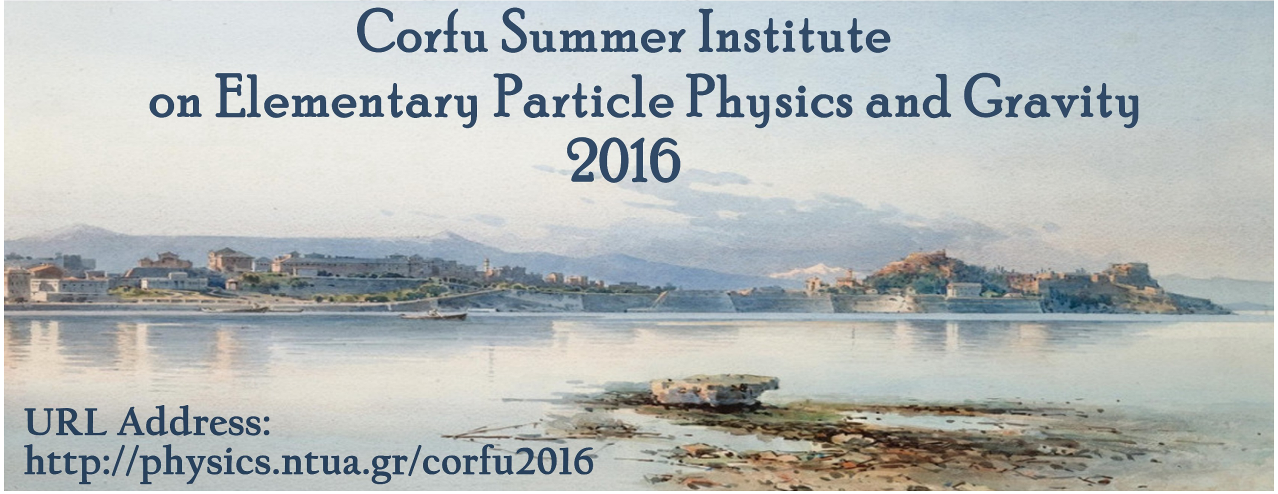


Neutrino Mass Matrix and The Sign of Universe's Baryon Asymmetry

Morimitsu Tanimoto @ Niigata University

with Y.Shimizu @ Hiroshima-U
Y.Kaneta @ Niigata-U
T.T.Yanagida @ IPMU

arXiv:1604.03315

CorfuSI2016 @ Corfu, Greece, September 10, 2016

Plan of my talk

1 Introduction

2 Neutrino Mass matrix with Occam 's Razor

3 The Sign of Universe's Baryon Asymmetry

4 Numerical Results

5 Summary

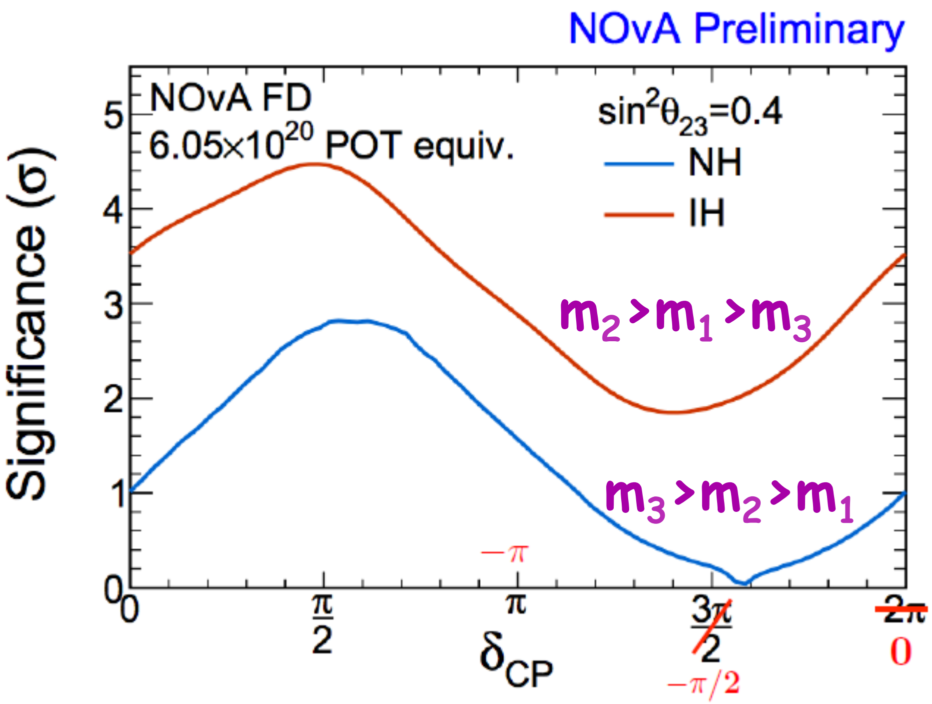
1 Introduction

δ_{CP}= -90° ?

NOvA

ICHEP2016

T2K



J. Bian [NOvA Collaboration]
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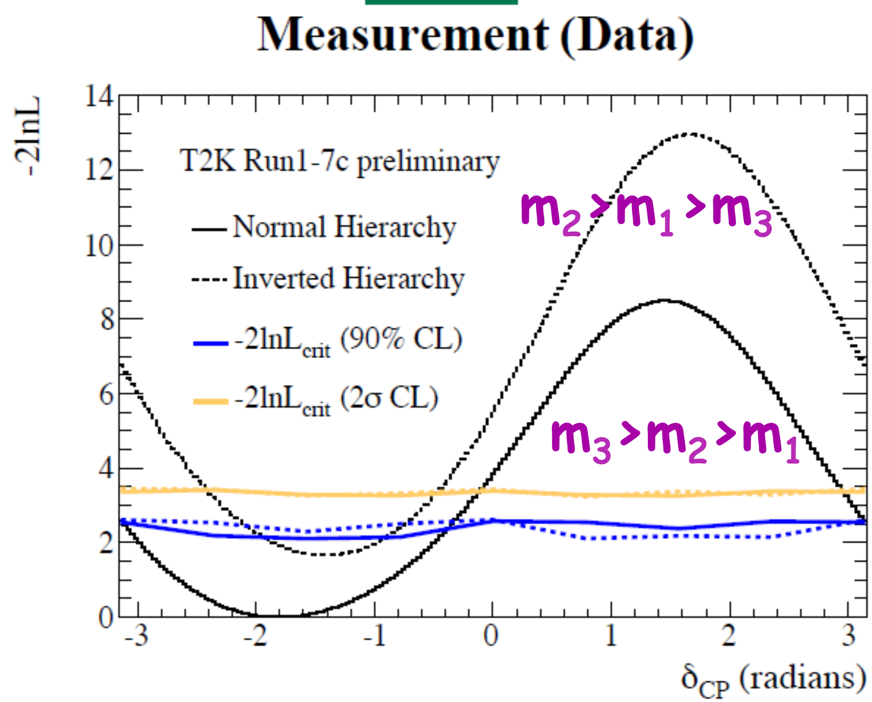

K. Iwamoto [T2K Collaboration]
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Normal Hierarchy of neutrino masses is favoured ? $m_3 > m_2 > m_1$

