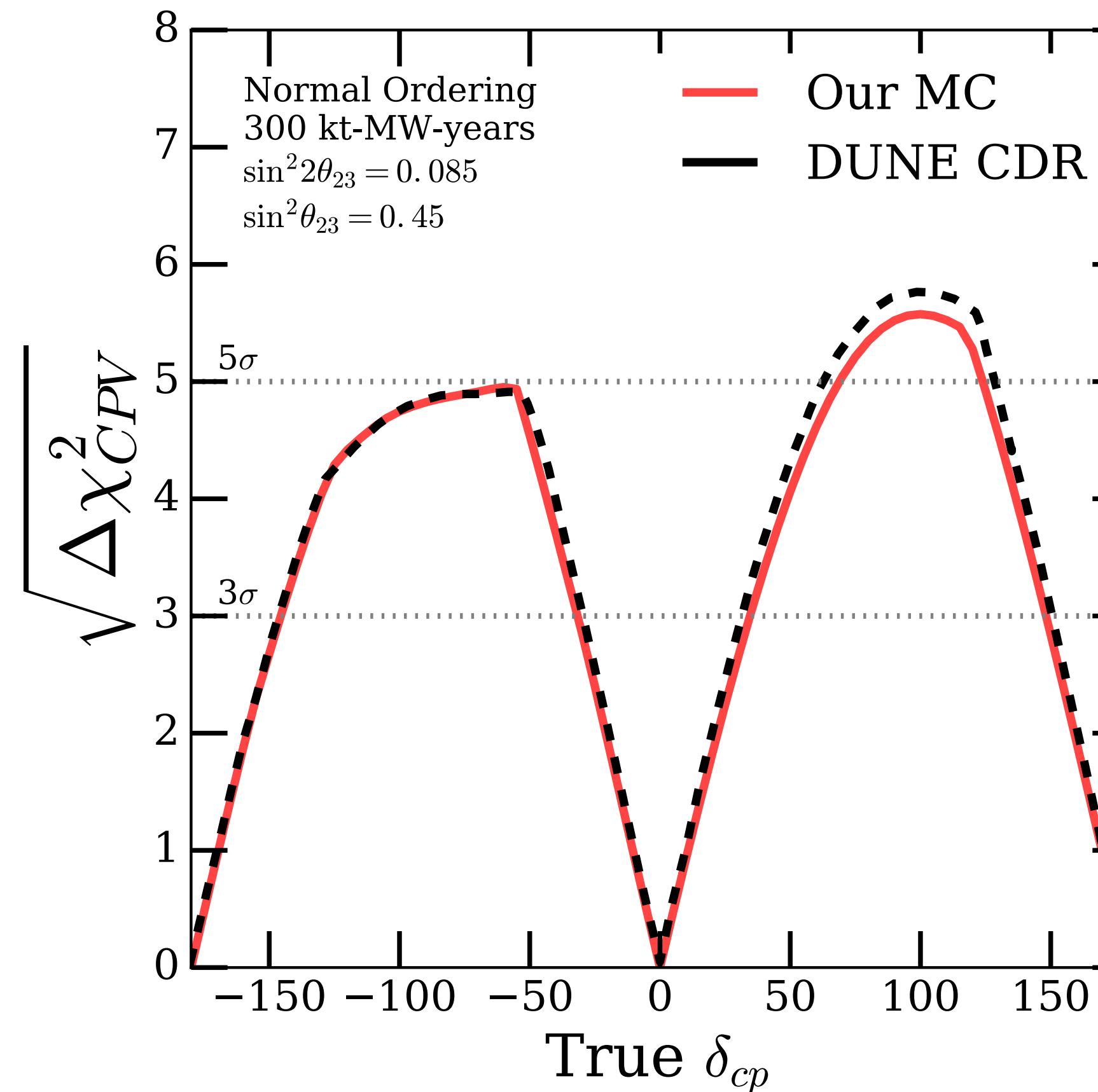
Parameter ambiguities @ DUNE with sterile neutrinos

- Bi-probability plot of oscillation probability; $P(\text{anti-}\bar{\nu}_\mu \rightarrow \text{anti-}\bar{\nu}_e)$ vs. $P(\nu_\mu \rightarrow \nu_e)$



Even one light sterile neutrino can invite severe overlaps in oscillation probabilities, thus ambiguities in oscillation parameters

