Effect of light sterile states on measurements at long-baseline experiments

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Standard three-flavor framework

Oscillation probabilities: $\mathcal{F}(\theta_{12}, \theta_{13}, \theta_{23}, \delta_{\text{CP}}, \Delta m^2_{21}, \Delta m^2_{31})$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{bmatrix} \begin{bmatrix} \cos\theta_{13} & 0 & \sin\theta_{13}\, e^{i\delta_{\text{CP}}} \\ 0 & 1 & 0 \\ -\sin\theta_{13}\, e^{-i\delta_{\text{CP}}} & 0 & \cos\theta_{13} \end{bmatrix} \begin{bmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

LBL superbeam +
Atmospheric exp.
$\overset{(-)}{\nu}_\mu \to \overset{(-)}{\nu}_\mu$

SBL reactor exp.
$\bar{\nu}_e \to \bar{\nu}_e$

Solar + LBL
reactor exp.
$\overset{(-)}{\nu}_e \to \overset{(-)}{\nu}_e$

Well-measured parameters:
(best-fit $\pm 1\sigma$)

$\theta_{12}(°) = 34.3 \pm 1.0$
$\Delta m^2_{21} = 7.50^{+0.22}_{-0.20} \times 10^{-5}\ \text{eV}^2$

$\theta_{13}(°) = 8.53^{+0.13}_{-0.12}$

$|\Delta m^2_{31}| = 2.55^{+0.02}_{-0.03} \times 10^{-3}\ \text{eV}^2$

Not so well measured:

$\theta_{23}(°) \approx 49.0$
3σ range (°) : $41.20 - 51.33$

What is the neutrino mass ordering
- **normal i.e. $m_3 \gg m_2 > m_1$ or**
- **inverted i.e. $m_2 > m_1 \gg m_3$?**
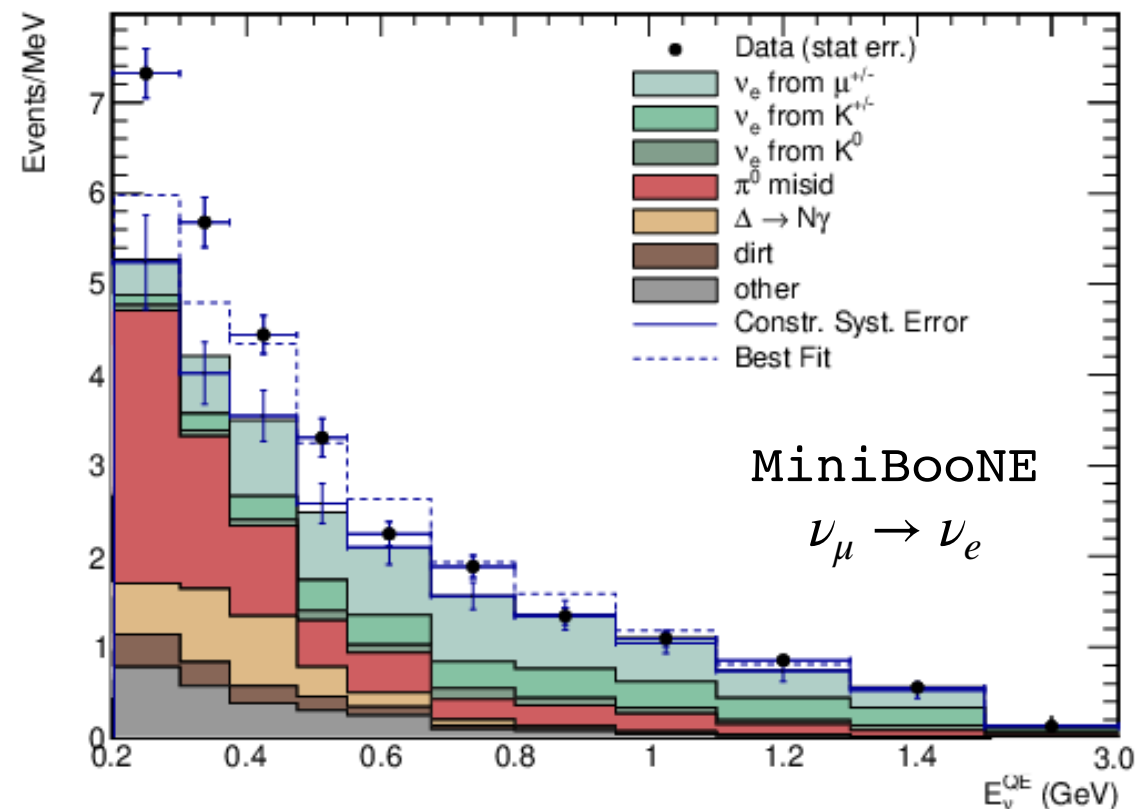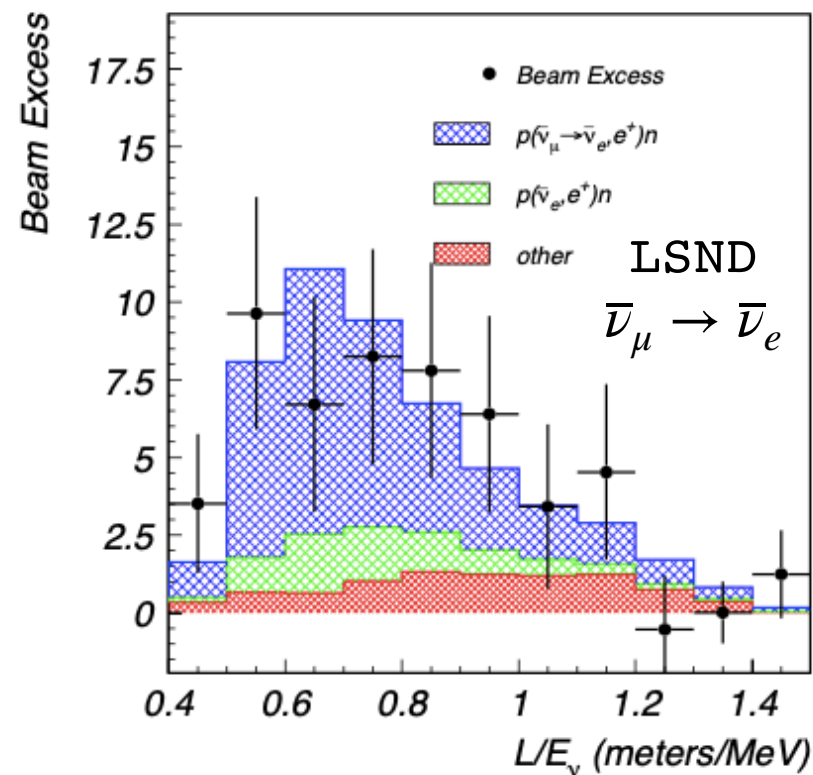
Do neutrinos violate CP?
- **Is $\text{P}(\nu_\alpha \to \nu_\beta) \neq \text{P}(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$?**
- $\delta_{\text{CP}}(°) = ??$

de Salas et.al. JHEP02(2021),071

Short-baseline anomalies

A bunch of unexplained anomalies when neutrinos travel very short distances !!

`Phys.Rev.D64(2001)112007`

LSND
$\overline{\nu}_\mu \to \overline{\nu}_e$

MiniBooNE
$\nu_\mu \to \nu_e$

Two flavor oscillation fit:
$$P\left(\nu_\mu \to \nu_e\right) = \sin^2 2\theta \, \sin^2 \frac{\Delta m^2 L}{4 E_\nu}$$
$$\left(\sin^2 2\theta, \Delta m^2\right) = \left(0.807, 0.043 \text{ eV}^2\right)$$
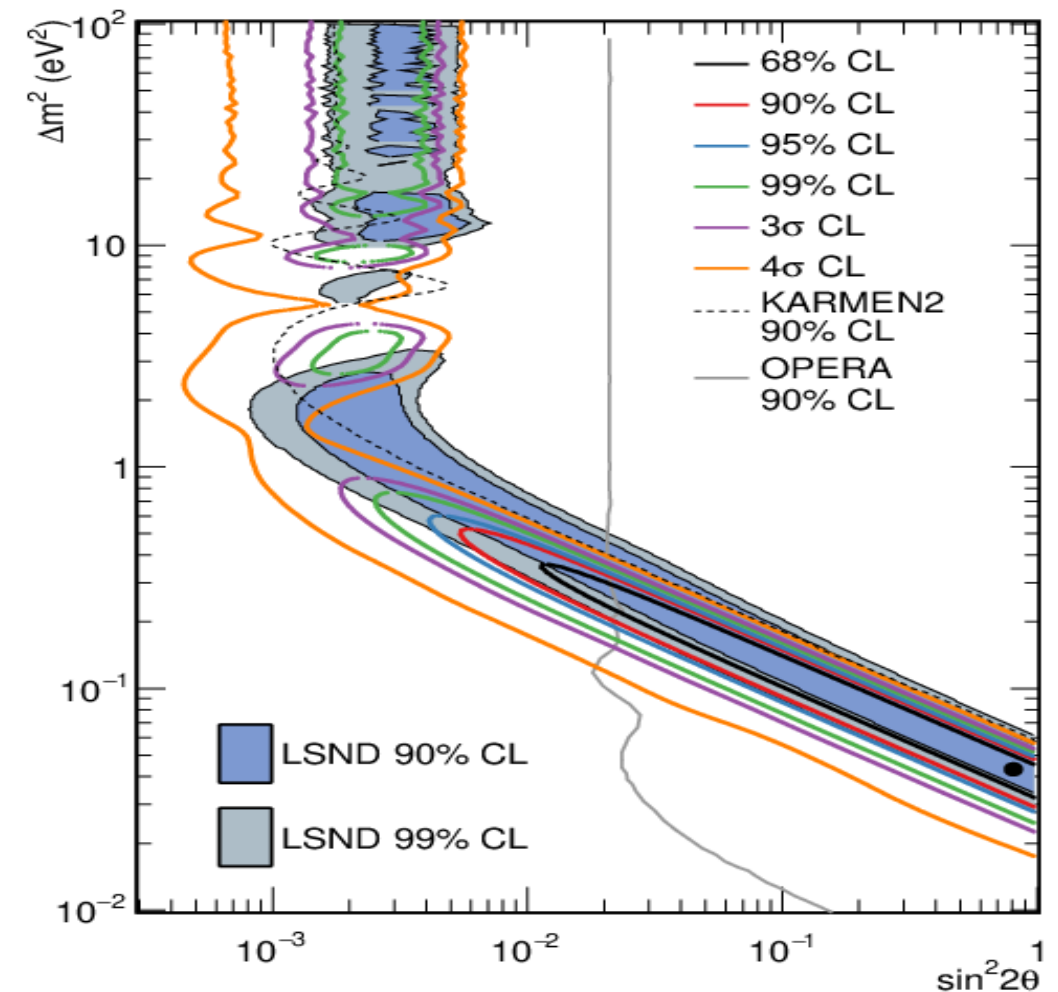
`Phys.Rev.Lett121(2018)221801`

Combined significance of LSND and MiniBooNE excess is ~ 6σ !