Parameterization of mixing angles and CP violating phase

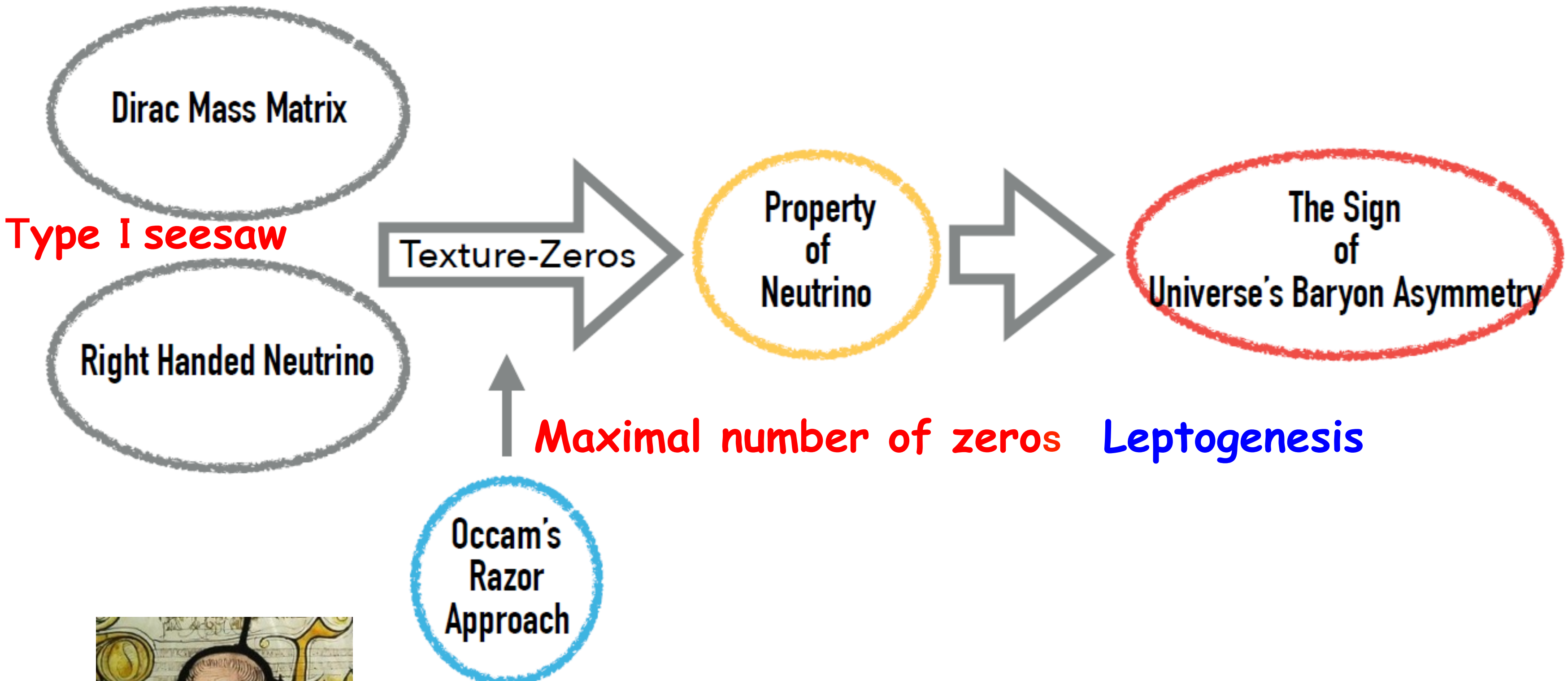
Lepton mixing matrix (PMNS)

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{\boxed{-i\delta_{CP}}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{CP}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{CP}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{CP}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{CP}} & c_{23}c_{13} \end{pmatrix}$$

$$\times \{ \mathrm{Exp}[i\,\alpha],\quad \mathrm{Exp}[i\,\beta],\quad 1\}$$

Diagonal Majorana Phases matrix

Our Framework of Predictions for CP violation



William of Ockham

"Entities should not be multiplied unnecessarily."

2　Neutrino Mass matrix with Occam's Razor

The Occam's Razor Approach

The first attempt

K. Harigaya, M. Ibe, T. T. Yanagida
Phys. Rev. D 86, 013002

Lepton mass term : $\overline{l_L} M_E e_R + \overline{l_L} m_D N + \frac{1}{2}\overline{N^C} M_R N + h.c.$

1. **Diagonal base** M_E M_R
2. **Impose Zeros to components of** m_D **.**

   5 physical values are observed by experiments

   Δm^2_{sol} Δm^2_{atm} θ_{12} θ_{23} θ_{13}

   NOW

   Prune parameters in neutrino sector to be #5.

They discussed two generations of M_R **(m_D is 3×2 matrix)**

OCCAM'S RAZOR

RESULTS

They predicted the δ_{CP}
and discovered that hierarchy of neutrino is IH only.

Case A Case B

$$m_{\nu D} = \begin{pmatrix} 0 & * & * \\ * & 0 & * \end{pmatrix}_{RL} , \quad m_{\nu D} = \begin{pmatrix} * & * & 0 \\ 0 & * & * \end{pmatrix}_{RL}$$

Asterisk is complex.

$$M_R = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}_{RR}$$

$m_3=0$

Three phases are removed away ! only one phase remains !

After seesaw, neutrino mass matrix is given by 5 parameters .

Inverted neutrino mass hierarchy !

Observed Baryon Asymmetry can be explained by the leptogenesis

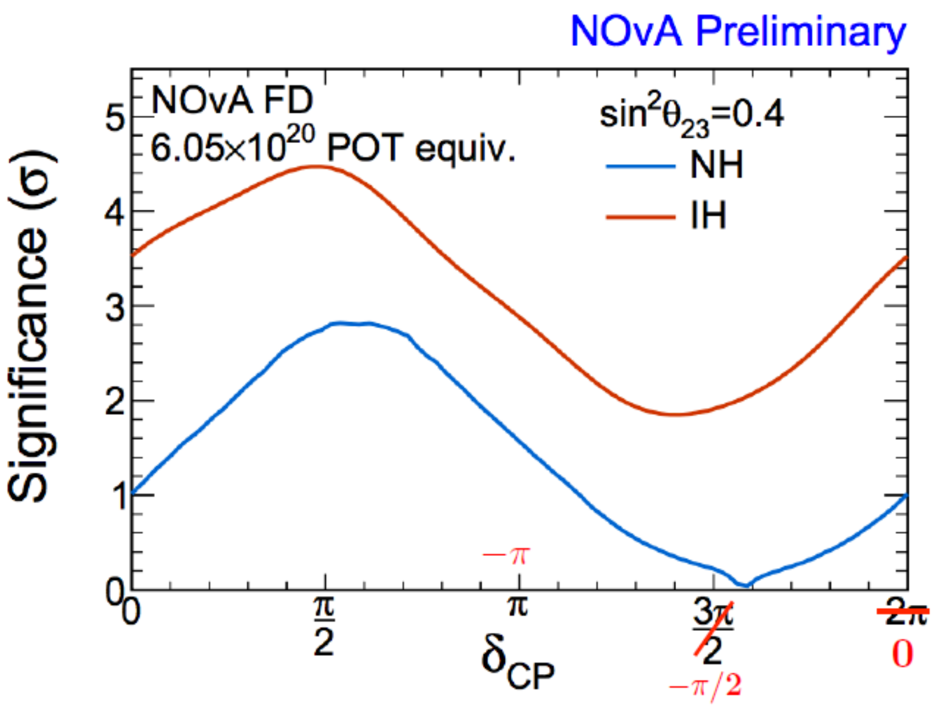
signs[δ_{cp}] > 0 for Case A and signs[δ_{cp}] < 0 for Case B

One phase controlls both δ_{cp} and Baryon Asymmetry !

