# UNDERSTANDING THE DEGENERACIES IN NO$\nu$A DATA

SUMAN BHARTI*, SUPRABH PRAKASH†, USHAK RAHAMAN* AND S. UMA SANKAR*
* IIT Bombay, INDIA and † UNICAMP, Campinas, BRAZIL. (arXiv:1805.10182)

## NO$\nu$A RESULTS

NO$\nu$A experiment has analyzed the data from one year neutrino run corresponding to $6 \times 10^{20}$ POT. They obtained three degenerate solutions with different values of the three unknowns: mass hierarchy, $\theta_{23}$ octant and $\delta_{\rm CP}$.

1. $\Delta_{31}$ +ve, $\sin^2\theta_{23} = 0.4$, $\delta_{\rm CP} = -90^\circ$ (NH, LO, $-90^\circ$),
2. $\Delta_{31}$ +ve, $\sin^2\theta_{23} = 0.62$, $\delta_{\rm CP} = 135^\circ$ (NH, HO, $135^\circ$) and
3. $\Delta_{31}$ -ve, $\sin^2\theta_{23} = 0.62$, $\delta_{\rm CP} = -90^\circ$ (IH, HO, $-90^\circ$).

## EFFECTS OF UNKNOWNS

- To understand the occurance of the three degenerate solutions, we first define the following reference point. We calculate the $\nu_e$ appearance events in NO$\nu$A for vacuum oscillations with $\theta_{23} = 45^\circ$ and $\delta_{\rm CP} = 0$. We the compute the change in this number induced by each of the three unknowns.
- We find that each unknown causes the same change.
- We define value of the unknown variable as '+' if it increases the number and as '-' if it decreases.
- The $\nu_e$ appearance events for NO$\nu$A are listed below for all combinations of the unknowns.

## $\nu_e$ APPERANCE EVENTS

| Hrchy–$sin^2\theta_{23}$–$\delta_{cp}$ | Label | Total eve. |
|---|---|---|
| NH–0.62– -90 | (+ + +) | 43.67 |
| NH–0.4– -90 | (+ - +) | 33.54 |
| NH–0.62– +90 | (+ + -) | 33.04 |
| IH–0.62– -90 | (- + +) | 30.94 |
| NH–0.4– +90 | (+ - -) | 22.79 |
| IH–0.4– -90 | (- - +) | 24.47 |
| IH–0.62– +90 | (- + -) | 22.63 |
| IH–0.4– +90 | (- - -) | 16.07 |

The three combinations $(++-)$, $(+-+)$ and $(--+)$ all are predicted to have the same number of events. The observed number of events by NO$\nu$A is equal to this number. Hence we get the three fold degenerate solutions.

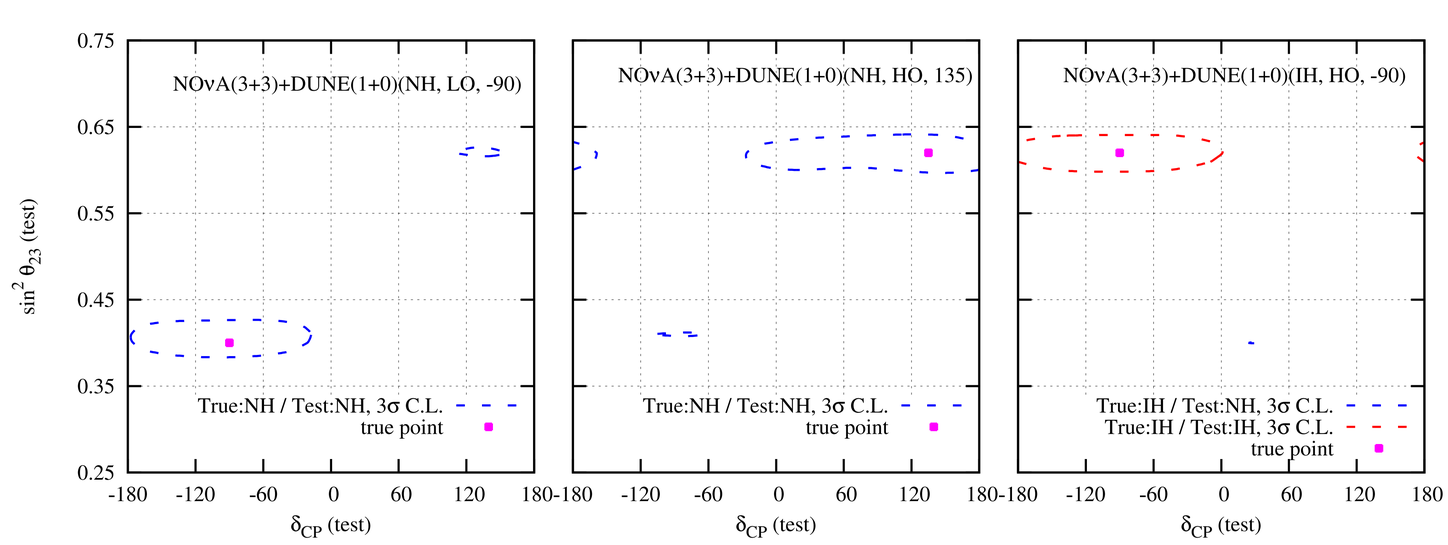
## $\bar{\nu}_e$ APPERANCE EVENTS

$\bar{\nu}_e$ appearance data of NO$\nu$A can not separate the two higher octant solutions with $\sin^2\theta_{23} = 0.62$. It does have some sensitivity to isolate the lower octant solution. But, for this solution, all the three knowns (hierarchy, octant and $\delta_{\rm CP}$) suppress $\bar{\nu}_e$ appearance events. The predicted number of events is too low and the statistics are not enough for a meaningful isolation.