Super-fast MC simulation for DUNE; CPV sensitivity



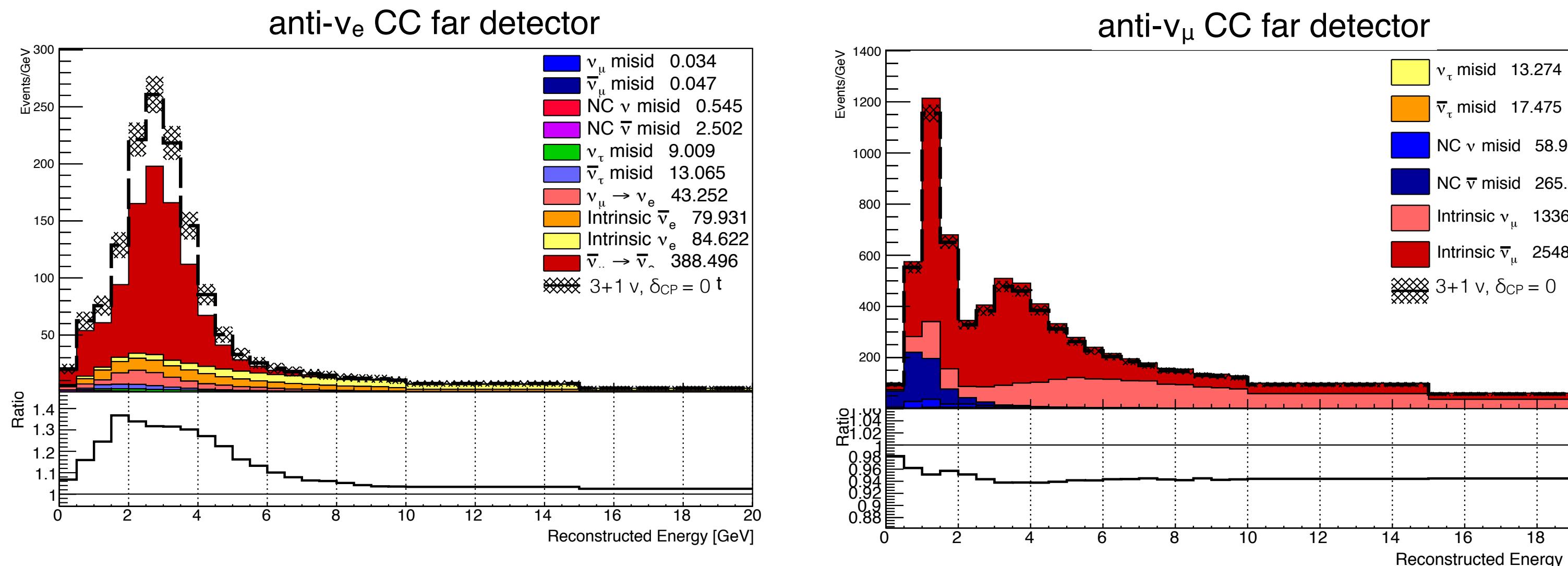
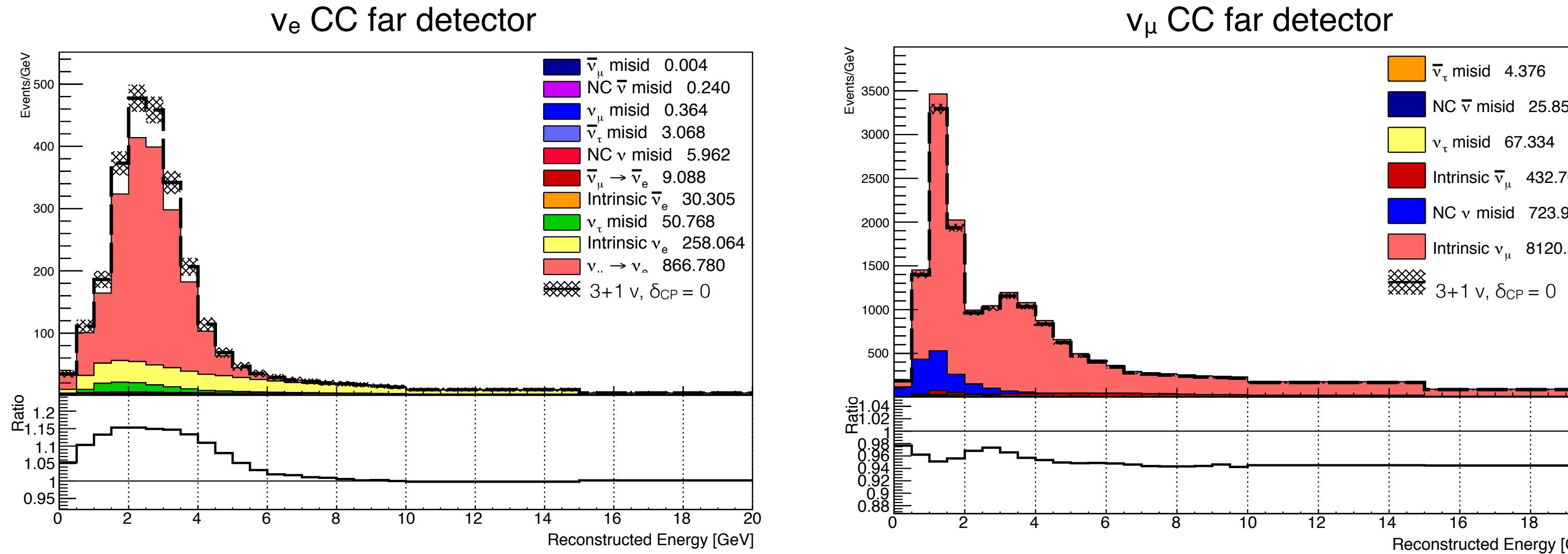
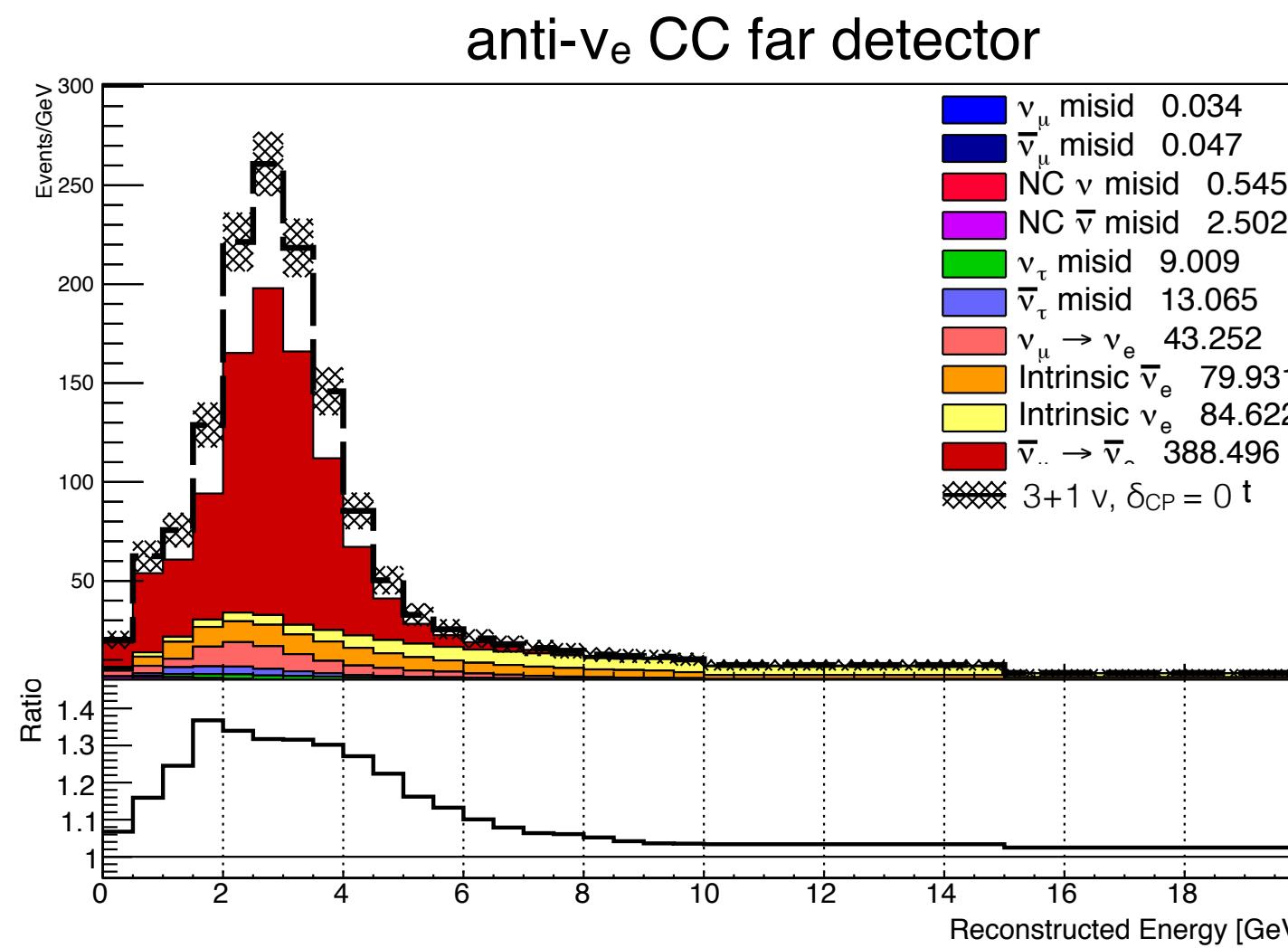