Sterile neutrino

* For the baselines and neutrino energies of the short-baseline experiments, the data cannot be explained by oscillations due to the solar or atmospheric mass-squared differences.

* The measurement of the invisible decay width of the Z boson limits the number of light SM active neutrinos to $N_\nu = 2.9840 \pm 0.0082$.

* The simplest way to explain the SBL anomalies is to assume the existence of new light neutrinos which are similar to active neutrinos in masses, mixings except that they do not undergo weak interactions.

* Conventionally, these new neutrinos have been called "Sterile". Sterile neutrinos are SM singlets.

* SBL anomalies can be explained if Active and Sterile neutrinos are mixed. In the simplest case of the 3+1 model, a sterile neutrino of mass $\sim 1eV$ is needed along with the 3 active neutrinos.

Deep Underground Neutrino Experiment
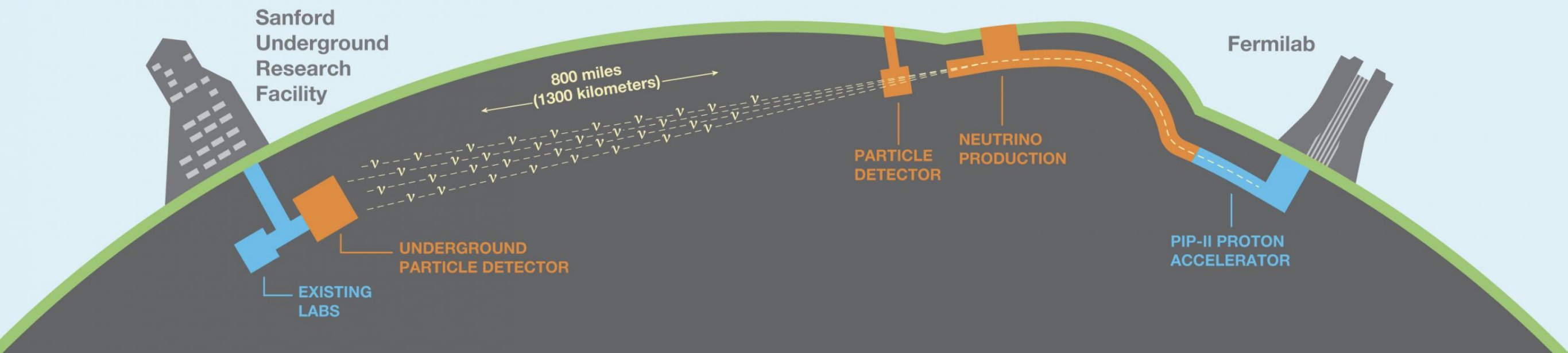
hep-ex/arXiv:2002.03005

1.2 MW neutrino beam
1.1×10^{21} protons-on-target/year
3.5 year ν + 3.5 year $\bar{\nu}$

Detector: Liquid Argon TPC

$E_\nu \in (0.5 \text{ GeV}, 10 \text{ GeV})$
Baseline: 1300 km

The primary science goals of DUNE are to measure:

- **CP phase**
- **Neutrino mass ordering**
- **Octant of 2-3 mixing angle**
- **Precision measurements**

Can $\Delta m^2 \sim 1 \text{ eV}^2$ oscillations impact LBL far-detector measurements?
If yes, how exactly?

Gandhi, Kayser, Masud, Prakash   JHEP11(2015)039
Dutta, Gandhi, Kayser, Masud, Prakash   JHEP11(2016)122

The 3+1 formalism

* We augment the standard neutrino theory (3+0) by a new heavier mass eigenstate ν_4 (3+1).

* This new state is sterile as far as the weak interactions are concerned but it can mix with the active neutrinos.

* The mass of ν_4 is around 1 eV such that $\Delta m_{41}^2 = m_4^2 - m_1^2 = 1 \text{ eV}^2$.

* $\Delta m_{41}^2 \sim \Delta m_{41}^2 \sim \Delta m_{43}^2 \gg |\Delta m_{31}^2| \sim |\Delta m_{32}^2| \gg \Delta m_{21}^2$

* The Δm_{4i}^2 - driven oscillations at the far detector with L/E ~ 500 km/GeV will be too fast to be resolved by the detector.

* The oscillations in 4x4 mixing matrix are characterized by **6 mixing angles**, **3 CP-violating phases** and **3 mass-squared differences**.

$$U_{\text{PMNS}}^{3+1} = \underbrace{O(\theta_{34}, \delta_{34})\, O(\theta_{24}, \delta_{24})\, O(\theta_{14})}_{\text{new mixing angles and phases}} \quad \underbrace{O(\theta_{23})\, O(\theta_{13}, \delta_{13})\, O(\theta_{12})}_{\text{standard PMNS}}$$

(Here O's are 4x4 Euler rotation matrices)

Constraints on the active-sterile mixings

* Constraints derived are calculated in the region of $\Delta m_{41}^2 \sim 1$ eV^2. At such values, the most stringent constraints come from the disappearance experiments.

* Consistent parameterisation.

* We assume the lower limits on the active-sterile mixings to be 0.

* ν_e and $\bar{\nu}_e$ disappearance searches probe $|U_{e4}| = \sin\theta_{14}$.

* ν_μ, $\bar{\nu}_e$ and NC disappearance searches probe
    $|U_{\mu 4}| = \cos\theta_{14}\sin\theta_{24}$ and
    $|U_{\tau 4}| = \cos\theta_{14}\cos\theta_{24}\sin\theta_{34}$.

* Daya Bay: $\theta_{14} \in [0, 13°]$ 95% C.L.   `PRL113,141802(2014)`
  IceCube: $\theta_{24} \in [0, 7°]$ 99% C.L.   `PRL117,071801(2016)`
  MINOS(+): $\theta_{34} \in [0, 26°]$ 90% C.L.   `PRL107,011802(2011)`

* The CP phases remain unconstrained.

* LSND: $\sin^2 2\theta_{\mu e} < 0.008$ for $\Delta m_{41}^2 \sim 1$ eV^2.

$\nu_\mu \to \nu_e$ in 3+1 in vacuum

$$P(\nu_\mu \to \nu_e) = 4\,|U_{\mu 4}U_{e4}|^2 \times 0.5 - 4\sum_{j<4,i<j} \mathrm{Re}(U_{\mu i}U_{ei}^*U_{\mu j}^*U_{ej})\;\sin^2 \Delta m_{ji}^2 + 2\sum_{j<4,i<j} \mathrm{Im}(U_{\mu i}U_{ei}^*U_{\mu j}^*U_{ej})\;\sin 2\Delta m_{ji}^2$$

$$= \frac{1}{2}\sin^2 2\theta_{\mu e}^{4\nu} + \left(a^2 \sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\sin^2 2\theta_{13}\sin^2 2\theta_{\mu e}^{4\nu}\right)\left[\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}\right]$$

$$+ \cos(\delta_{13})\,ba^2\sin 2\theta_{\mu e}^{3\nu}\left[\cos 2\theta_{12}\sin^2\Delta_{21} + \sin^2\Delta_{31} - \sin^2\Delta_{32}\right]$$

$$+ \cos(\delta_{24})\,ba\sin 2\theta_{\mu e}^{4\nu}\left[\cos 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21} - \sin^2\theta_{13}(\sin^2\Delta_{31} - \sin^2\Delta_{32})\right]$$

$$+ \cos(\delta_{13}+\delta_{24})\,a\sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\left[-\frac{1}{2}\sin^2 2\theta_{12}\cos^2\theta_{13}\sin^2\Delta_{21}\right.$$

$$+ \left.\cos 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32})\right]$$

$$- \frac{1}{2}\sin(\delta_{13})\,ba^2\sin 2\theta_{\mu e}^{3\nu}\left[\sin 2\Delta_{21} - \sin 2\Delta_{31} + \sin 2\Delta_{32}\right]$$

$$+ \frac{1}{2}\sin(\delta_{24})\,ba\sin 2\theta_{\mu e}^{4\nu}\left[\cos^2\theta_{13}\sin 2\Delta_{21} + \sin^2\theta_{13}(\sin 2\Delta_{31} - \sin 2\Delta_{32})\right]$$

$$+ \frac{1}{2}\sin(\delta_{13}+\delta_{24})\,a\sin 2\theta_{\mu e}^{3\nu}\sin 2\theta_{\mu e}^{4\nu}\left[\cos^2\theta_{12}\sin 2\Delta_{31} + \sin^2\theta_{12}\sin 2\Delta_{32}\right]$$

$$+ \left(b^2 a^2 - \frac{1}{4}a^2\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{3\nu} - \frac{1}{4}\cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2 2\theta_{\mu e}^{4\nu}\right)\sin^2\Delta_{21}$$

Here:
$$\Delta_{ji} = \Delta m_{ji}^2$$
$$\sin 2\theta_{\mu e}^{3\nu} = \sin 2\theta_{13}\sin\theta_{23}$$
$$\sin 2\theta_{\mu e}^{4\nu} = \sin 2\theta_{14}\sin\theta_{24}$$
$$a = \cos\theta_{14}\cos\theta_{24}$$
$$b = \cos\theta_{13}\cos\theta_{23}\sin 2\theta_{12}$$