| Hrchy–$sin^2\theta_{23}$–$\delta_{cp}$ | Label | Total eve. |
|---|---|---|
| NH–0.404– -86 | (+ - +) | 6.85 |
| NH–0.62– +135 | (+ + -) | 11.78 |
| IH–0.62– -90 | (- + +) | 12.86 |

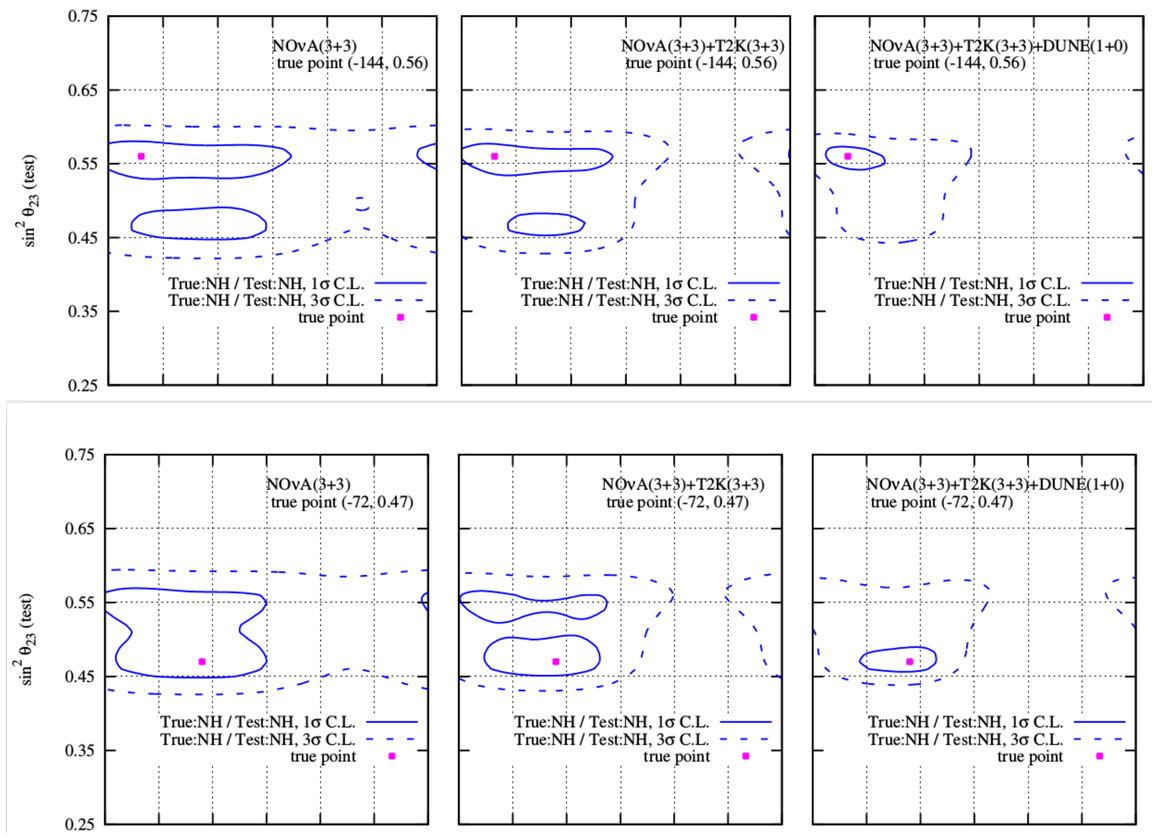
## DUNE MAKES A DISTINCTION

DUNE has a longer baseline and hence higher neutrino energy which leads to a larger matter effect. It can clearly separate the higher octant solutions with different hierarchies. The synergy between DUNE neutrino data and NO$\nu$A anti-neutrino data helps in isolating the the lower octant solution. Thus any one of the three solutions can be clearly identified if one year of neutrino data of DUNE is added to NO$\nu$A data of equal three year $\nu$ and $\bar{\nu}$ runs.




## NEW ANALYSIS OF NO$\nu$A

Early this year, NO$\nu$A did a reanlysis of their neutrino data which included some more exposure compared to 2017 analysis. As a result of the analysis with the new procedure, NO$\nu$A finds a best-fit solution in the higher octant at (NH, $\sin^2\theta_{23} = 0.56$, $\delta_{\rm CP} = -144^\circ$). There is a nearly degenerate solution in the lower octant at (NH, $\sin^2\theta_{23} = 0.47$, $\delta_{\rm CP} = -72^\circ$). There is no IH solution at $1\,\sigma$.




From the above figures we see that $(3\nu + 3\bar{\nu})$ runs of NO$\nu$A and T2K can not distinguish between the two solutions. Addition of one year neutrino data of DUNE does lead to a separation but does rule out the wrong solution at $3\,\sigma$. It does rule out the wrong hierarchy (IH) is ruled out at $3\,\sigma$.

## DISCOVERY OF CP-VIOLATION

With a $(5\nu + 5\bar{\nu})$ run of DUNE can rule out CP-conservation at $5\,\sigma$ for the LO solution but not the HO solution. Also, such a run can distinguish between the two solutions only at $3\,\sigma$.