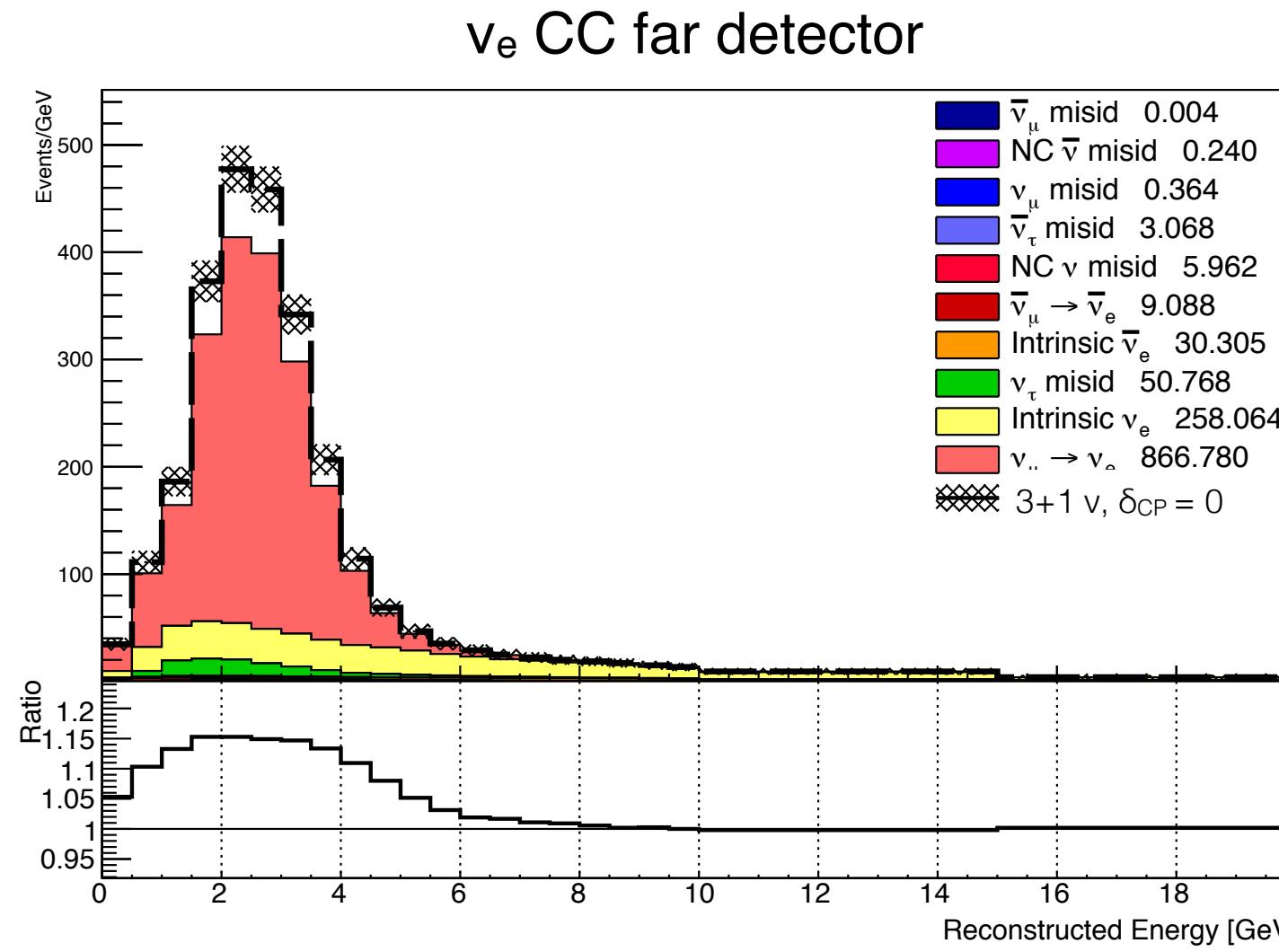
$$\Delta\chi^2_{CPV} = \text{Min}[\Delta\chi^2_{CP}(\delta_{CP}^{test} = 0), \Delta\chi^2_{CP}(\delta_{CP}^{test} = \pi)]$$