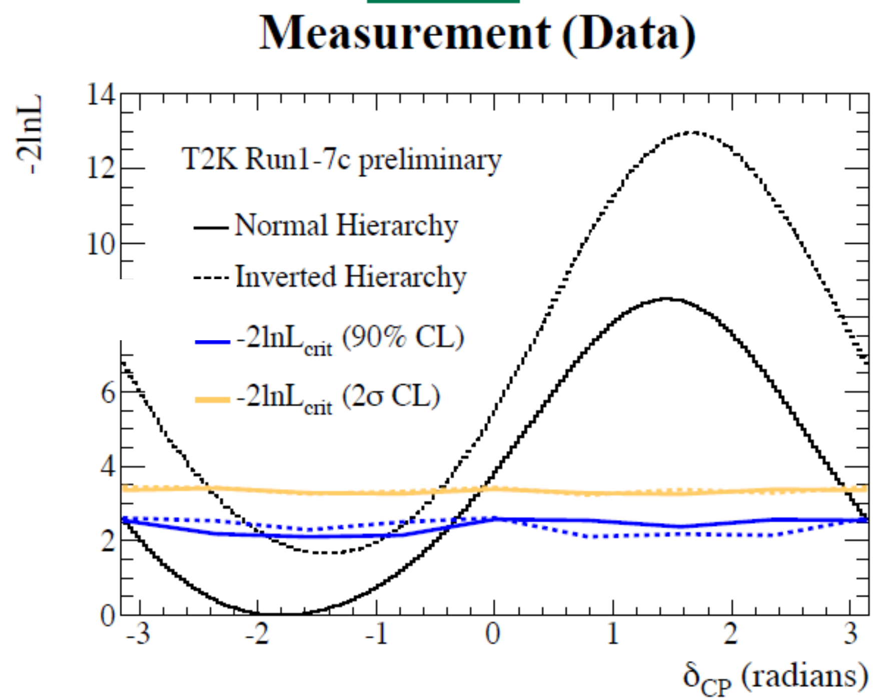
Normal Hierarchy !!

of neutrino masses is favoured

NOvA



T2K



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The Occam's Razor Approach to realize NH

We discuss three generations of M_R

1. **Diagonal base** M_E M_R **(m_D and M_R are 3×3 matrices)**

   Add 1 complex parameter (2 real parameters).

   Total number of parameters is 7 now.

Experiments will observe 7 physical values

$\Delta m^2_{\rm sol}$ $\Delta m^2_{\rm atm}$ θ_{12} θ_{23} θ_{13} δ_{CP} m_{ee}

In the Future

2. **Impose Zeros to components of** m_D **.**

   Four-Zeros Dirac mass matrix

   is the maximal number of zeros.

(Our set up) OCCAM'S RAZOR

Minimal textures with NH

G.C.Branco, D.Emmanuel-Costa, M.N.Rebelo and P.Roy
Phys. Rev. D 77 (2008) 053011 [arXiv:0712.0774 [hep-ph]]

4 zeros textures of Dirac neutrino mass matrix

with three Right-handed Majorana Neutrinos

Example
$$m_{\nu D} = \begin{pmatrix} 0 & * & 0 \\ * & 0 & * \\ 0 & * & * \end{pmatrix}_{LR} , \quad M_R = \begin{pmatrix} M_1 & 0 & 0 \\ 0 & M_2 & 0 \\ 0 & 0 & M_3 \end{pmatrix}_{RR} , \quad m_E = \begin{pmatrix} m_e & 0 & 0 \\ 0 & m_\mu & 0 \\ 0 & 0 & m_\tau \end{pmatrix}_{LR}$$

Asterisk is complex.

M_1, M_2, M_3 are taken to be real and positive.

5 complex parameters in Dirac neutrino mass matrix
3 real parameters in M_R

3 phases are absorbed by 3 left-handed neutrino fields!
2 phases remainds, they are so called right-handed Majorana phases!

8 real parameters and 2 phases: 10 parameters

Parametrization

$$m_D = \begin{pmatrix} 0 & A & 0 \\ A' & 0 & B \\ 0 & B' & C \end{pmatrix}_{LR} \qquad M_R = M_0 \begin{pmatrix} \frac{1}{k_1}e^{-i\phi_A} & 0 & 0 \\ 0 & \frac{1}{k_2}e^{-i\phi_B} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

after the see-saw mechanism

M_R^{-1}

$$m_\nu = m_D M_R^{-1} m_D^T$$

$$= m_D \begin{pmatrix} k_1' & 0 & 0 \\ 0 & k_2' & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} K_1 e^{i\phi_A} & 0 & 0 \\ 0 & K_2 e^{i\phi_B} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} k_1' & 0 & 0 \\ 0 & k_2' & 0 \\ 0 & 0 & 1 \end{pmatrix} m_D^T \, M_0^{-1}$$

$$= \begin{pmatrix} 0 & A & 0 \\ A' & 0 & B \\ 0 & B' & C \end{pmatrix} \begin{pmatrix} k_1' & 0 & 0 \\ 0 & k_2' & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} 0 & Ak_2' & 0 \\ A'k_1' & 0 & B \\ 0 & B'k_2' & C \end{pmatrix}$$

Without loss of generality

Symmetric mass matrix

$A'k_1' = Ak_2'$ **=a**

$B'k_2' = B$ **=b**

M_0 is absorbed into a, b, C

7 parameters: a, b, C, K_1, K_2, Φ_A, Φ_B

We can rewrite as:

For example,

So called Fritzsch type mass matrix

$$m_D = \begin{pmatrix} 0 & ae^{i\phi_B/2} & 0 \\ ae^{i\phi_A/2} & 0 & b \\ 0 & be^{i\phi_B/2} & c \end{pmatrix} \qquad M_R = M_0 \begin{pmatrix} \frac{1}{K_1} & 0 & 0 \\ 0 & \frac{1}{K_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

See-Saw mechanism

$$m_\nu = \frac{1}{M_0} \begin{pmatrix} a^2K_2e^{i\phi_B} & 0 & abK_2e^{i\phi_B} \\ 0 & a^2K_1e^{i\phi_A} + b^2 & bc \\ abK_2e^{i\phi_B} & bc & b^2K_2e^{i\phi_B} + c^2 \end{pmatrix}$$

(1,2)=(2,1)
entries are zero !