* In vacuum, $P(\nu_\mu \to \nu_e)$ does not depend on θ_{34} and δ_{34}.
* In vacuum, there are only two effective CP-violating phases: δ_{24} and $(\delta_{13}+\delta_{24})$.
* Terms marked in red are the ones which lead to substantial differences between 3+0 and 3+1.
* These are interference terms which depend on the sines and cosines of the CP-violating phases.
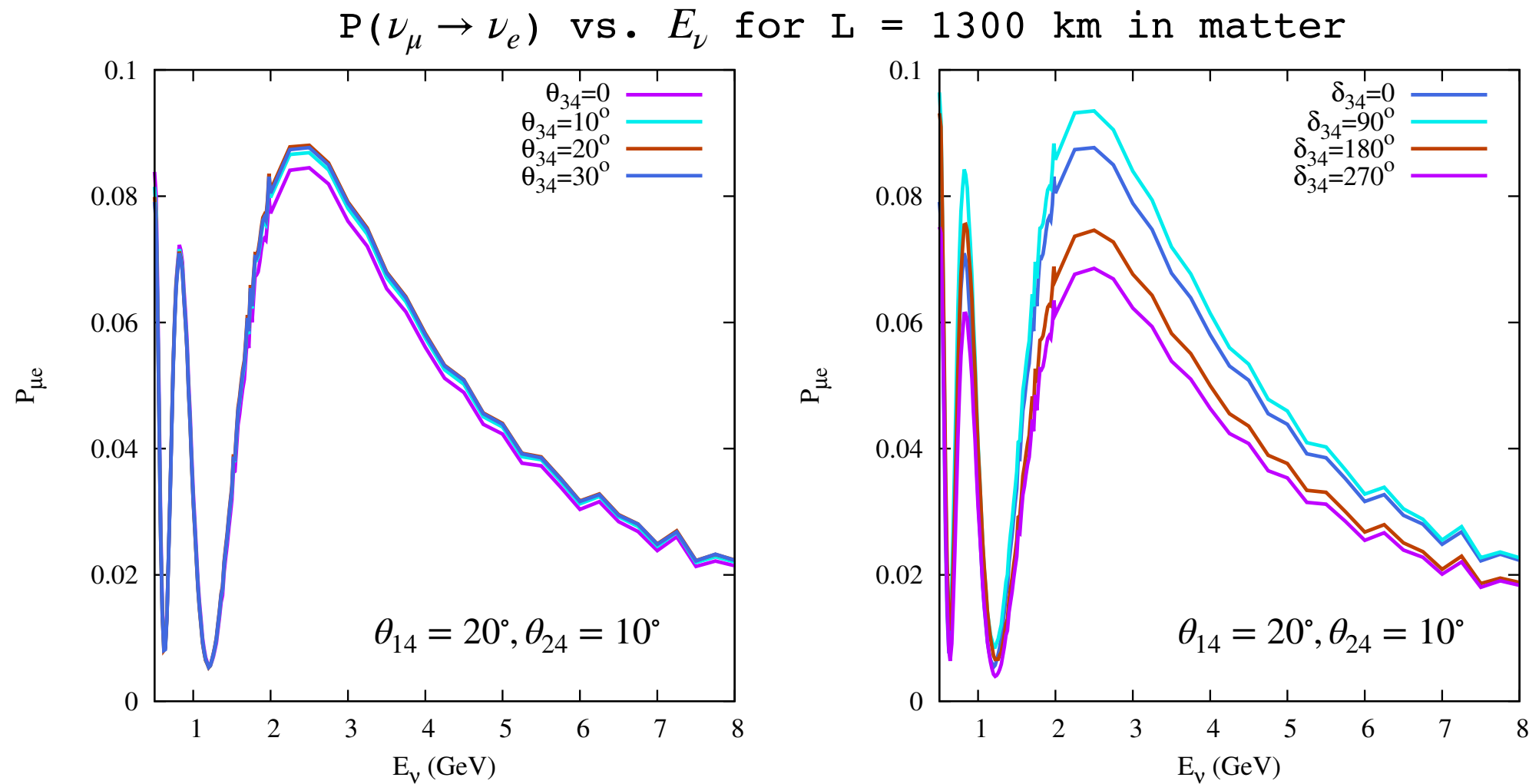
$\nu_\mu \to \nu_e$ in 3+1 in matter

We calculate exact oscillation probabilities in matter using GLoBES.

Comput.Phys.Commun.167(2005)195

Left plot: CP-violating phases are equal to 0, θ_{34} is varied $\in [0, 30°]$.

Right plot: θ_{34} is fixed equal to 30°, CP-violating phases are varied $\in [0, 360°]$.

P($\nu_\mu \to \nu_e$) vs. E_ν for L = 1300 km in matter

* θ_{34} **and** δ_{34} **play significant roles in matter.**

* **These parameters play no role in vacuum or at short-baselines**

* **Considerations for vacuum/SBL do not carry over to matter/LBL!**

$\nu_\mu \to \nu_e$ in 3+1 in matter

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CP-violation across different channels in 3+1
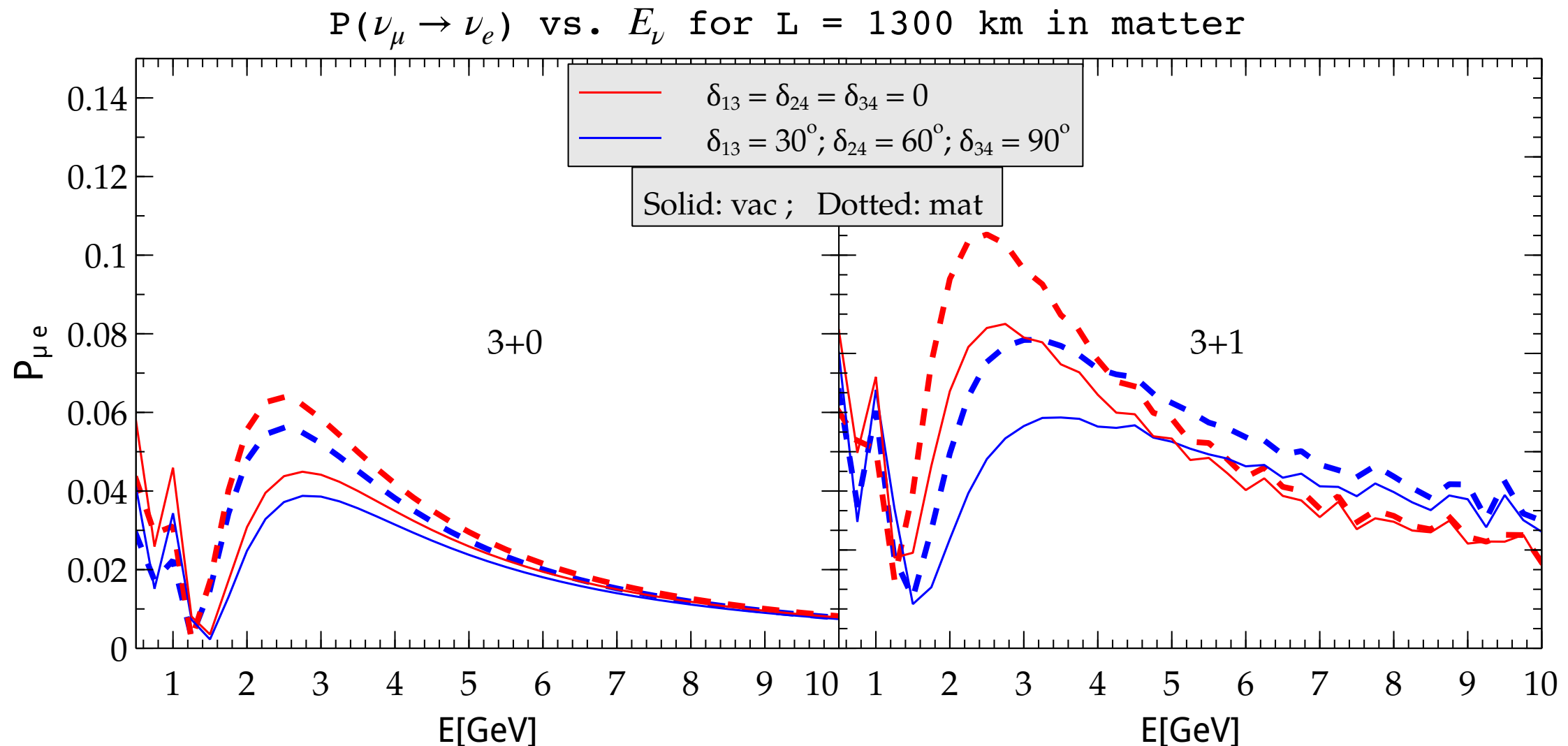
* The measure of CP violation (in vacuum) can be given by $\Delta P_{\alpha\beta} = P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

* $\Delta P_{\alpha\beta} = -\Delta P_{\beta\alpha}$ due to CPT invariance $\implies$ $\Delta P_{\alpha\alpha} = 0$ i.e. no CPV in disappearance channels.

* In 3+0, we can have 3 independent CP violating differences: $\Delta P_{\mu e}$, $\Delta P_{\mu\tau}$, $\Delta P_{e\tau}$ while in 3+1, we can have 6 independent CP violating differences: $\Delta P_{\mu e}$, $\Delta P_{\mu\tau}$, $\Delta P_{e\tau}$, ΔP_{es}, $\Delta P_{\mu s}$, $\Delta P_{\tau s}$.

* From the conservation of probability, we have

$$P_{\mu e} + P_{\mu\mu} + P_{\mu\tau} = \bar{P}_{\mu e} + \bar{P}_{\mu\mu} + \bar{P}_{\mu\tau} = 1$$

$$\implies \Delta P_{\mu e} + \Delta P_{\mu\tau} = 0$$

Similarly, we get: $\Delta P_{\tau e} + \Delta P_{\tau\mu} = 0$

This means, $\Delta P_{\mu e} = -\Delta P_{\mu\tau} = \Delta P_{e\tau}$

* Thus, in 3+0, the extent of CP violation is the same across all channels. If we find CP to be conserved in one channel, it will also be conserved in the other ones.

However, in 3+1, using the same logic, we get relations such as: $\Delta P_{\mu e} = \Delta P_{\tau\mu} - \Delta P_{\mu s}$