$$\Delta\chi^2_{CP} = \chi^2_{\delta_{CP}^{test}} - \chi^2_{\delta_{CP}^{true}}$$

For 3+0 ν, our CPV sensitivity
is close to DUNE CDR.

DUNE Collaboration CDR, arXiv:1512.06148

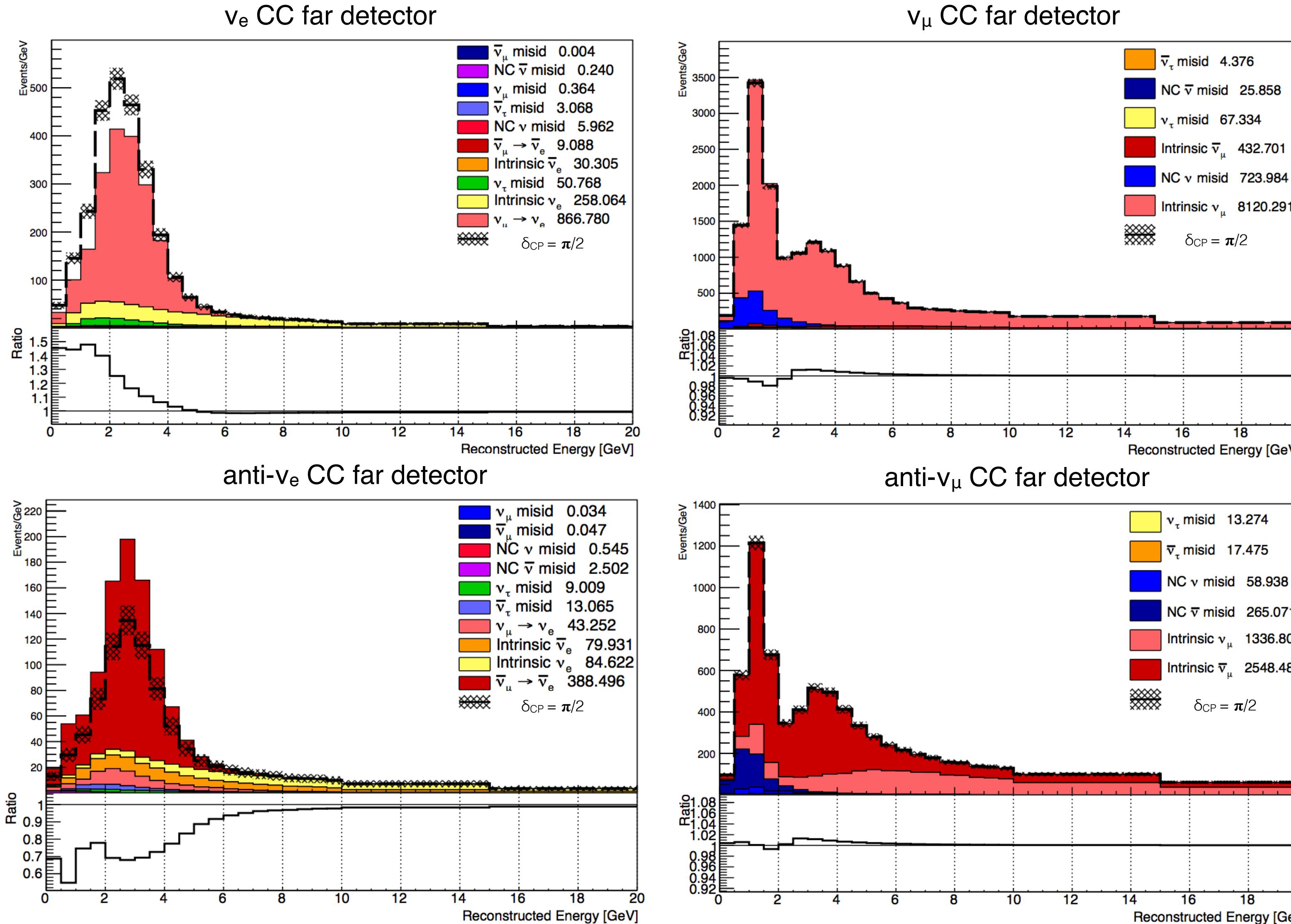
DUNE far detector spectra (3+1 ν best-fit, $\delta_{CP} = 0$)



- Sterile neutrino will have impact on far detector signal.
- $\Delta m_{41} = 0.92$, $U_{e4}=0.15$, $U_{\mu 4}=0.17$