These matrices give Jarlskog invariant and δ_{CP}

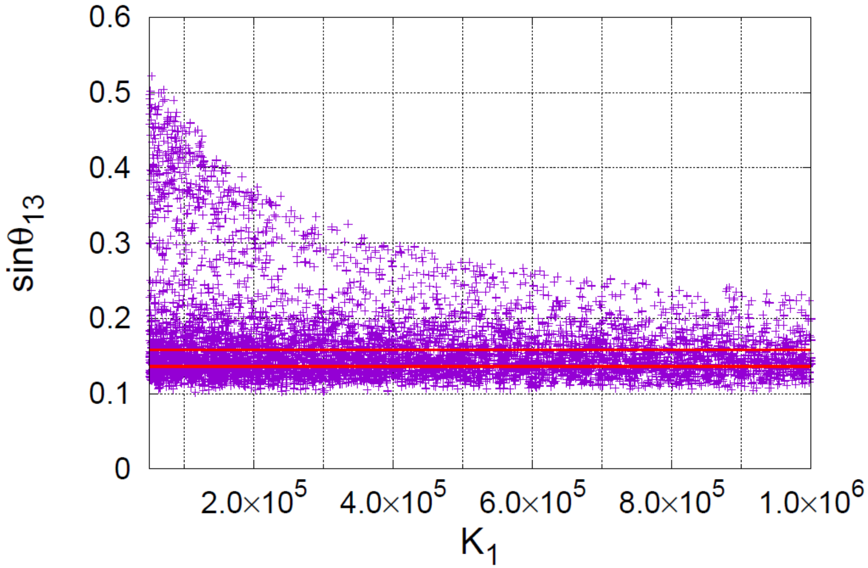
$$J_{CP} \simeq \frac{a^4b^4c^2K_1K_2^3\{a^2\sin(\phi_A - \phi_B) + b^2\sin(\phi_A + \phi_B)\}}{(\Delta m^2_{\rm atm})^2\Delta m^2_{\rm sol}}$$

$$\sin\delta_{\rm CP} = J_{\rm CP}/(s_{23}c_{23}s_{12}c_{12}s_{13}c_{13}^2)$$

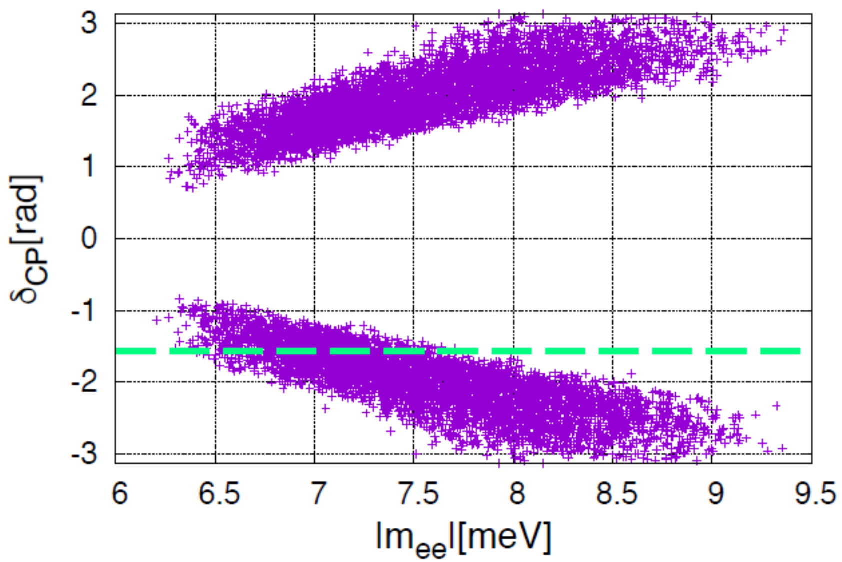
Φ_A, Φ_B are related to δ_{CP}

Since (1,2) entry of m_ν is zero, we have predictions:

$$0 = c_{12}c_{13}(-s_{12}c_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{2i\alpha}m_1 + s_{12}c_{13}(c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{2i\beta}m_2 + s_{13}s_{23}c_{13}e^{-i\delta_{CP}}m_3$$



$K_1 = M_3/M_1$



No crucial predictions at present

$$< m_{ee} >= U_{e1}^2 m_1 + U_{e2}^2 m_2 + U_{e3}^2 m_3$$

3 The Sign of Universe's Baryon Asymmetry

Φ_A, Φ_B are related to Leptogenesis !

Leptogenesis

M. Fukugita, T. Yanagida, *Phys. Lett.* ***B*** 174(1986) 45.

$$\epsilon = \frac{\Gamma(N_1 \to l\phi) - \Gamma(N_1 \to \bar{l}\bar{\phi})}{\Gamma(N_1 \to l\phi) + \Gamma(N_1 \to \bar{l}\bar{\phi})}$$
$$= -\frac{1}{8\pi}\frac{1}{v^2}\frac{1}{(m_D^\dagger m_D)_{11}}\sum_i \mathrm{Im}\left[\left\{(m_D^\dagger m_D)_{i1}\right\}^2\right] f\left(\frac{M_i^2}{M_1^2}\right)$$

For example,

Suppose $M_1 \ll M_2, M_3$

$$m_D = \begin{pmatrix} 0 & a e^{i\phi_B/2} & 0 \\ a e^{i\phi_A/2} & 0 & b \\ 0 & b e^{i\phi_B/2} & c \end{pmatrix} \qquad m_D^\dagger m_D = \begin{pmatrix} a^2 & * & * \\ 0 & * & * \\ abe^{i\phi_A/2} & * & * \end{pmatrix}$$

$$\varepsilon \approx -\frac{1}{8\pi}\frac{1}{v^2} b^2 \frac{M_3}{M_1} \sin\phi_A$$

Lepton number violation transfers baryon number violation by Sphaleron process.

$$Y_B = -\frac{28}{79} Y_L \propto -\epsilon \propto \sin\phi_A \qquad \left(Y_B \equiv \frac{n_B - n_{\bar{B}}}{s}\right)$$

Can we determine The Sign of Universe's Baryon Asymmetry ?

Physics Letters B 548 (2002) 119–121

www.else

Cosmological sign of neutrino CP violation

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Received 9 October 2002; accepted 14 October 2002

Right Handed Neutrino with two generations

$$\mathcal{L} = \frac{1}{2}(N_1, N_2)\begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}\begin{pmatrix} N_1 \\ N_2 \end{pmatrix} + (N_1, N_2)\begin{pmatrix} a & a' & 0 \\ 0 & b & b' \end{pmatrix}\begin{pmatrix} l_1 \\ l_2 \\ l_3 \end{pmatrix} H + \text{h.c.}, \qquad (1)$$

$$D = \begin{pmatrix} a & 0 & a' \\ 0 & b & b' \end{pmatrix}$$

$$B \propto \xi_H = (\operatorname{Im} D D^\dagger)^2_{12} = \operatorname{Im}(a'b)^2 = +Y^2 a^2 b^2 \sin 2\delta$$

One phase $a, b, M_1, M_2, Y > 0$ $\theta_{13} = 0$

$\underline{B > 0}$

therefore $\delta > 0$

Our Challenge !

4 zero textures with normal mass hierarchy

We introduced 7 physical parameters.
If 7 physical values are exactly determined,
there are no degree of freedom in the matrix!!

$\Delta m^2_{\rm sol}\ \Delta m^2_{\rm atm}\ \theta_{12}\ \ \theta_{23}\ \theta_{13}\ \delta_{CP}\ m_{ee}$

$$Y_B \propto \sin\phi_A$$

Can present data constrain $\sin\Phi_A$?