Thus, extent of CP-violation across all channels in 3+1 may not be equal. We may not be able to conclude definitively by measuring only one CP-violating channel.
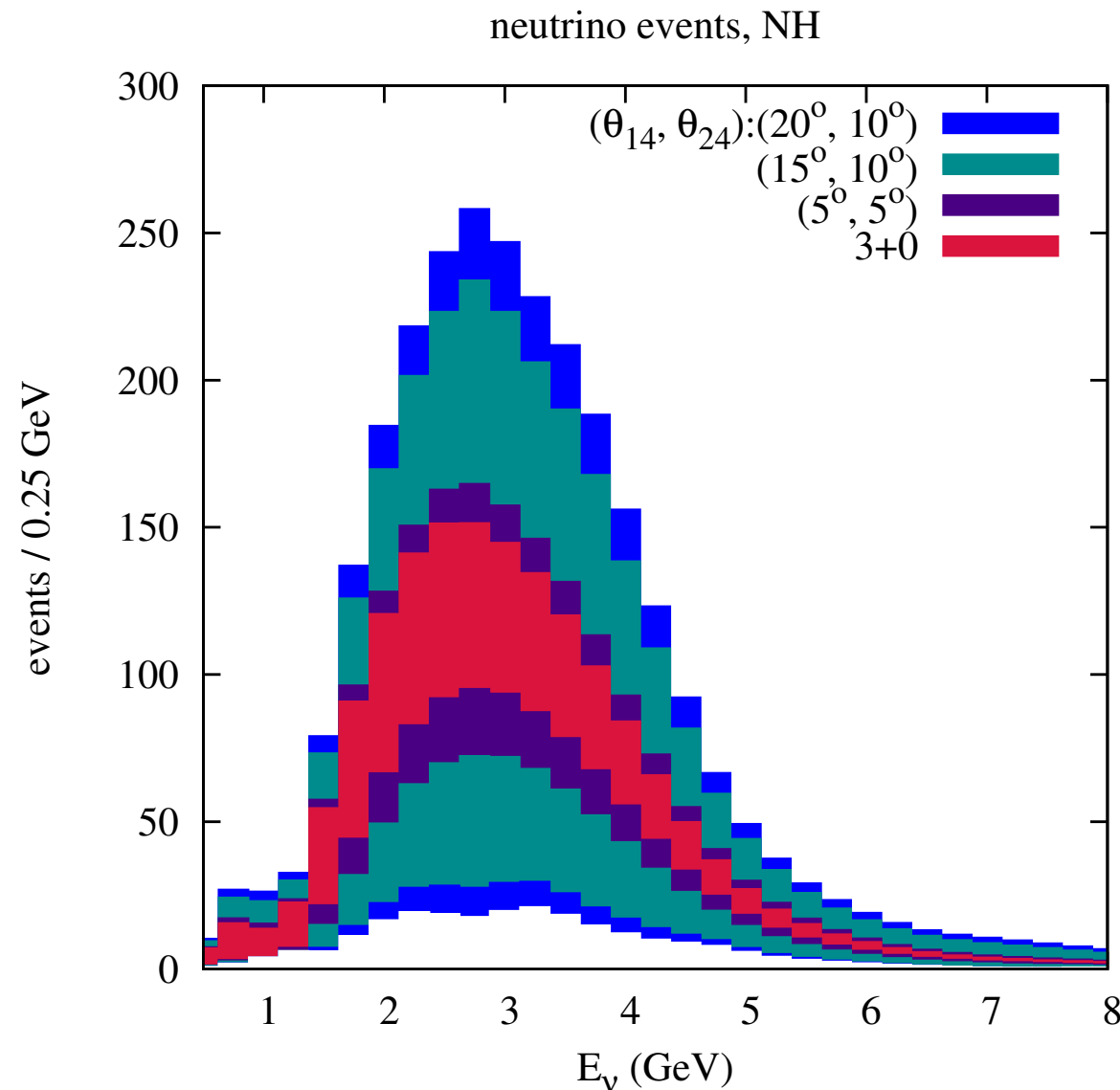
Event rates at DUNE

We calculate events rates for DUNE by performing realistic simulations.

Red band: corresponds to 3+0 and variation of $\delta_{CP} \in [0, 360°]$.

Other bands: correspond to 3+1 and variation of $\theta_{34} \in [0, 30°]$ and $\delta_{13}, \delta_{24}, \delta_{34} \in [0, 360°]$.

neutrino events, NH

* **Too large or too small events rates may be pointers to sterile states**

* **3+0 encompassed by 3+1: leading to substantial degeneracy**

* **If observed events in the red band then degenerate solutions possible!**

CP violation in 3+1

**Excluding CP-conserving values as a function of true oscillation parameters**

Results for the DUNE experiment:

* We compare 3+0 and 3+1.

* 3+0: test values: $\delta_{13} = 0, \pm \pi$.

* 3+1: test values: $\delta_{13}, \delta_{24}, \delta_{34} = 0, \pm \pi$.

* 3+0 oscillation parameters held fixed in fit.

* χ^2 marginalized over CP-conserving values and in allowed ranges of test $\theta_{14}, \theta_{24}, \theta_{34}$.

Small mixings: Sensitivity decreases

Large mixings: Sensitivity spans on both sides of the 3+0 sensitivity

Significant amplification of sensitivity even when true $\delta_{CP} = 0$
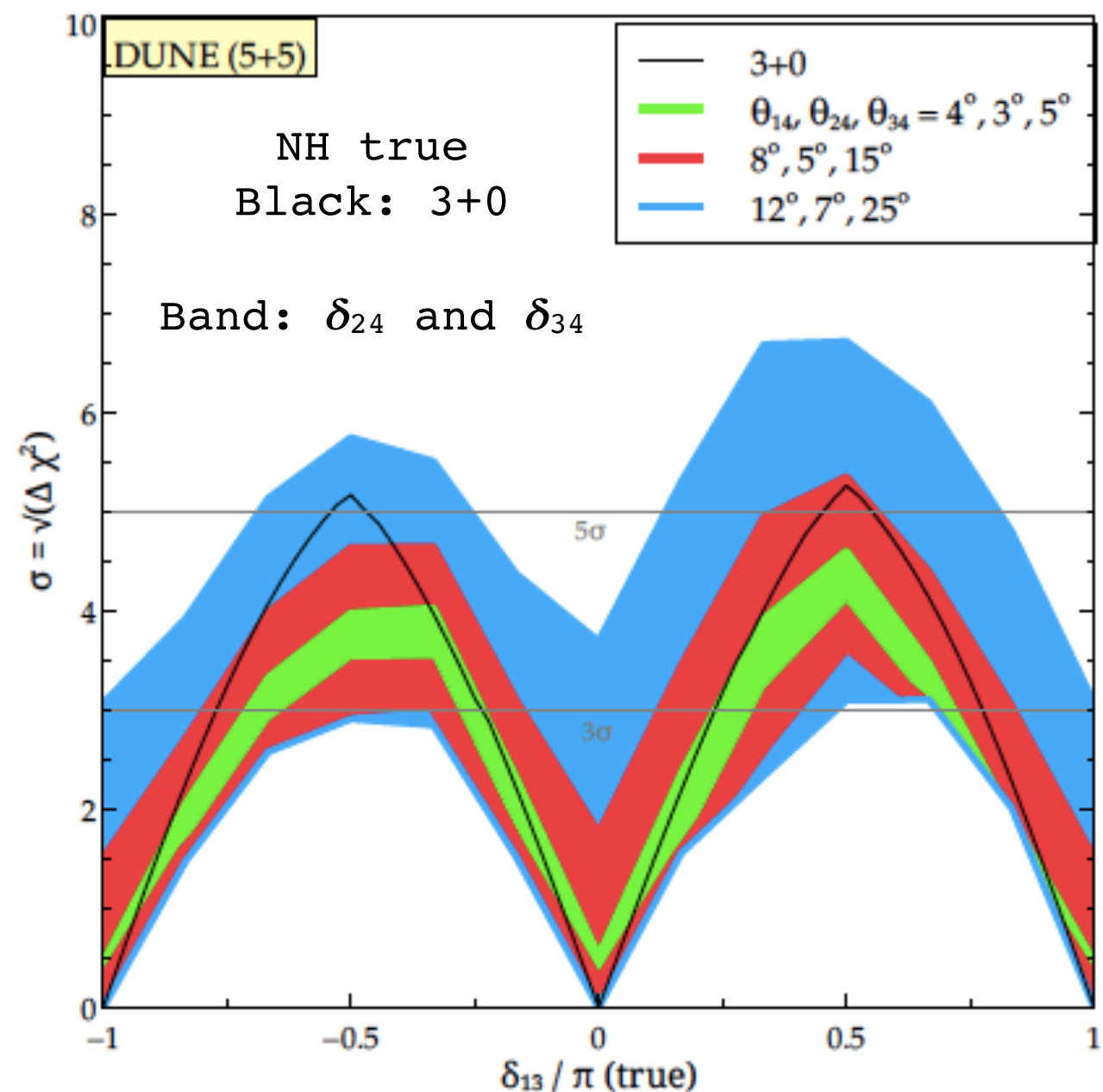
Assuming 3+1 is true and CPV has been observed, can we identify its source?

Results for the DUNE experiment:
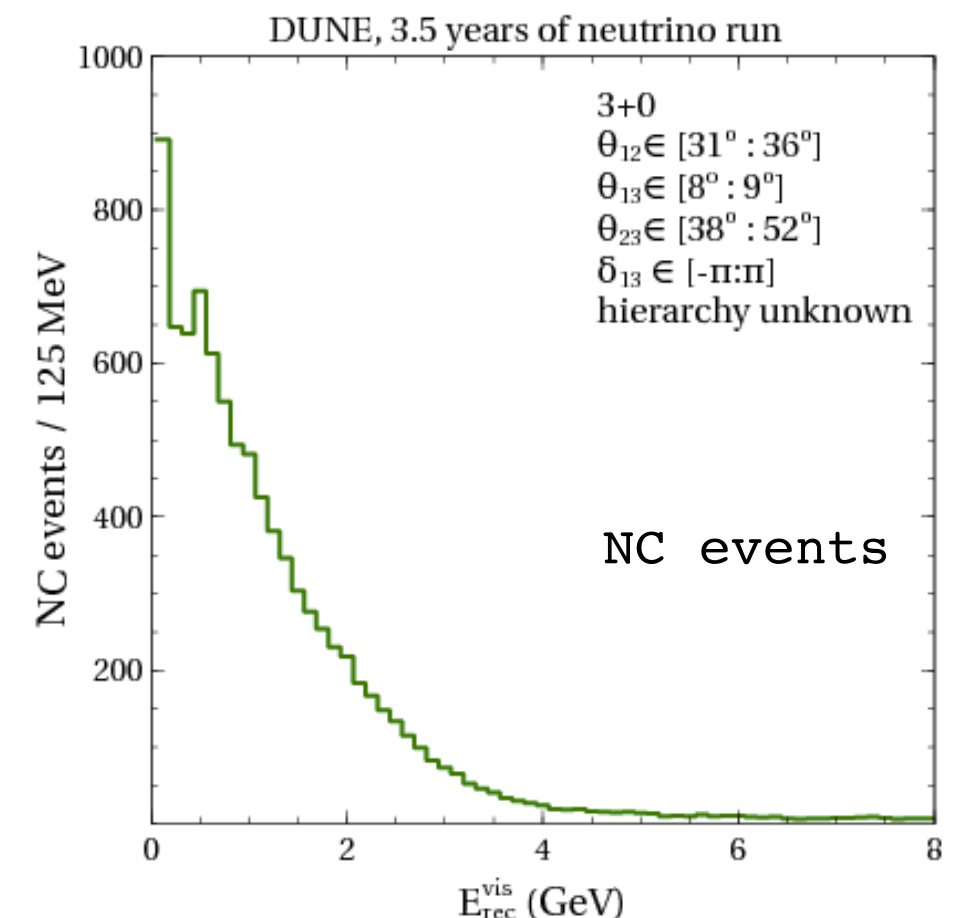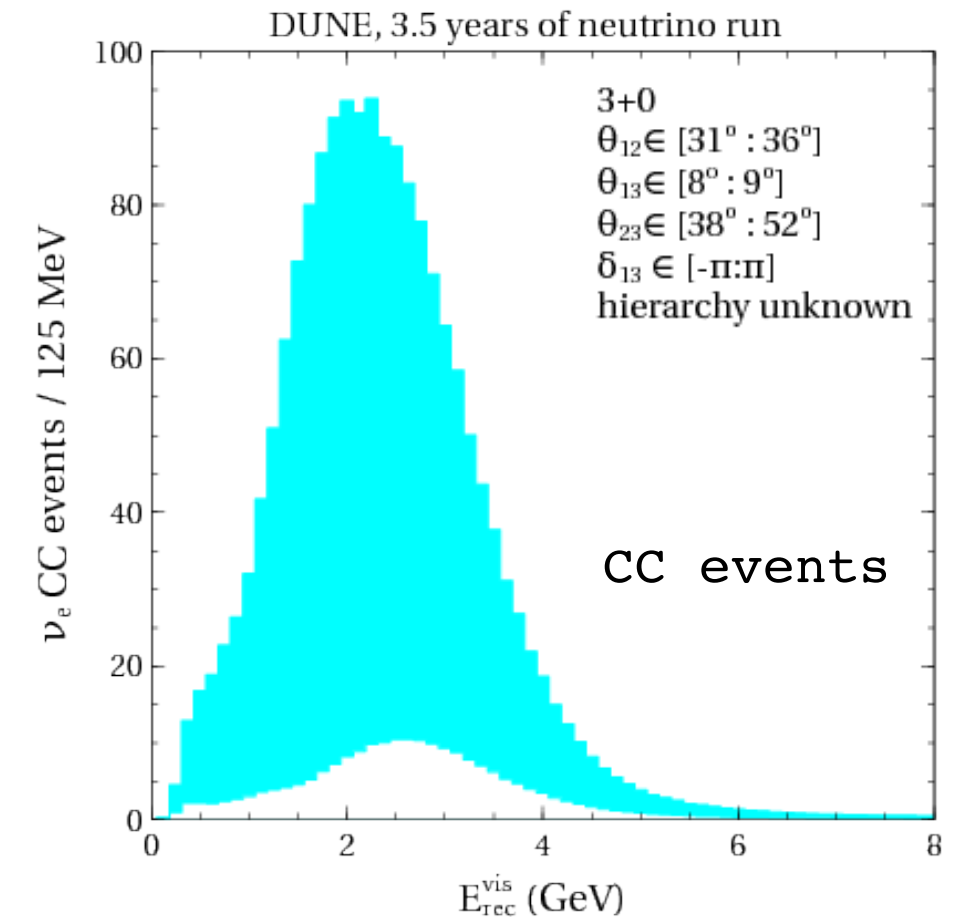
* We assume 3+1 to be the true case.