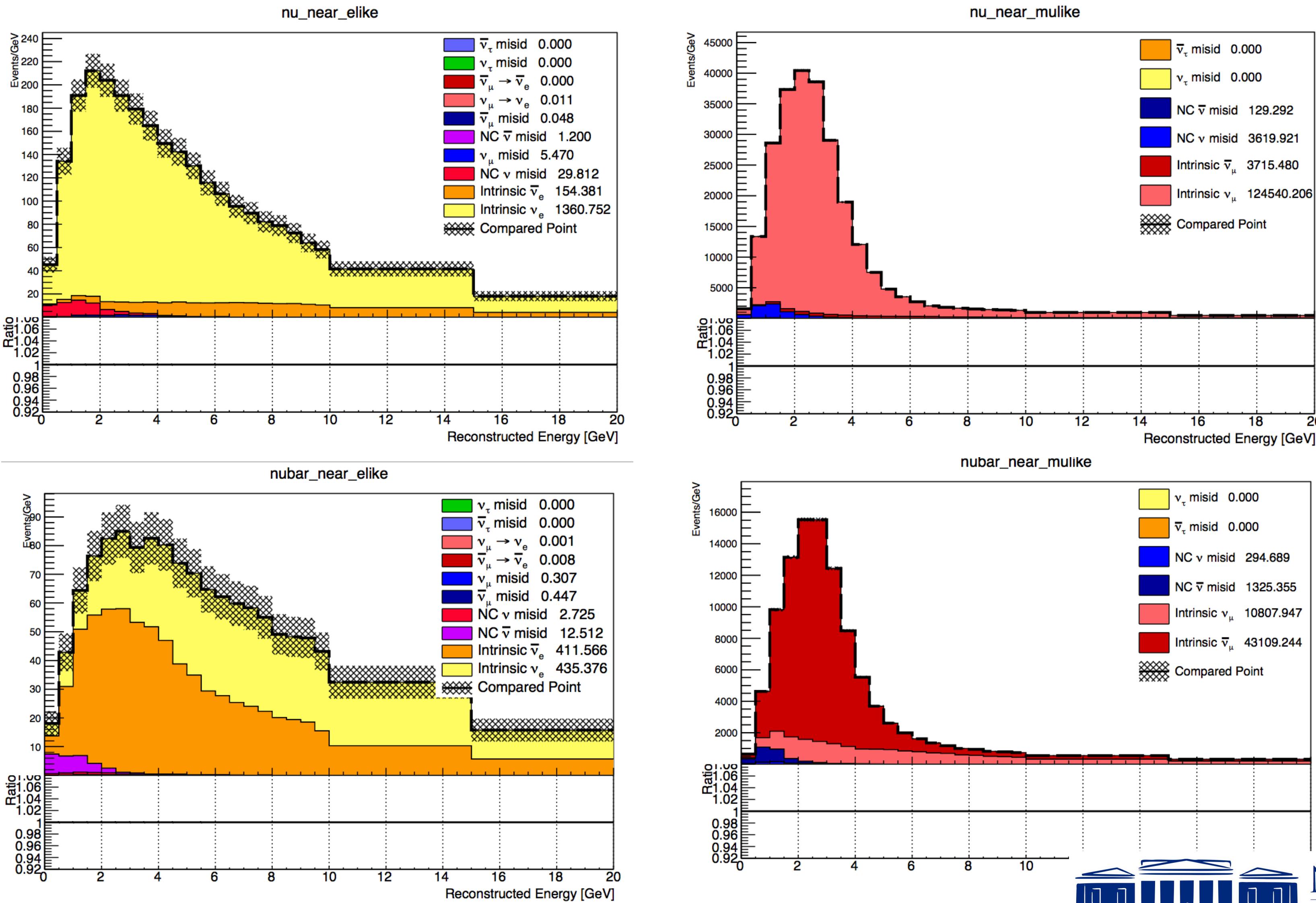


DUNE far detector spectra (3+0 v, $\delta_{CP} = \pi/2$)