4 Numerical Results

Input 5 data (Global Analysis Results)

M. C. Gonzalez-Garcia, M. Maltoni and T. Schwetz, arXiv:1512.06856

$$\Delta m^2_{\rm atm} = 2.457 \pm 0.047 \times 10^{-3}{\rm eV}^2 \ , \qquad \Delta m^2_{\rm sol} = 7.50^{+0.19}_{-0.17} \times 10^{-5}{\rm eV}^2 \ ,$$

$$\sin^2\theta_{12} = 0.304^{+0.013}_{-0.012} \ , \quad \sin^2\theta_{23} = 0.452^{+0.052}_{-0.028} \ , \quad \sin^2\theta_{13} = 0.0218 \pm 0.0010$$

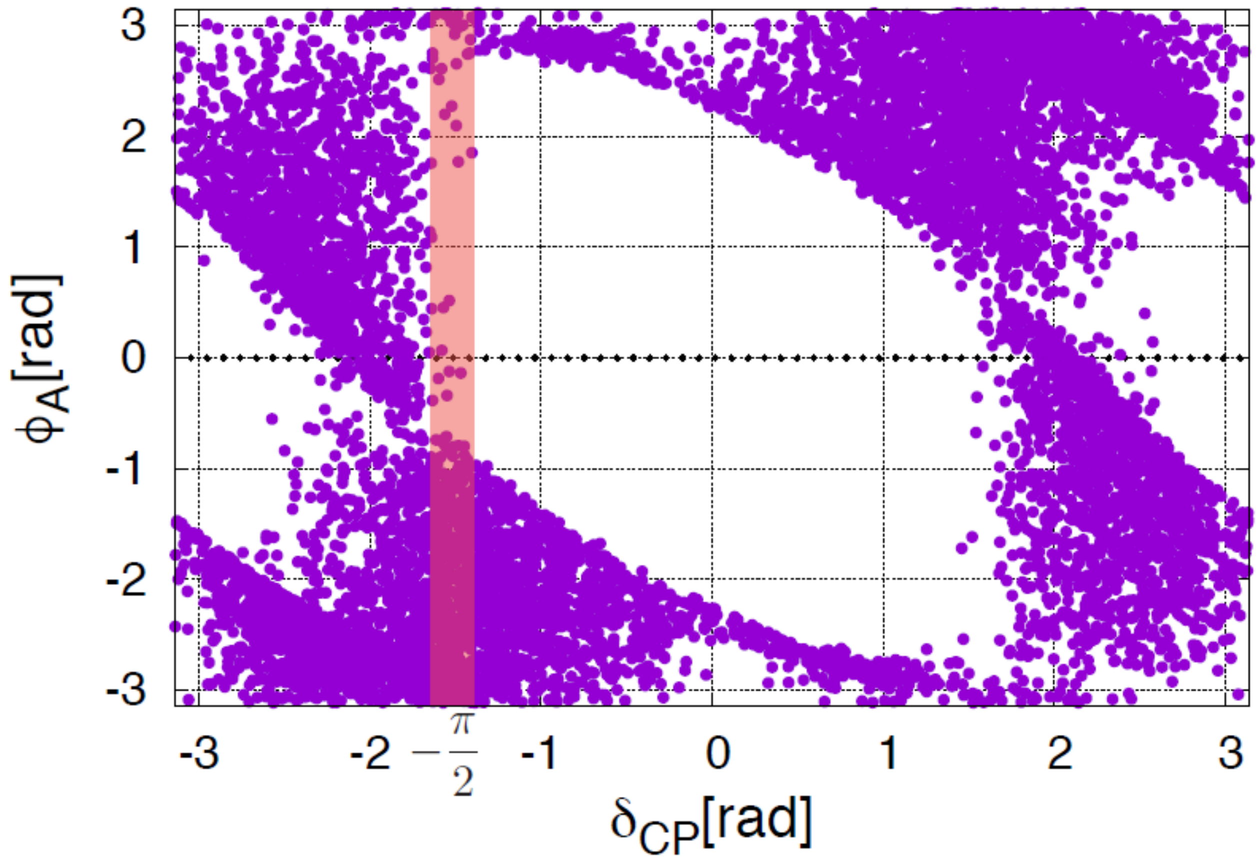
90% C.L.

The Sign of Universe's Baryon Asymmetry

$$m_D = \begin{pmatrix} 0 & ae^{i\phi_B/2} & 0 \\ ae^{i\phi_A/2} & 0 & b \\ 0 & be^{i\phi_B/2} & c \end{pmatrix}$$

Suppose $M_1 \ll M_2$, M_3

$$Y_B \propto +\sin\phi_A$$



However, there are many four zeros textures !

Classified by G.C.Branco, D.Emmanuel-Costa, M.N.Rebelo and P.Roy
``Four Zero Neutrino Yukawa Textures in the Minimal Seesaw Framework''
Phys. Rev. D 77 (2008) 053011 [arXiv:0712.0774 [hep-ph]]

$m_i \neq 0$ and Four-Zero Dirac mass matrices are 72 patterns !

18 textures $(m_\nu)_{12} = (m_\nu)_{21} = 0$

18 textures $(m_\nu)_{13} = (m_\nu)_{31} = 0$

18 textures $(m_\nu)_{23} = (m_\nu)_{32} = 0$ ⇨ degenerate neutrino masses

6 textures $|(m_\nu)_{11}(m_\nu)_{23}| - |(m_\nu)_{21}(m_\nu)_{13}| = \arg\{(m_\nu)_{11}(m_\nu)_{23}(m_\nu)^*_{21}(m_\nu)^*_{13}\} = 0$

6 textures $|(m_\nu)_{22}(m_\nu)_{13}| - |(m_\nu)_{12}(m_\nu)_{23}| = \arg\{(m_\nu)_{22}(m_\nu)_{13}(m_\nu)^*_{12}(m_\nu)^*_{23}\} = 0$

6 textures $|(m_\nu)_{33}(m_\nu)_{12}| - |(m_\nu)_{13}(m_\nu)_{32}| = \arg\{(m_\nu)_{33}(m_\nu)_{12}(m_\nu)^*_{13}(m_\nu)^*_{32}\} = 0$

There are relations between δ_{CP} and the phase of leptogenesis in the framework of four zeros textures:

S. Choubey, W. Rodejohann and P. Roy
``Phenomenological consequences of four zero neutrino Yukawa textures''
Nucl. Phys. B 808 (2009) 272, Erratum: [Nucl. Phys. B {¥bf 818} (2009) 136]
[arXiv:0807.4289 [hep-ph]]

Suppose $M_1 \ll M_2, M_3$

Among 54 patterns,

the Dirac neutrino mass matrices determing a sign of BAU by one phase with normal hierachy of neutrino masses are:

24 textures !