* 3+1: true values: $\theta_{14}, \theta_{24}, \theta_{34} = 12°, 7°, 25°$.

* 3+1: true values: $\delta_{13}, \delta_{24}, \delta_{34} = 0, -90°, 0$.

* 3+0 oscillation parameters held fixed in fit.

* χ^2 marginalized over test δ_{34} values and in allowed ranges of test $\theta_{14}, \theta_{24}, \theta_{34}$.

Test values close to (90°, 0) and (90°, 180°) allowed at 3σ

Attributing CP violation unambiguously to any one phase may not be possible at 3σ

Neutral Current measurements
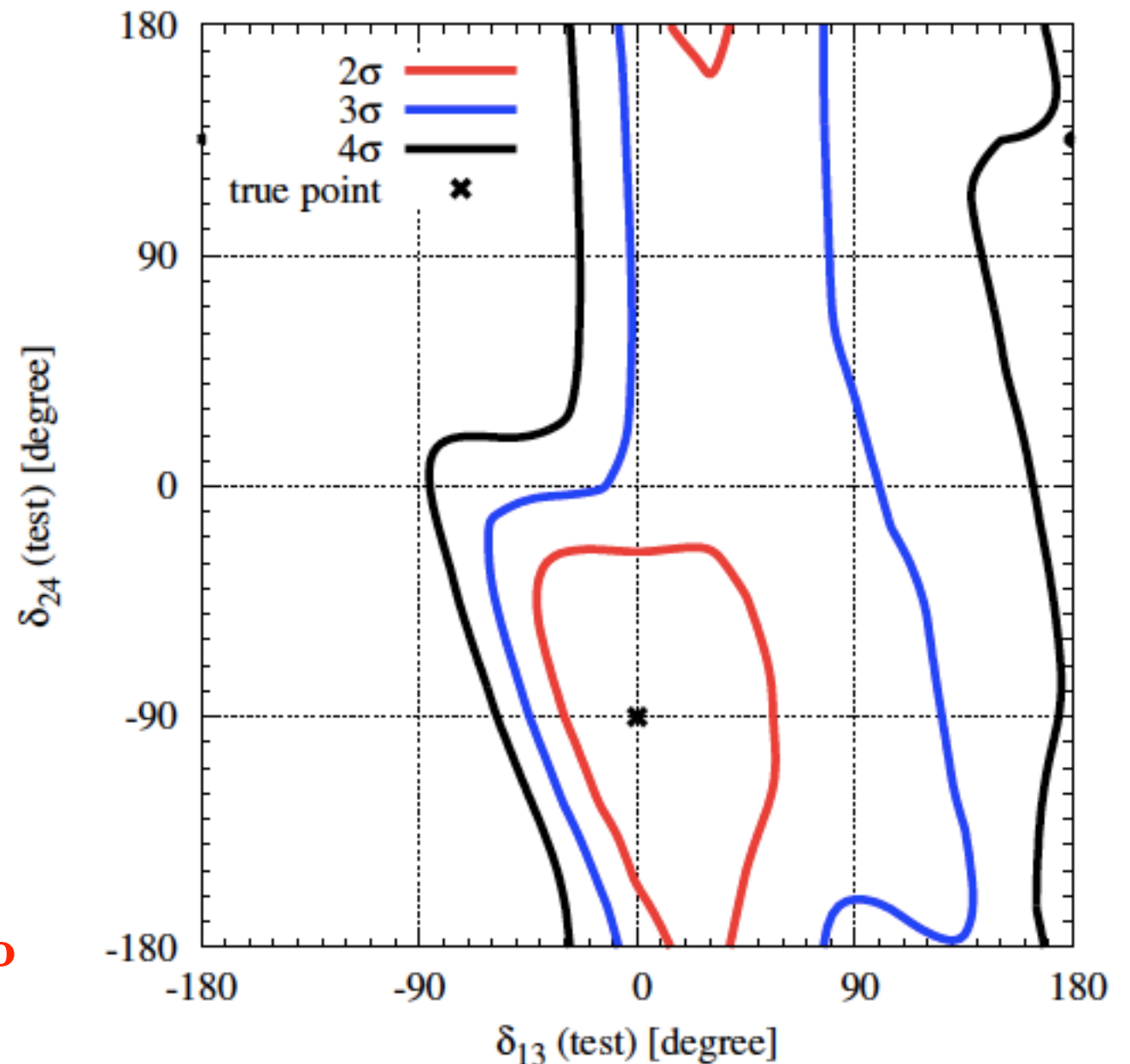
* We investigate how the NC measurements made at DUNE far-detector can help in the search of new physics scenarios.

* NC events are insensitive to oscillations and therefore the uncertainties related to them. Any deviation from the expected events rates may be pointer to new physics.

* NC events are statistically very rich. At DUNE near detector, events in surplus of 400,000 per year are expected and at the far detector too, NC events are much more than what is observed in CC.

* As we show in the following, NC events are also less prone to matter effects and may provide qualitatively different and complementary measurements to the CC events.

DUNE, 3.5 years of neutrino run

3+0
$\theta_{12} \in [31° : 36°]$
$\theta_{13} \in [8° : 9°]$
$\theta_{23} \in [38° : 52°]$
$\delta_{13} \in [-\pi : \pi]$
hierarchy unknown

CC events

ν_e CC events / 125 MeV

E_{rec}^{vis} (GeV)

DUNE, 3.5 years of neutrino run

3+0
$\theta_{12} \in [31° : 36°]$
$\theta_{13} \in [8° : 9°]$
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hierarchy unknown

NC events

NC events / 125 MeV

E_{rec}^{vis} (GeV)

Gandhi, Kayser, Prakash, Roy   JHEP11(2017)202

For a $\overset{(-)}{\nu}_\mu$ beam, we define $\overset{(-)}{P}_{NC} = \overset{(-)}{P}_{\mu e} + \overset{(-)}{P}_{\mu\mu} + \overset{(-)}{P}_{\mu\tau}$

In 3+0, $\overset{(-)}{P}_{NC} = 1$ For 3+1, $\overset{(-)}{P}_{NC} = 1 - \overset{(-)}{P}_{\mu s} = \overset{(-)}{P}_{\mu e} + \overset{(-)}{P}_{\mu\mu} + \overset{(-)}{P}_{\mu\tau} < 1$

$$P^{vac}_{\mu s} \simeq \cos^4\theta_{14}\cos^2\theta_{34}\sin^2 2\theta_{24}\sin^2\frac{\Delta m^2_{41}L}{4E}$$

$$+\left[\cos^4\theta_{13}\cos^2\theta_{24}\sin^2\theta_{34} - \cos^2\theta_{13}\cos^2\theta_{24}\cos^2\theta_{34}\sin^2\theta_{34}\right.$$

$$\left.+\frac{1}{\sqrt{2}}\sin 2\theta_{13}\sin 2\theta_{34}\sin\theta_{14}\cos^3\theta_{24}\cos(\delta_{13}+\delta_{34})\right]\sin^2\frac{\Delta m^2_{31}L}{4E}$$

$$+\frac{1}{2}\cos^2\theta_{13}\cos^2\theta_{24}\sin 2\theta_{34}\sin\theta_{24}\sin(\delta_{34}-\delta_{24})\sin\frac{\Delta m^2_{31}L}{4E}$$


∗ The first term is a rapidly oscillating term.

∗ The dependence on CP phases only in linear combinations: $\delta_1 = \delta_{13} + \delta_{34}$ and $\delta_2 = \delta_{34} - \delta_{24}$.

∗ There is very little matter effects in P_{NC}.