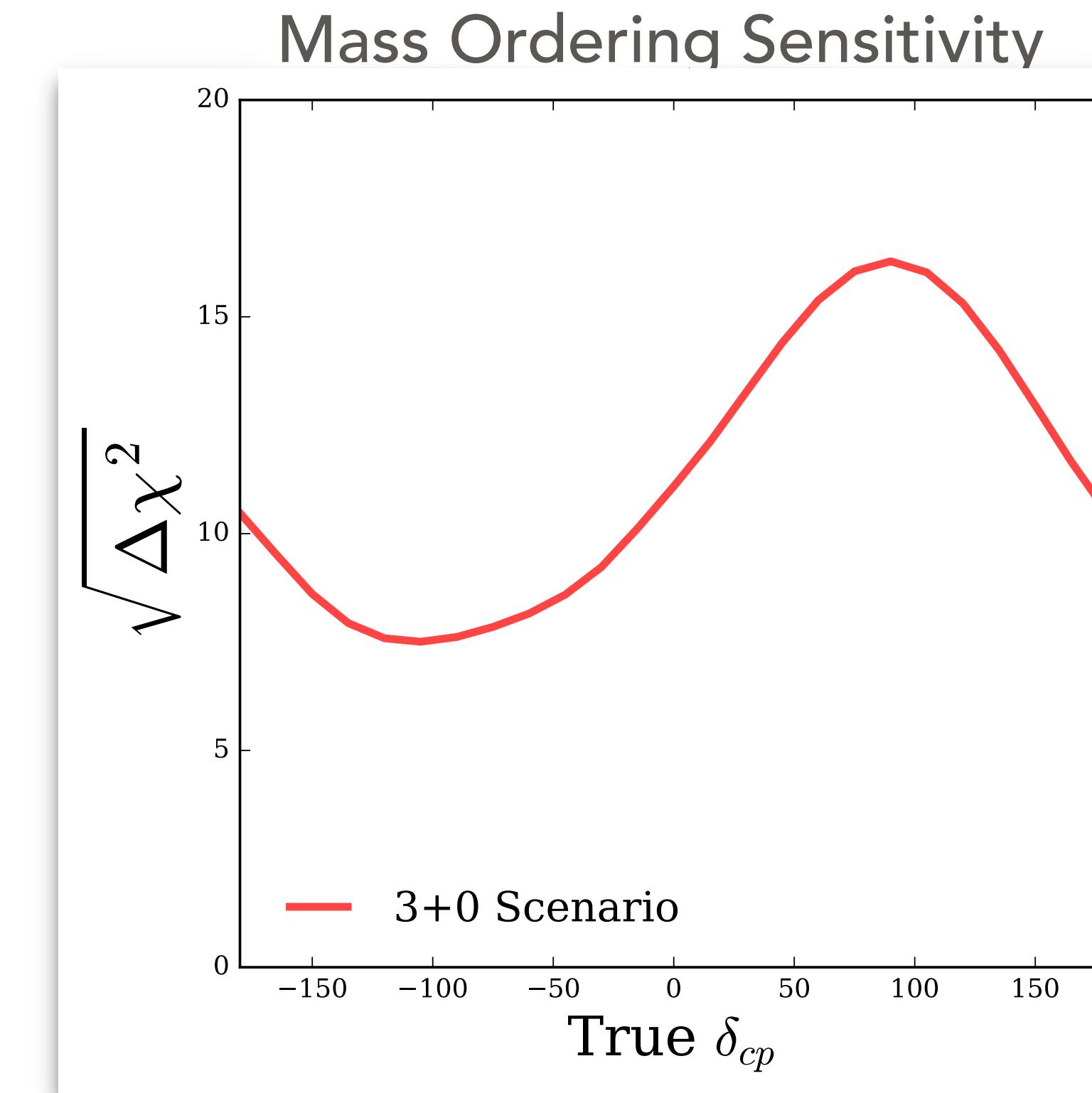
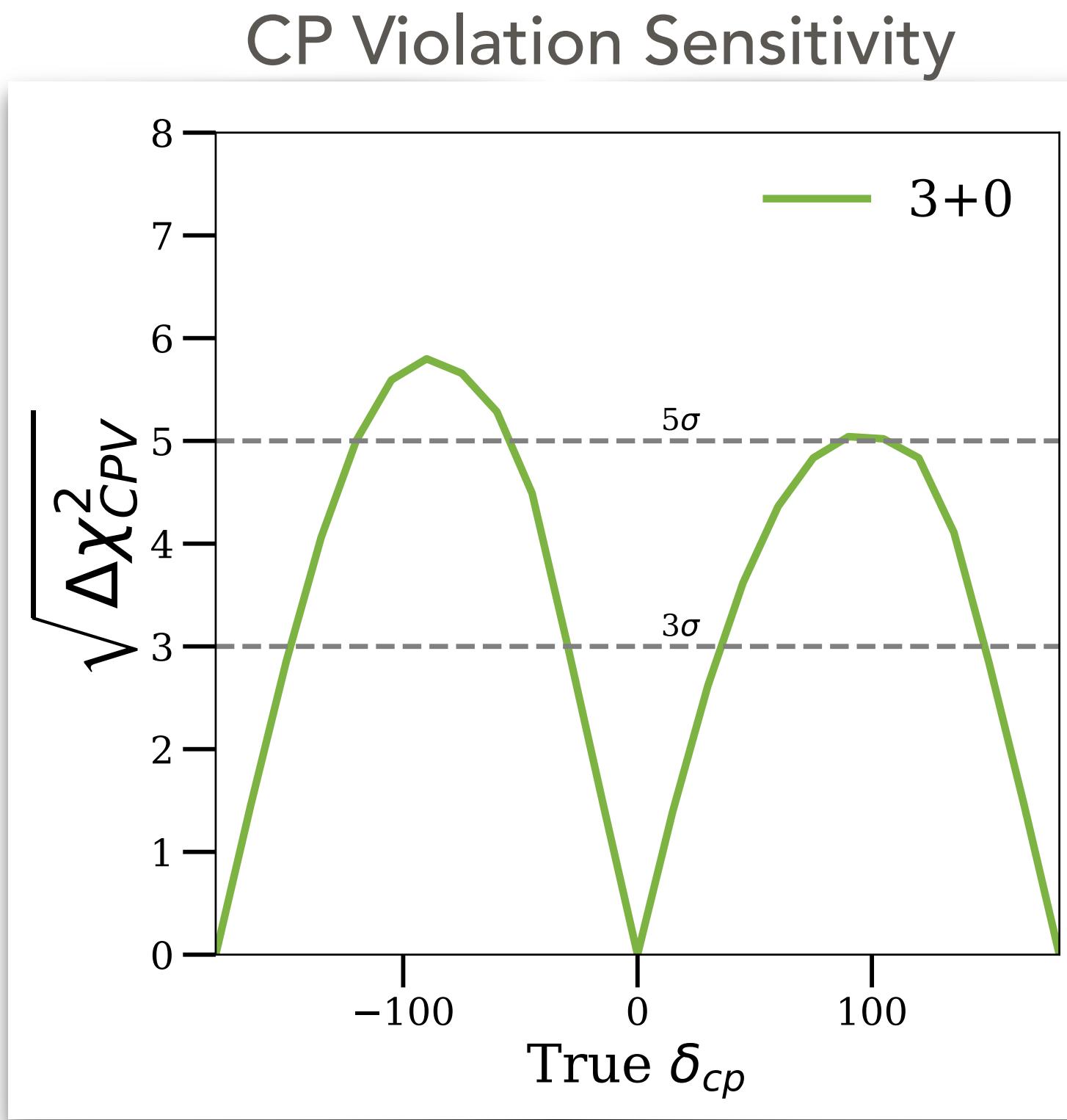
- Maximally violating CP
- CPV has large effect on signal event rate in v_e CC and anti- v_e CC

$3+0 \delta_{CP} = \pi/2$, near detector



DUNE's sensitivities

(Inverse ordering, 3+0 neutrino)