$$\mathrm{Im}\left[\left\{(m_D^\dagger m_D)_{i1}\right\}^2\right] = 0 \text{ for } i=2 \text{ or } 3$$

$$\boxed{\begin{pmatrix} 0 & a_2 & 0 \\ b_1 & 0 & b_3 \\ 0 & c_2 & c_3 \end{pmatrix}} \quad \begin{pmatrix} a_1 & 0 & 0 \\ 0 & b_2 & b_3 \\ c_1 & c_2 & 0 \end{pmatrix} \quad \begin{pmatrix} a_1 & 0 & 0 \\ 0 & b_2 & b_3 \\ c_1 & 0 & c_3 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & a_3 \\ b_1 & b_2 & 0 \\ 0 & c_2 & c_3 \end{pmatrix}$$

$$\boxed{\begin{pmatrix} 0 & a_2 & a_3 \\ b_1 & 0 & 0 \\ c_1 & 0 & c_3 \end{pmatrix}} \quad \begin{pmatrix} 0 & a_2 & a_3 \\ b_1 & 0 & 0 \\ c_1 & c_2 & 0 \end{pmatrix} \quad \begin{pmatrix} a_1 & a_2 & 0 \\ 0 & 0 & b_3 \\ 0 & c_2 & c_3 \end{pmatrix} \quad \begin{pmatrix} a_1 & 0 & a_3 \\ 0 & b_2 & 0 \\ 0 & c_2 & c_3 \end{pmatrix}$$

$$\boxed{\begin{pmatrix} 0 & a_2 & 0 \\ 0 & b_2 & b_3 \\ c_1 & 0 & c_3 \end{pmatrix}} \quad \begin{pmatrix} a_1 & 0 & 0 \\ b_1 & b_2 & 0 \\ 0 & c_2 & c_3 \end{pmatrix} \quad \begin{pmatrix} a_1 & 0 & 0 \\ b_1 & 0 & b_3 \\ 0 & c_2 & c_3 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & a_3 \\ 0 & b_2 & b_3 \\ c_1 & c_2 & 0 \end{pmatrix}$$

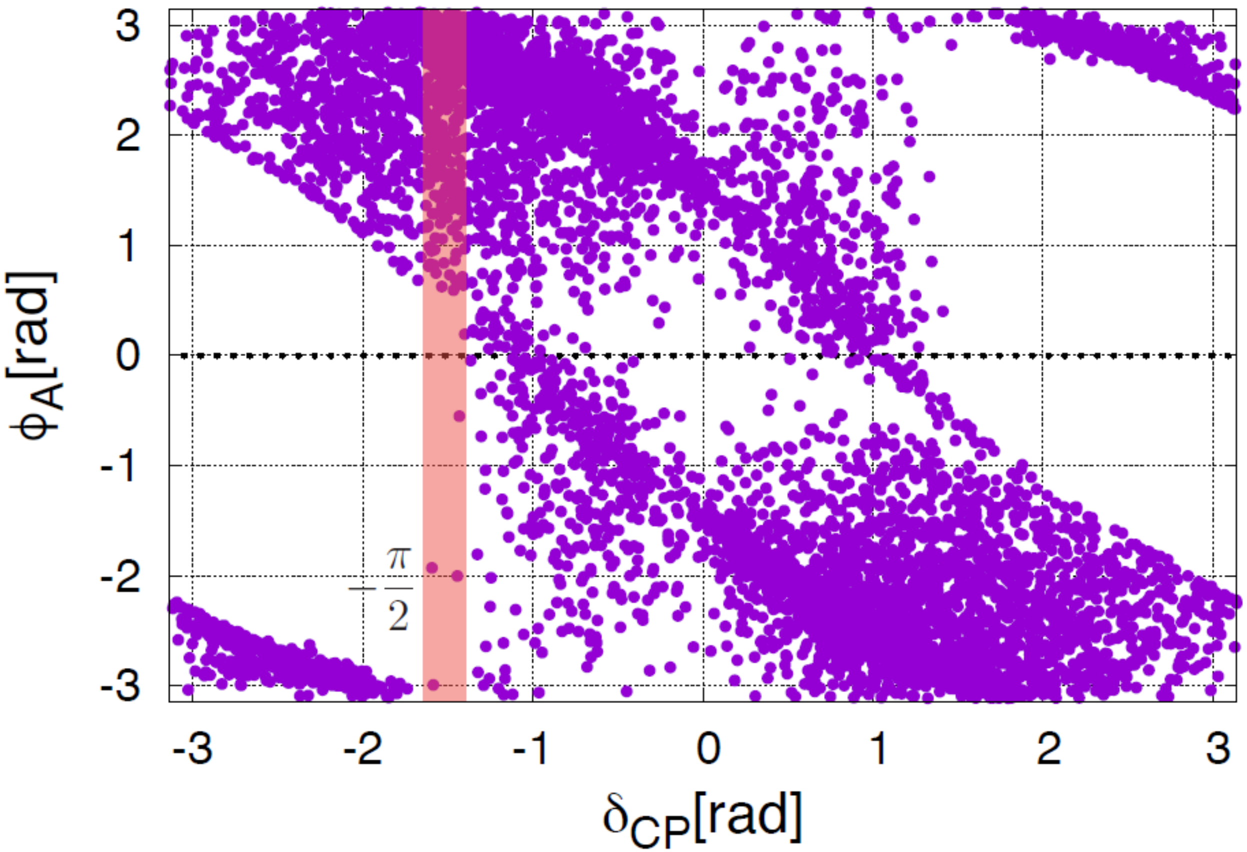
etc.

The Sign of Universe's Baryon Asymmetry

$$m_D = \begin{pmatrix} 0 & a_2 e^{i\phi_B/2} & 0 \\ 0 & b_2 e^{i\phi_B/2} & b_3 \\ c_1 e^{i\phi_A/2} & 0 & c_3 \end{pmatrix}_{LR}$$

Suppose $M_1 \ll M_2, M_3$

$$Y_B \propto +\sin\phi_A$$

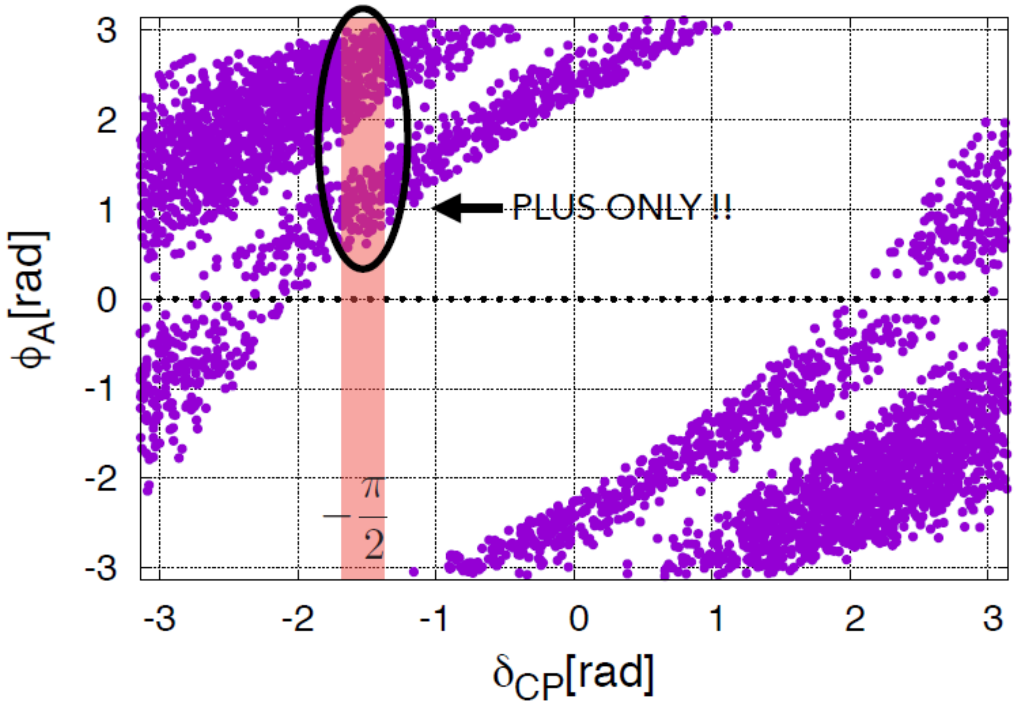


The Sign of Universe's Baryon Asymmetry

$$m_D = \begin{pmatrix} 0 & a_2 e^{i\phi_B/2} & a_3 \\ b_1 e^{i\phi_A/2} & 0 & 0 \\ c_1 e^{i\phi_A/2} & 0 & c_3 \end{pmatrix}_{LR}$$

Suppose $M_1 << M_2, M_3$

$$Y_B \propto +\sin\phi_A$$



constraint by

$(\Delta m^2_{\rm sol},\ \Delta m^2_{\rm atm},\ \theta_{12},\ \theta_{23},\ \theta_{13})$

in 90% C.L.