∗ Very similar curves for anti-neutrino probabilities.
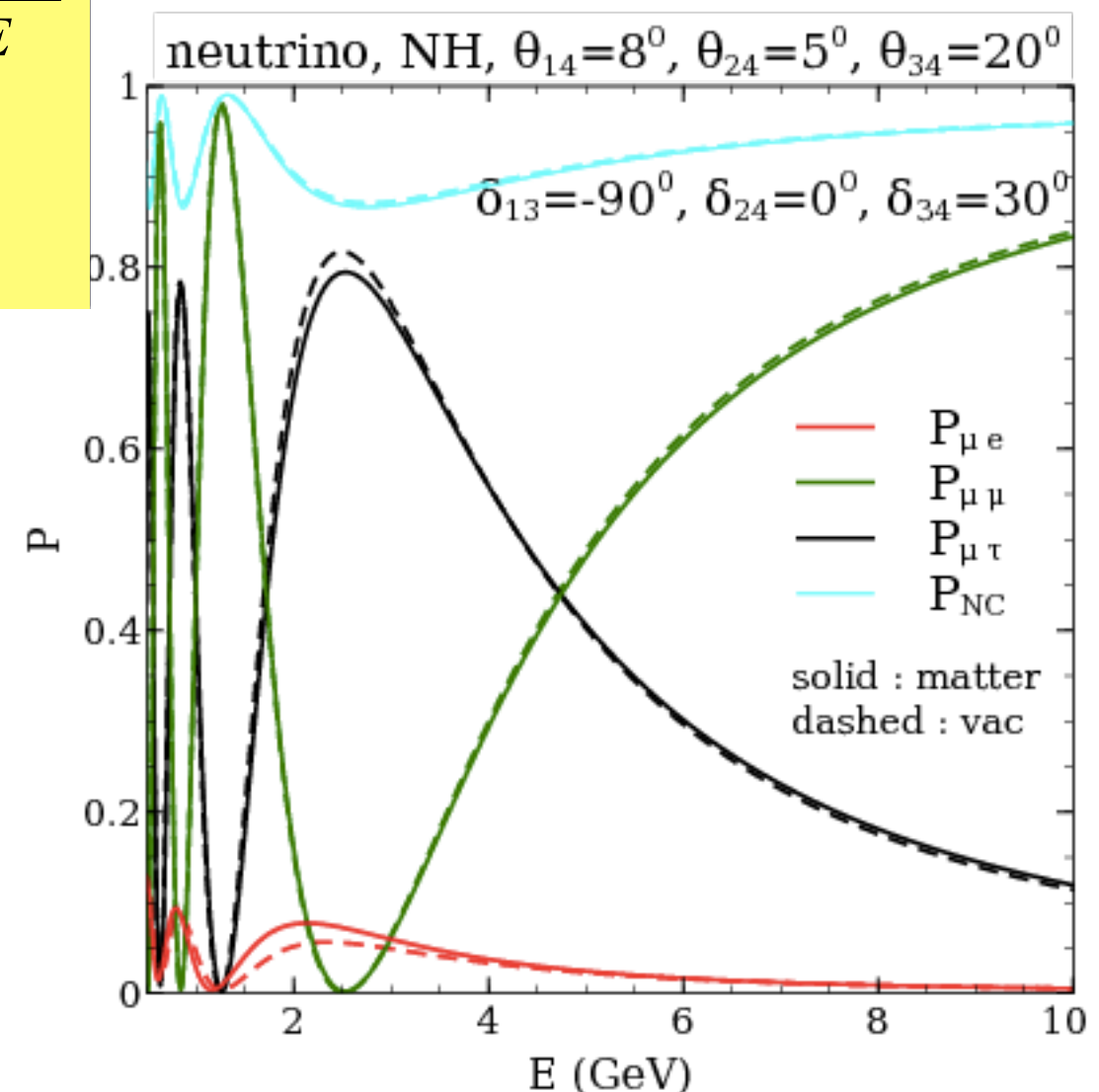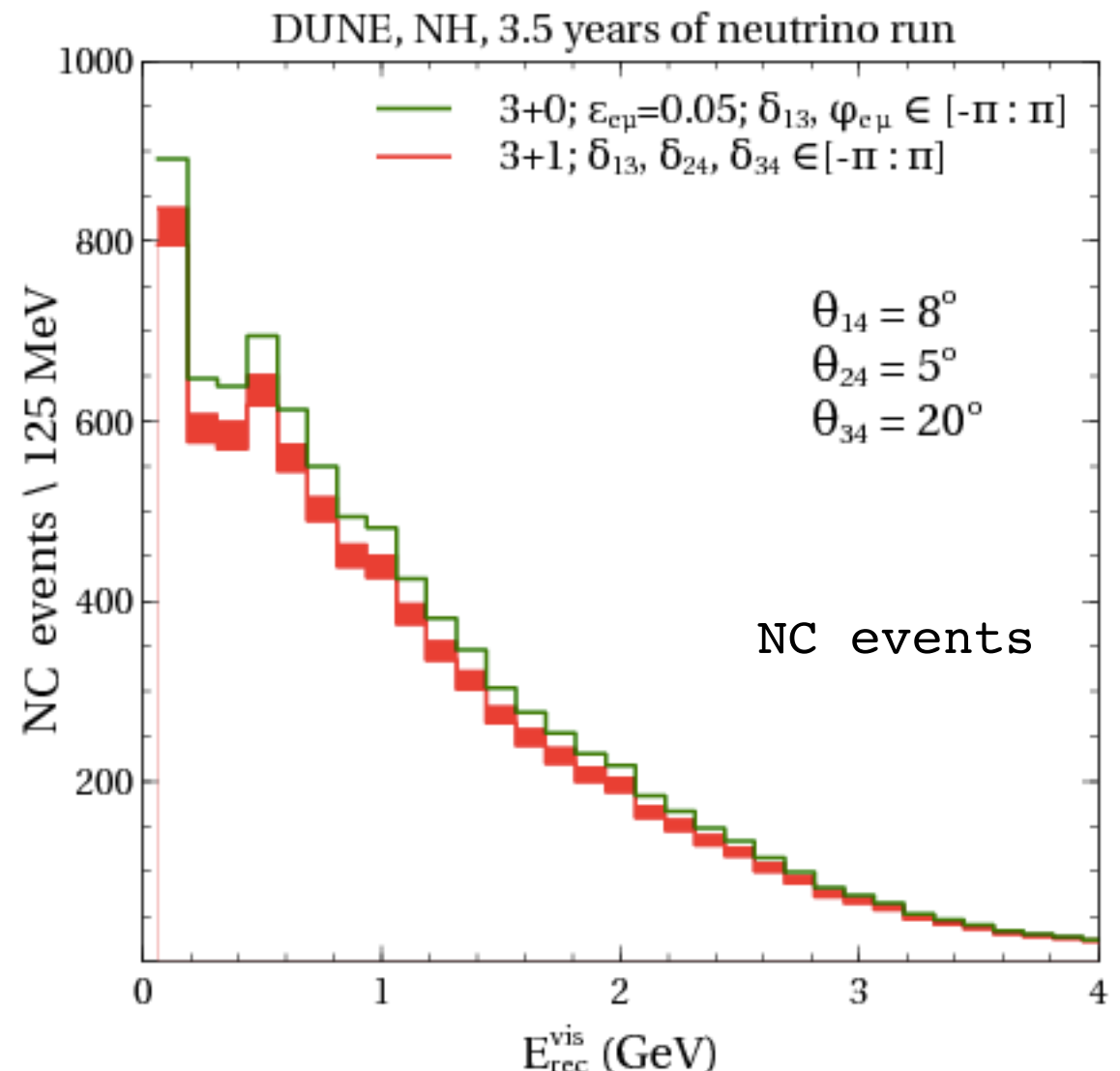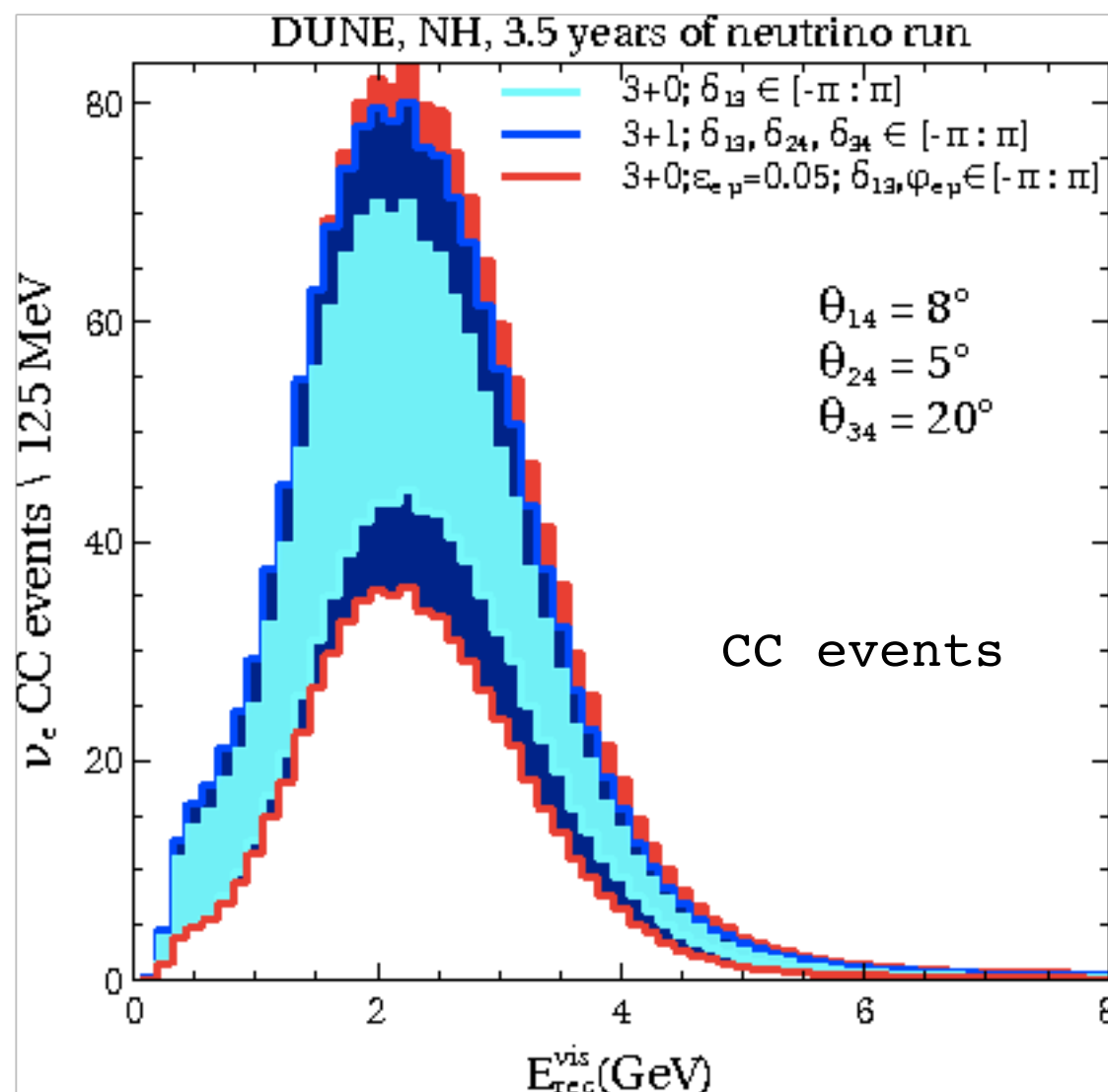
Effects of CP phases on P_{NC}