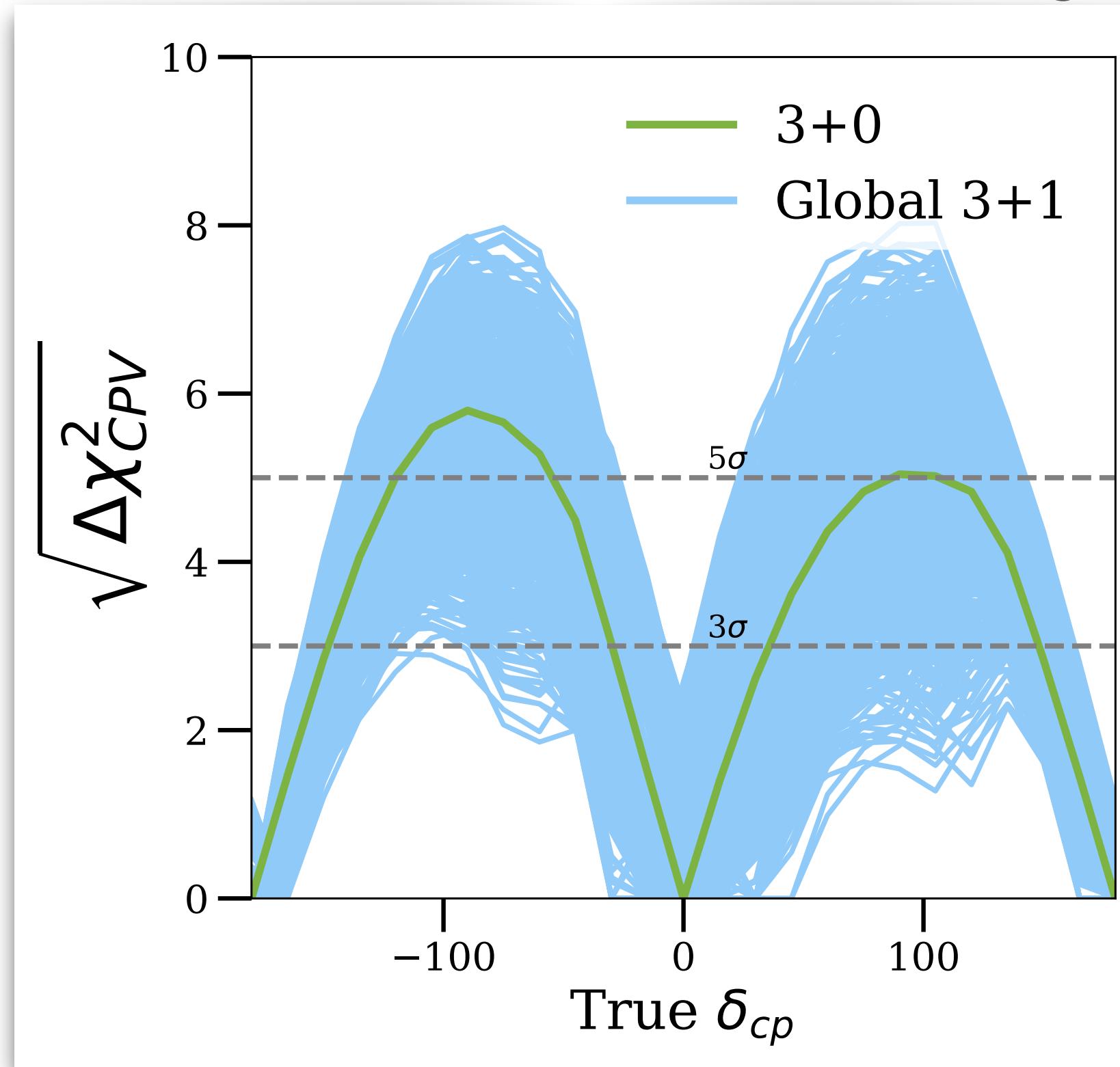


Our simulated results of 3 neutrino model in DUNE shows CPV sensitivity over 5 sigma for maximally violating phases, sensitivity of mass ordering over 5 sigma over all δ_{CP} .