If $\delta_{\rm CP}$ will be fixed close to $-\pi/2$,

The matrix is candidate of determining the sign of Universe's Baryon Asymmetry!!

However,
the hierachy of the right-handed neutrino masses are not specified.

Let us impose Froggatt-Nielsen mechanism to specify M_R hierarchy.

Consider the case :

$$m_{\nu D} = \begin{pmatrix} 0 & a_2 & a_3 \\ b_1 & 0 & 0 \\ c_1 & 0 & c_3 \end{pmatrix}_{LR} , \quad M_R = M_0 \begin{pmatrix} K_1^{-1} & 0 & 0 \\ 0 & K_2^{-1} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{RR}$$

FN charges: L (L_1, L_2, L_3) , R (R_1, R_2, 0) with $R_1 > R_2 > 0$

$$m_{\nu D} = \begin{pmatrix} 0 & \lambda^{L_1+R_2} & \lambda^{L_1} \\ \lambda^{L_2+R_1} & 0 & 0 \\ \lambda^{L_3+R_1} & 0 & \lambda^{L_3} \end{pmatrix}_{LR} , \quad M_R = M_0 \begin{pmatrix} \lambda^{2R_1} & 0 & 0 \\ 0 & \lambda^{2R_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}_{RR}$$

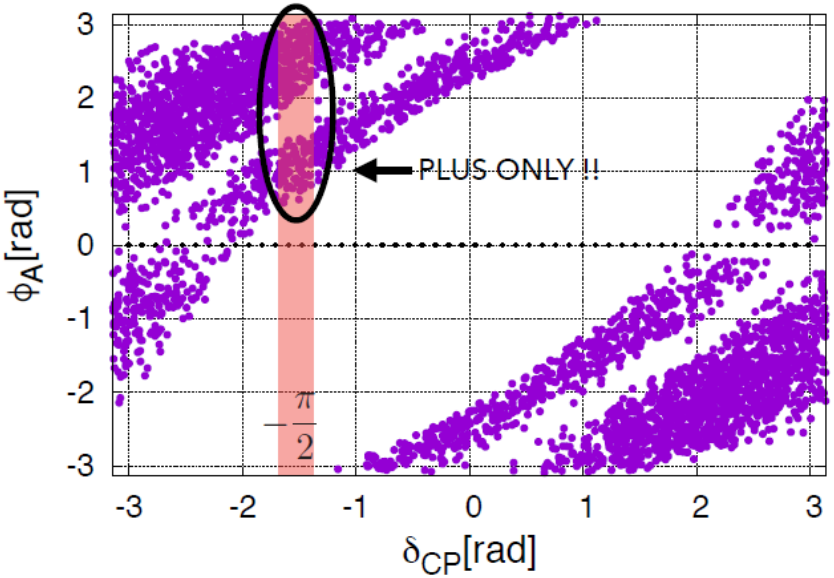
If we take following K_1 and K_2, we can adjust FN framework.

$$K_1 = (c_3/c_1)^2 = \lambda^{-2R_1} \qquad K_2 = (a_3/a_2)^2 = \lambda^{-2R_2}$$

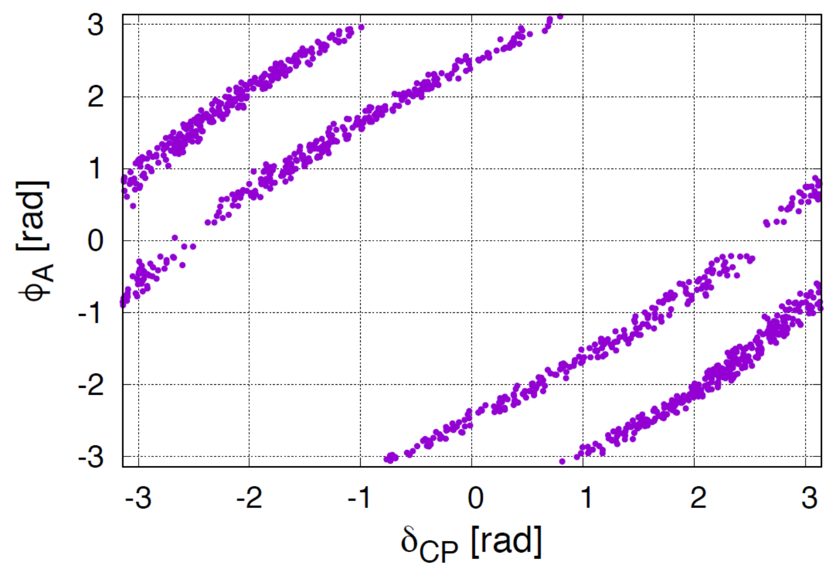
Let us allow error-bar of 50% in these relations !

Prediction in Froggatt-Nielsen Framework

without FN



with FN



In progress

5 Summary

Occam's Razor imposes 4 zeros in the Dirac neutrino mass matrix with 3 Right-handed Majorana neutrinos.

7 parameters in the neutrino mass matrix m_ν with NH

Two CP violating phases appear !

Φ_A, Φ_B are related to δ_{CP} and Leptogenesis

Some textures for Dirac neutrino mass matrix
with 4 zeros are successful to predict
the sign of Universe's Baryon Asymmetry.

Five zeros cannot explain the experimental data of the neutrino mixing !

More than four zero textures

$$m_D = \begin{pmatrix} 0 & A & 0 \\ A' & 0 & B \\ 0 & B' & C \end{pmatrix} \qquad M_R = M_0 \begin{pmatrix} \frac{1}{k_1}e^{-i\phi_A} & 0 & 0 \\ 0 & \frac{1}{k_2}e^{-i\phi_B} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

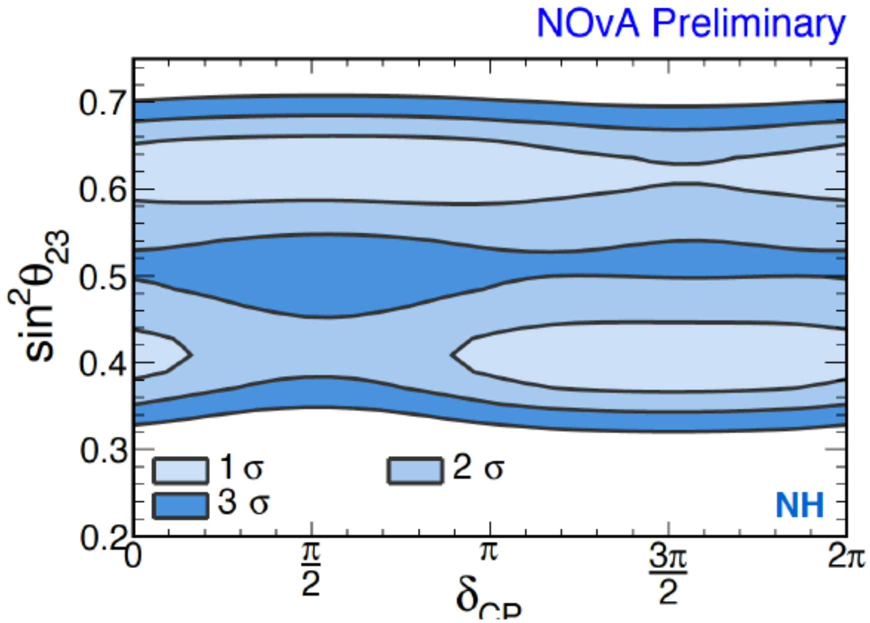
- Imposing more zeros?