* Left panel: The differences between P_{NC} and $\overline{P}_{NC}$ are small. Right panel: δ_{34} induces larger differences between P_{NC} and $\overline{P}_{NC}$

* Larger differences at higher energies. Large CP-asymmetry in NC events may point to a CP-violating value of δ_{34}

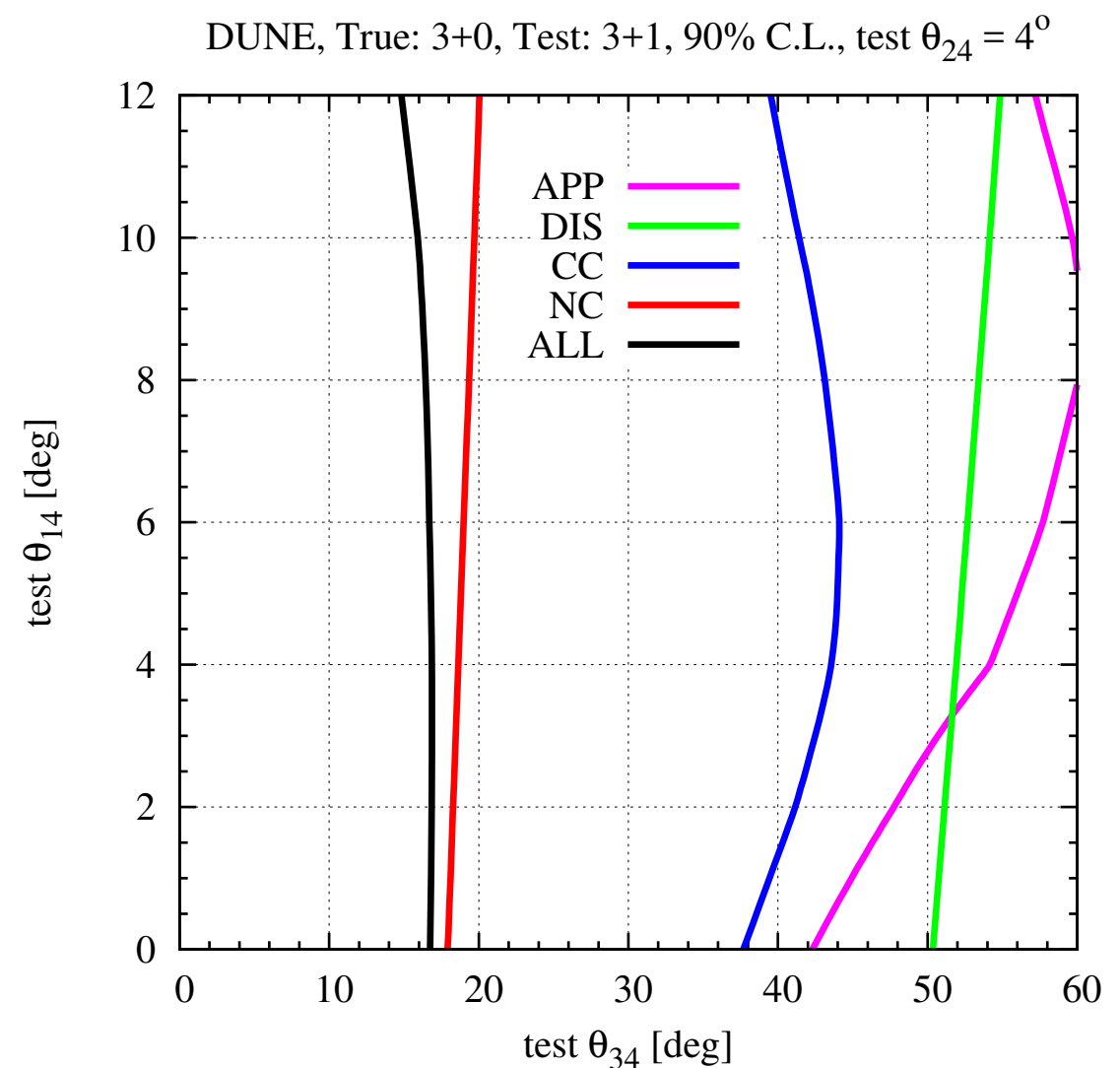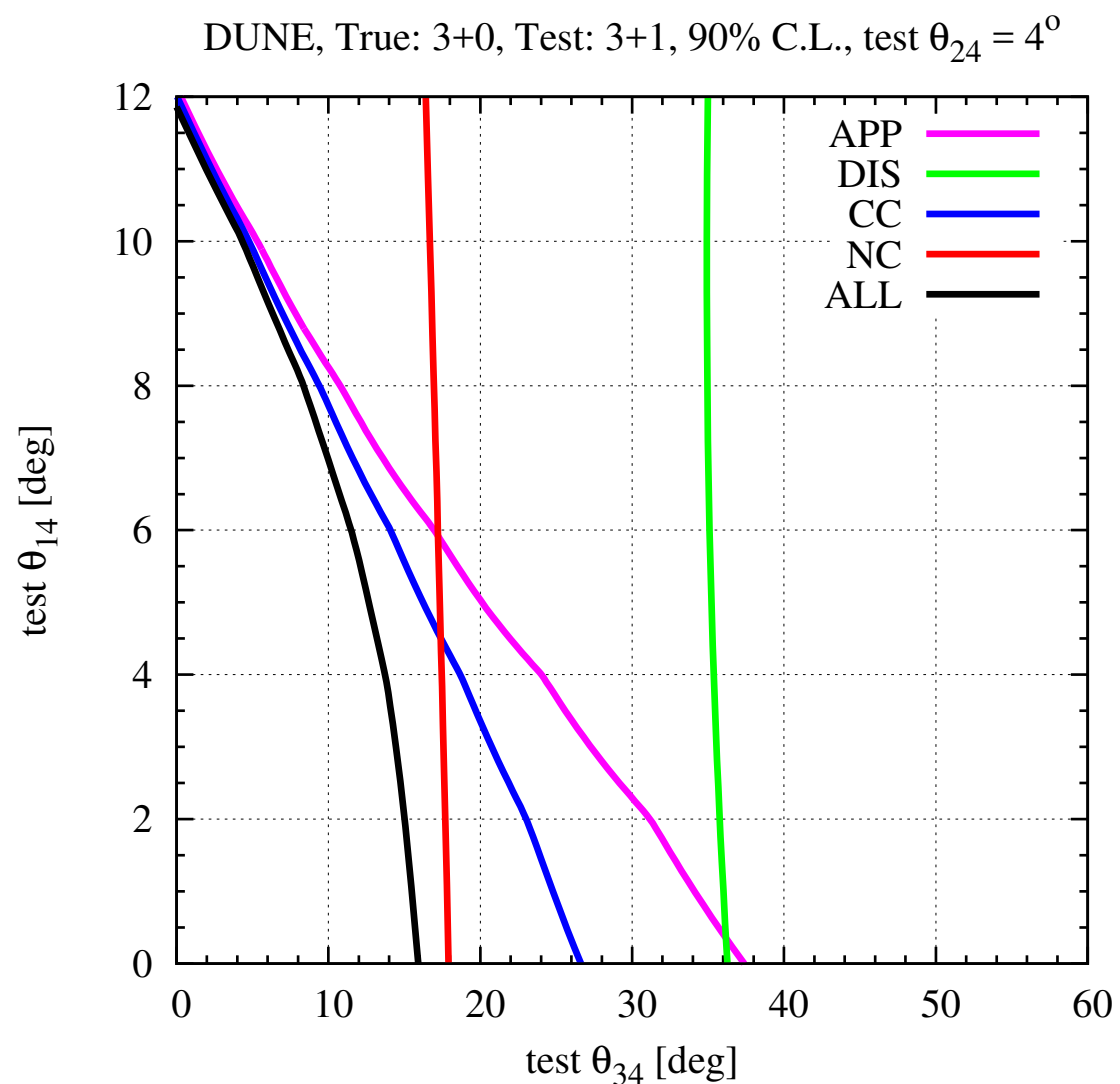**Gandhi, Kayser, Prakash, Roy   JHEP11(2017)202**
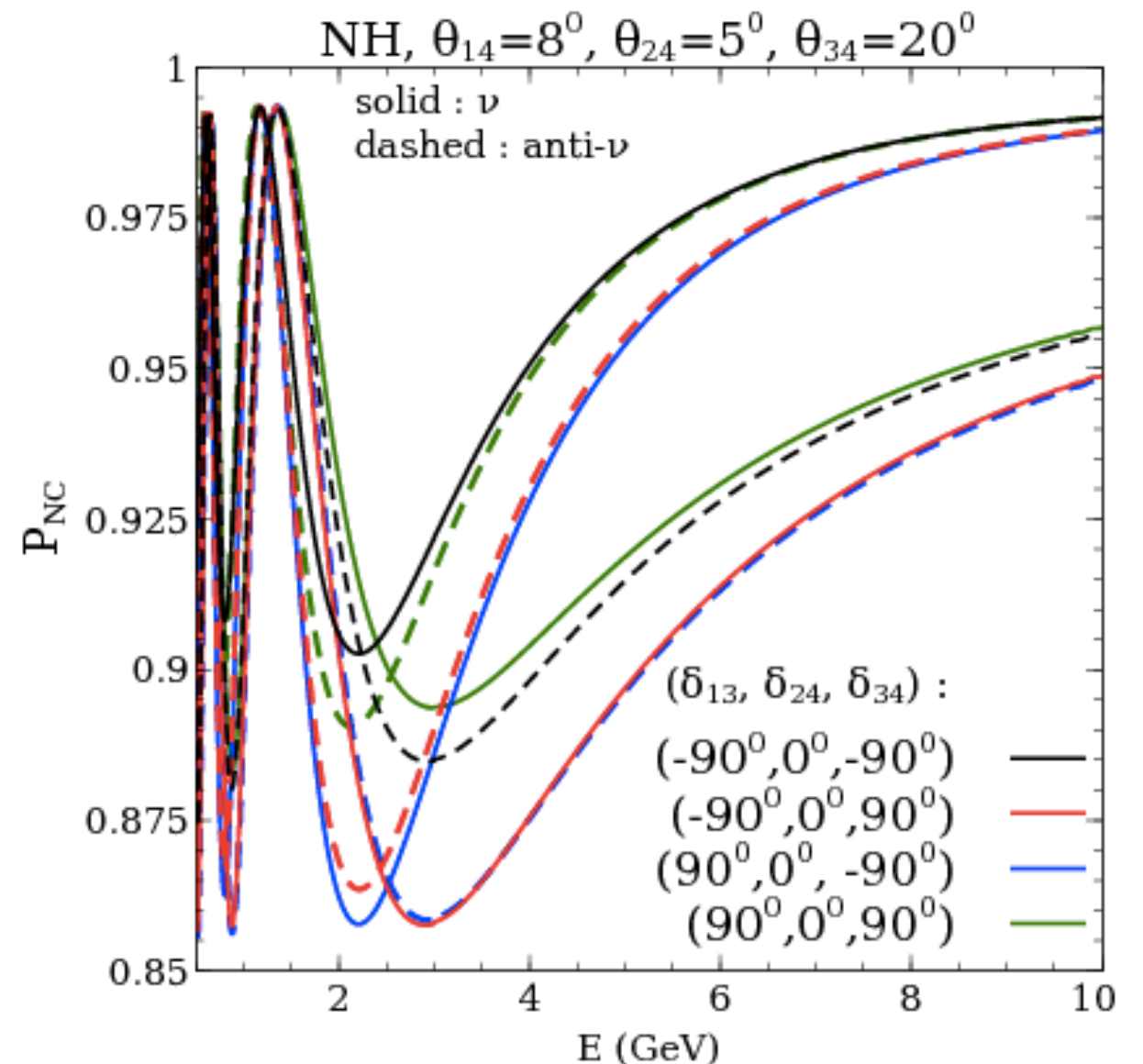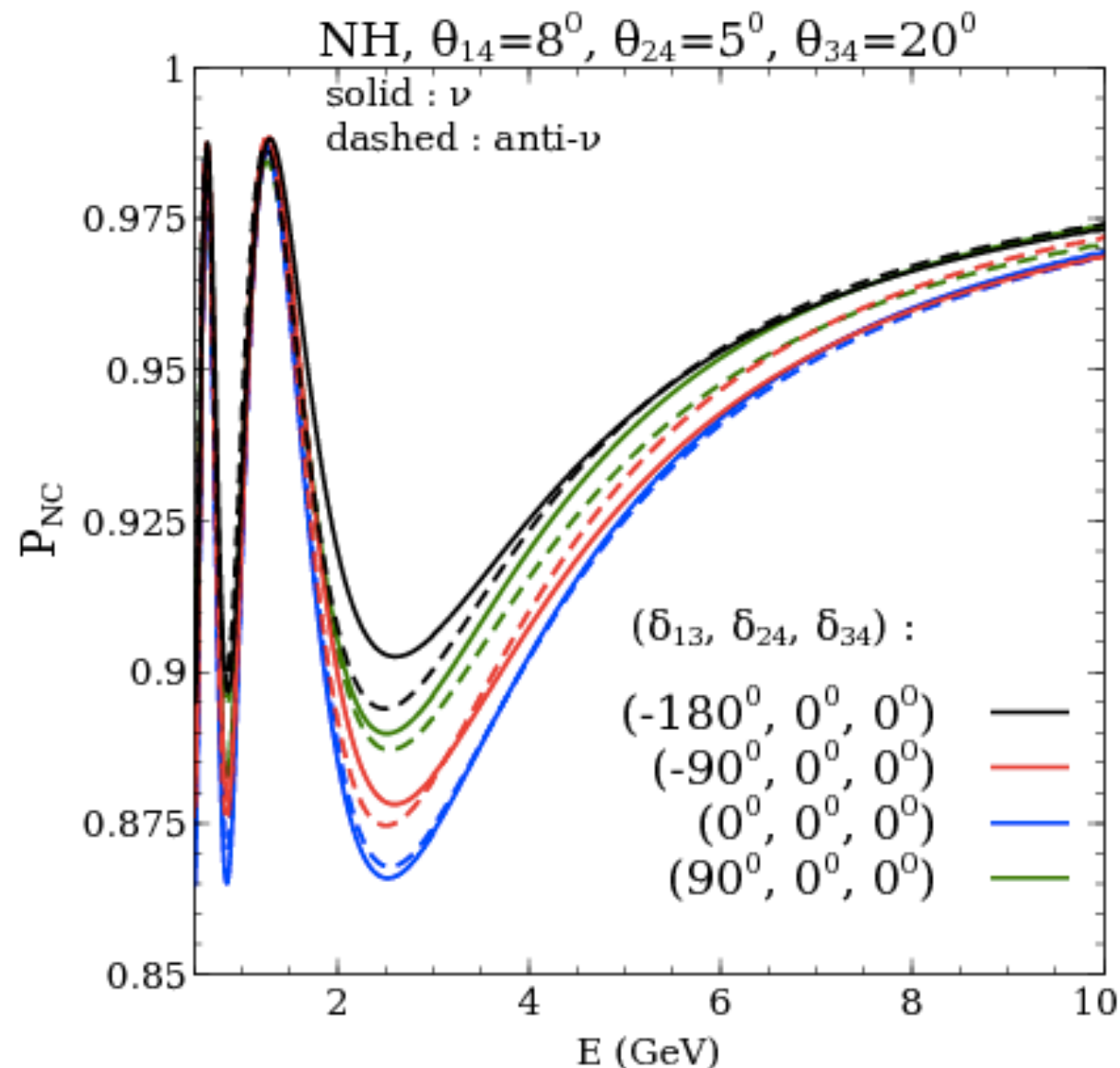
NC events as new-physics discriminator