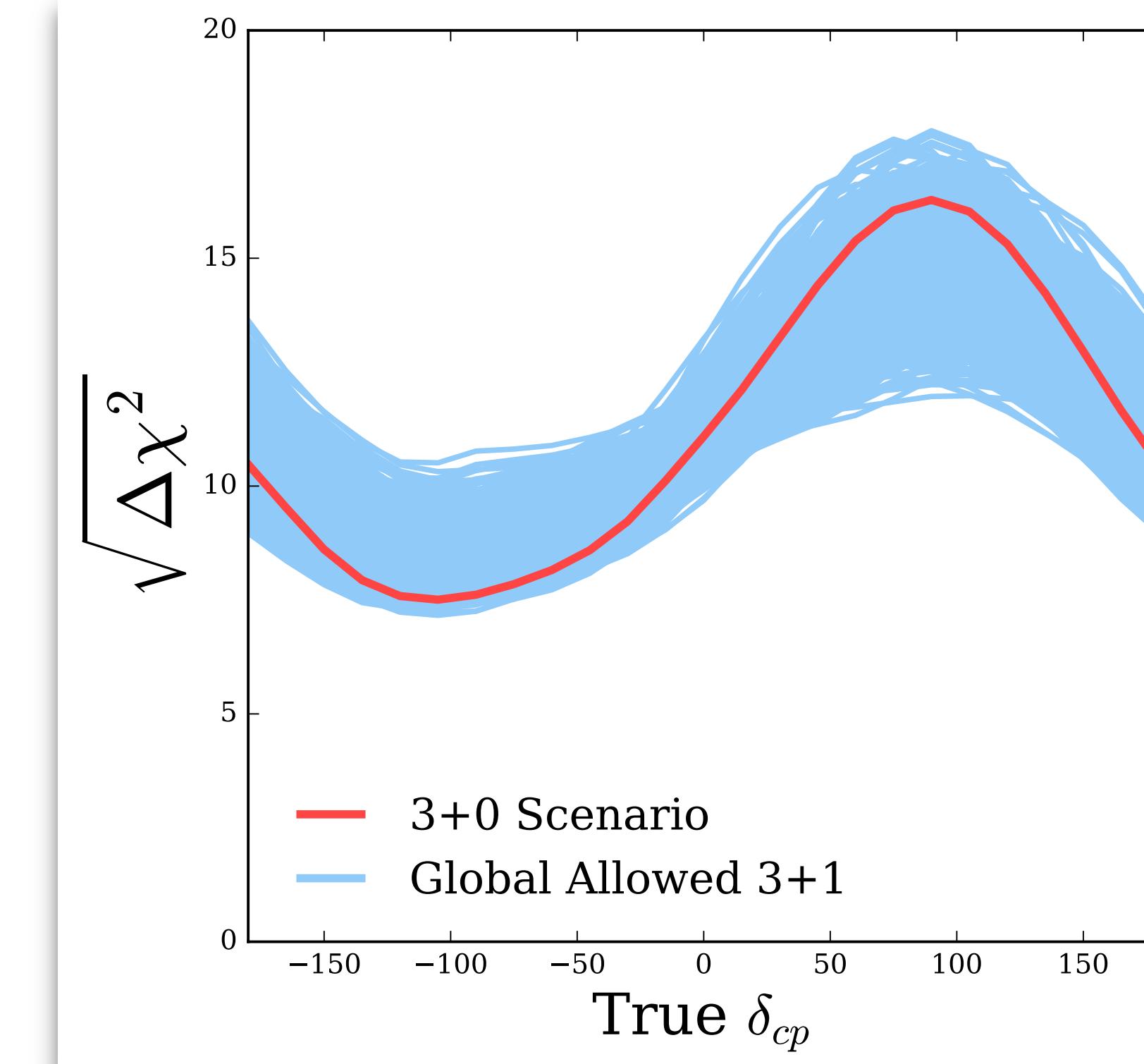
DUNE's sensitivities

(Inverse ordering, 3+1 Global)

CP Violation (Inverse Ordering)



Mass Ordering

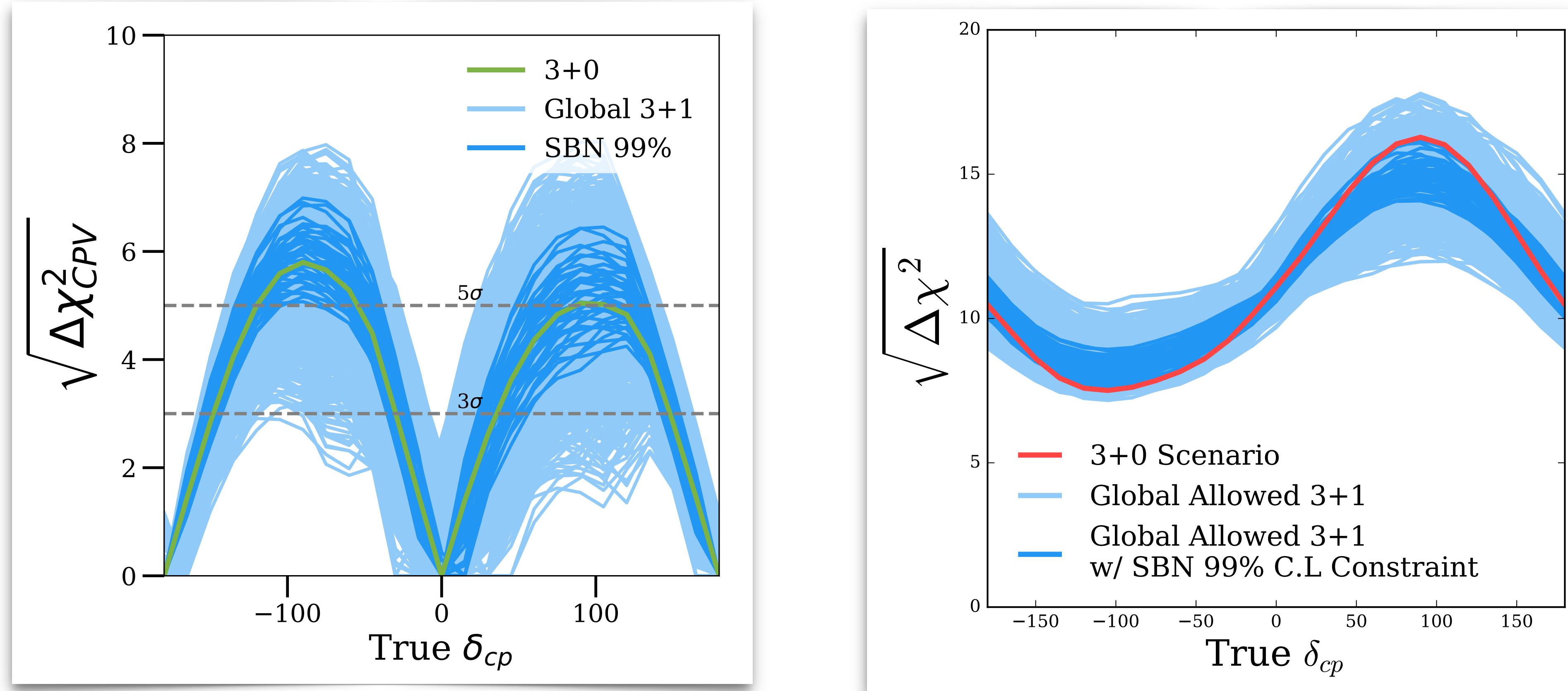


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3+0 fit

Within globally allowed 3+1 region, DUNE's sensitivities in CPV and mass ordering can be ranging with large uncertainty.

DUNE's sensitivities

(Inverse ordering, 3+1 Global, SBN 99% constraint)



With SBN, uncertainties in CPV and mass ordering sensitivity can be shrunk to the level of retainment of CPV sensitivity over 5 significance at maximally violating δ_{CP} angles.