  if) $C = 0$ **(5th Zeros)**

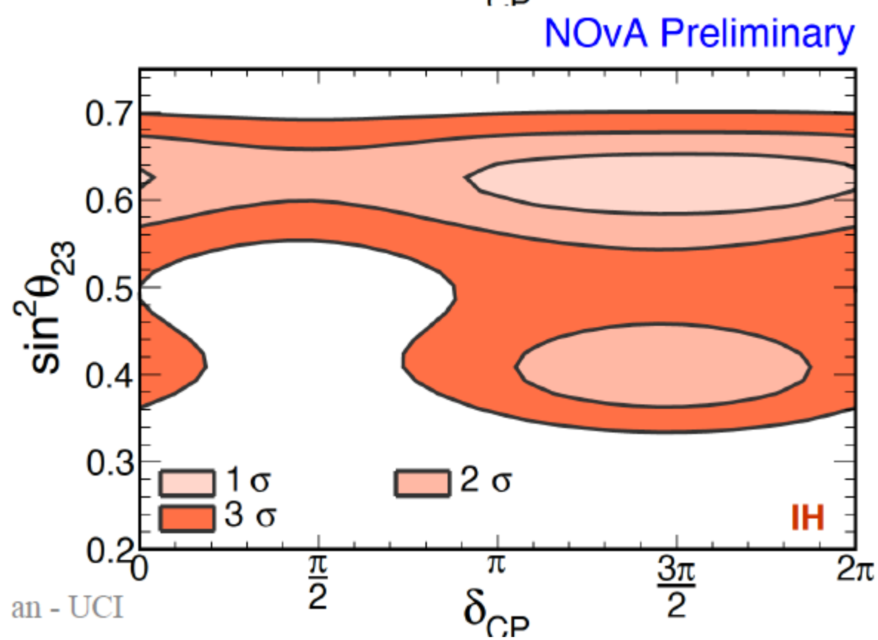
$$m_\nu = \frac{1}{M_0} \begin{pmatrix} A^2 k_2 e^{i\phi_B} & 0 & AB'k_2 e^{i\phi_B} \\ 0 & A'^2 k_1 e^{i\phi_A} + B^2 & BC \\ AB'k_2 e^{i\phi_B} & BC & B'^2 k_2 e^{i\phi_B} + C^2 \end{pmatrix}$$

θ_{12} and θ_{23} become zero !!

NOvA


NOvA Preliminary
$\sin^2\theta_{23}$
0.7
0.6
0.5
0.4
0.3
0.2
1 σ
2 σ
3 σ
NH
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
δ_{CP}

NH

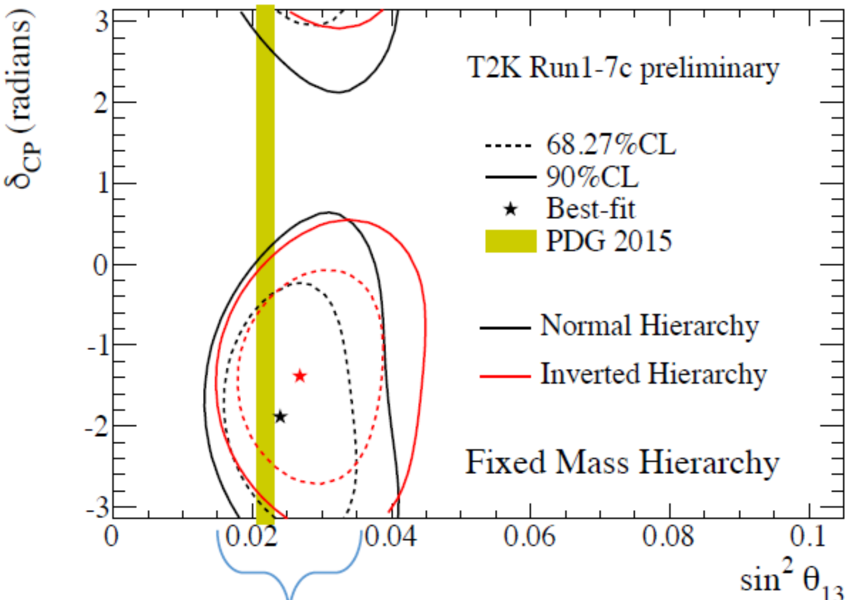

NOvA Preliminary
$\sin^2\theta_{23}$
0.7
0.6
0.5
0.4
0.3
0.2
1 σ
2 σ
3 σ
IH
0
$\frac{\pi}{2}$
π
$\frac{3\pi}{2}$
2π
δ_{CP}

IH

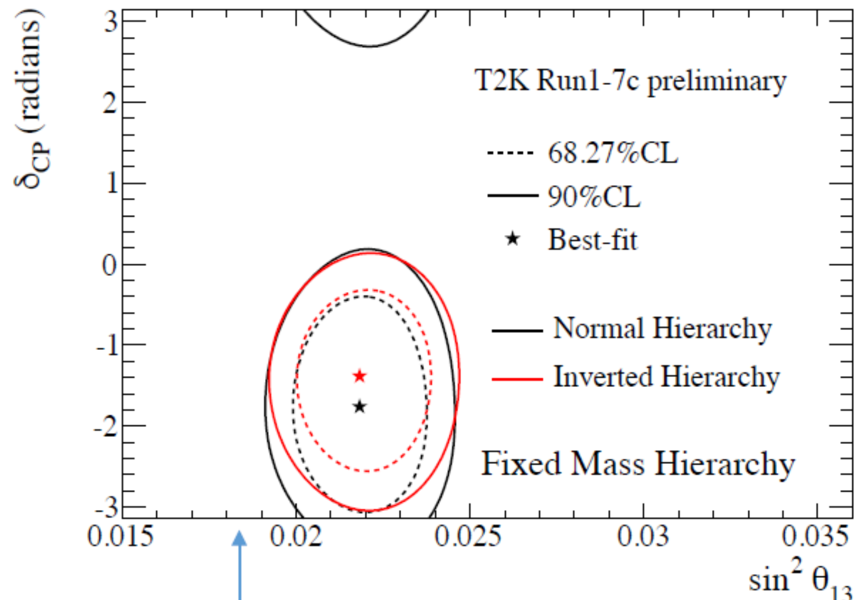
θ_{13} and δ_{cp}

T2K

T2K-Only



T2K Result with Reactor Constraint
($sin^2 2\theta_{13} = 0.085 \pm 0.005$)



- T2K-only result consistent with the reactor measurement
- Favors the $\delta_{cp} \sim -\frac{\pi}{2}$ region