✳ Left panel: CC events with standard and new physics scenarios. Right panel: NC events with standard and new physics scenarios

✳ Left panel: significant degeneracy between two new physics. Right panel: NC events discriminate between unitarity-violating and unitarity-preserving scenarios


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Constraints on 3+1 with NC

Left: CP phases fixed at true values   **Right**: CP phases varied in the fit

DUNE, True: 3+0, Test: 3+1, 90% C.L., test $\theta_{24} = 4^o$

DUNE, True: 3+0, Test: 3+1, 90% C.L., test $\theta_{24} = 4^o$

Constraints from CC depend a lot on the knowledge of CP phases while those from NC seem to be immune to CP phases

Constraints on 3+1 with NC

NH, DUNE, True: 3+0, Test: 3+1, 90% C.L.

NH, DUNE, True: 3+0, Test: 3+1, 90% C.L.
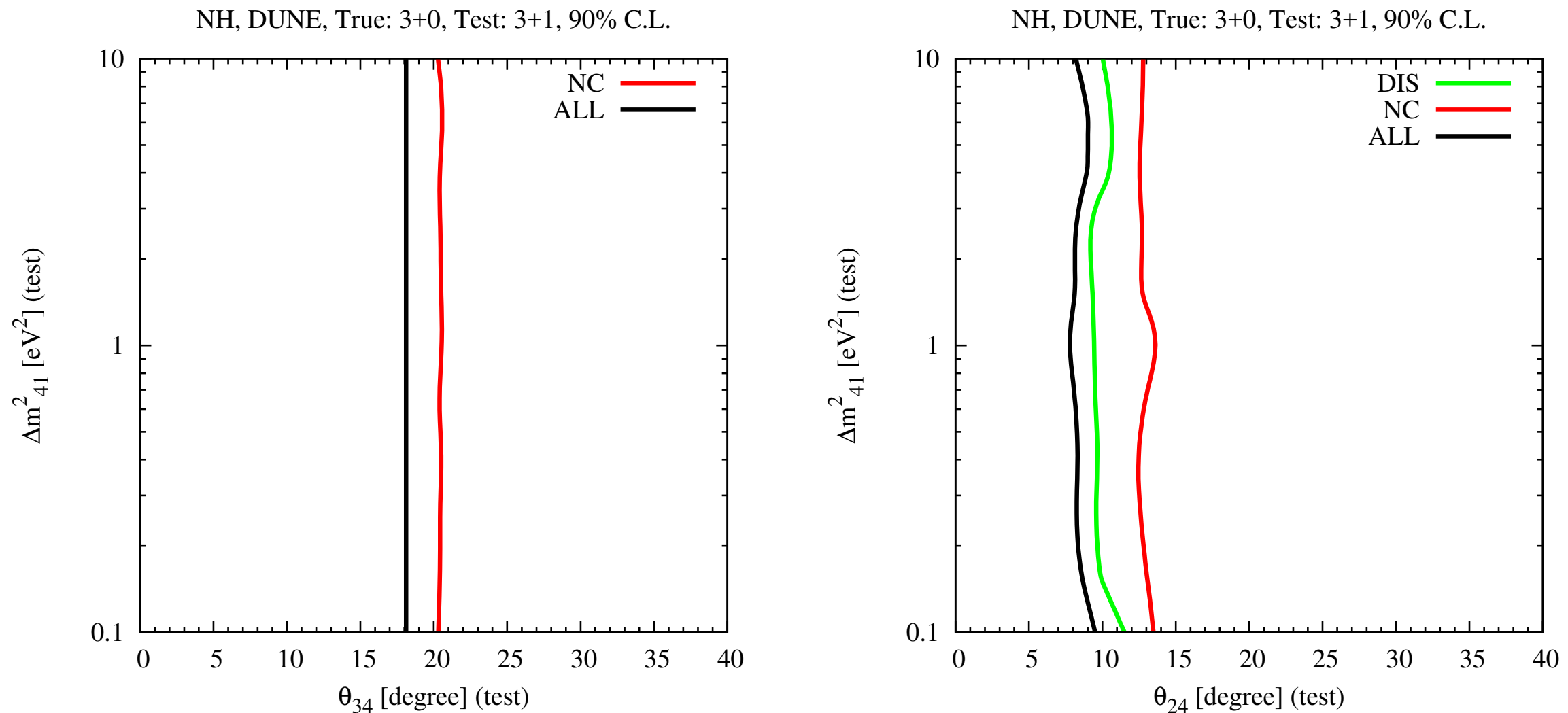
* Left plot: Sensitivity to exclusion of θ_{34} mainly from the NC data.

* Right panel: Sensitivity to exclusion of θ_{24} mainly from the disappearance data.

* Both: Sensitivity almost independent of the value of test Δm^2_{41}. As a comparison, the sensitivity from IceCube reduces to $\theta_{24} \lesssim 45°$ at 10 eV^2 `Phys.Rev.Lett.117(2016)071801`

Gandhi, Kayser, Prakash, Roy   JHEP11(2017)202

Highlights...

* From a probability and event rate analysis, we show that there are large effects of the sterile oscillation parameters at long-baselines especially via parameters which do not play a role in short-baseline experiments.

* In the presence of even a single sterile neutrino, conclusions such as a) CP is conserved or violated, or, b) if the latter, whether the violation is ascribable to the active neutrinos or the additional sterile neutrino, or a combination of the two, are all rendered significantly ambiguous.

* Our work stresses on the need to have a dedicated short baseline program which can put very stringent constraints on the existence of sterile neutrinos.

* We show how NC events can synergistically aid the search for new physics and CP violation when combined with other measurements.

* NC events offer a window to CP phases and mixing angles that is complementary to that accessed by CC measurements.

* They can break degeneracies existing in CC measurements, allowing one to distinguish between new physics that violates 3+0 unitarity and new physics that does not.

Thank you for your attention!