Neutrino CP Violation and Sign of Baryon Asymmetry

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Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201;
Phys. Lett. B778 (2018) 6.

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HIROSHIMA UNIVERSITY

Hiroshima University Theoretical Particle Physics Group

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Plan of my talk

1. Introduction

2. Lepton model

   - Toward a minimal model consistent with neutrino oscillation experiments

   - CP violation and leptogenesis

3. Summary

1. Introduction

- Standard model (SM): $SU(3)_Q \times SU(2)_L \times U(1)_Y$

Particle	First	Second	Third	Mixing matrix
Quark	$\begin{pmatrix} u \\ d \end{pmatrix}_L$ u^c_R d^c_R	$\begin{pmatrix} c \\ s \end{pmatrix}_L$ c^c_R s^c_R	$\begin{pmatrix} t \\ b \end{pmatrix}_L$ t^c_R b^c_R	CKM matrix (Cabibbo-Kobayashi-Maskawa)
Lepton	$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$ e^c_R	$\begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L$ μ^c_R	$\begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L$ τ^c_R	PMNS matrix (Pontecorvo-Maki-Nakagawa-Sakata)

- Generation (flavor) problems

- Masses of SM particles are different each generation.
- Flavor mixing matrices are different in the lepton and quark sectors.

- Neutrino mass squared differences:

$$\Delta m^2_{\rm sol} \equiv m_2^2 - m_1^2, \quad \left|\Delta m^2_{\rm atm}\right| \equiv \left|m_3^2 - m_1^2\right|.$$

- Neutrino mass hierarchies:

  - Normal hierarchy (NH) → $m_1 < m_2 < m_3$
  - Inverted hierarchy (IH) → $m_3 < m_1 < m_2$
  - Quasi degenerate (QD) → $m_1 \sim m_2 \sim m_3$

- SM fermions get masses through Higgs mechanism.

$$\mathcal{L}_Y = y\bar{\psi}_L H \psi_R \to y\langle H\rangle \bar{\psi}_L \psi_R = m_f \bar{\psi}_L \psi_R.$$

  Neutrinos cannot get masses because there are no right-handed neutrinos in the SM.

- Seesaw mechanism

Minkowski '77; Gell-Mann, Ramond, Slansky; Yanagida; Glashow; Mohapatra, Senjanovic '79

  - We introduce three right-handed Majorana neutrinos:

$$M = \begin{pmatrix} 0 & M_D \\ M_D^T & M_N \end{pmatrix} \xrightarrow{\text{Diagonalization}} M_\nu \simeq -M_D^T M_N^{-1} M_D$$

  - If $M_N >> M_D$, the left-handed Majorana neutrinos get non-zero masses.

- Lepton flavor mixing matrix (PMNS matrix)

$$U \equiv \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{\mathrm{CP}}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{\mathrm{CP}}} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{\mathrm{CP}}} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

  - δ_{CP} : Dirac phase, α, β : Majorana phases

- Experimental situations

- Reactor neutrino experiments indicate non-zero θ_{13}

Global fit of the neutrino oscillation:

NuFIT 3.2 (2018)

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 4.14$)		Any Ordering
	bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range	3σ range
$\sin^2\theta_{12}$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.307^{+0.013}_{-0.012}$	$0.272 \to 0.346$	$0.272 \to 0.346$
$\theta_{12}/^\circ$	$33.62^{+0.78}_{-0.76}$	$31.42 \to 36.05$	$33.62^{+0.78}_{-0.76}$	$31.43 \to 36.06$	$31.42 \to 36.05$
$\sin^2\theta_{23}$	$0.538^{+0.033}_{-0.069}$	$0.418 \to 0.613$	$0.554^{+0.023}_{-0.033}$	$0.435 \to 0.616$	$0.418 \to 0.613$
$\theta_{23}/^\circ$	$47.2^{+1.9}_{-3.9}$	$40.3 \to 51.5$	$48.1^{+1.4}_{-1.9}$	$41.3 \to 51.7$	$40.3 \to 51.5$
$\sin^2\theta_{13}$	$0.02206^{+0.00075}_{-0.00075}$	$0.01981 \to 0.02436$	$0.02227^{+0.00074}_{-0.00074}$	$0.02006 \to 0.02452$	$0.01981 \to 0.02436$
$\theta_{13}/^\circ$	$8.54^{+0.15}_{-0.15}$	$8.09 \to 8.98$	$8.58^{+0.14}_{-0.14}$	$8.14 \to 9.01$	$8.09 \to 8.98$
$\delta_{CP}/^\circ$	234^{+43}_{-31}	$144 \to 374$	278^{+26}_{-29}	$192 \to 354$	$144 \to 374$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$7.40^{+0.21}_{-0.20}$	$6.80 \to 8.02$	$6.80 \to 8.02$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.494^{+0.033}_{-0.031}$	$+2.399 \to +2.593$	$-2.465^{+0.032}_{-0.031}$	$-2.562 \to -2.369$	$\begin{bmatrix} +2.399 \to +2.593 \\ -2.536 \to -2.395 \end{bmatrix}$

- Flavor mixing matrices in the lepton and quark sectors
  - Lepton flavor mixing: PMNS matrix (NuFIT 3.2 (2018))

$$|U_{\mathrm{PMNS}}| \simeq \begin{pmatrix} 0.823 & 0.548 & 0.149 \\ 0.425 & 0.721 & 0.548 \\ 0.377 & 0.425 & 0.823 \end{pmatrix}$$

Lepton flavor mixing angles are large except for reactor angle θ_{13}.

$$\sin\theta_{13} \simeq 0.149$$

  - Quark flavor mixing: CKM matrix (PDG 2018)

$$|V_{\mathrm{CKM}}| \simeq \begin{pmatrix} 0.974 & 0.225 & 0.00365 \\ 0.224 & 0.974 & 0.0421 \\ 0.00896 & 0.0413 & 0.999 \end{pmatrix}$$

Quark flavor mixing angles are small except for Cabibbo angle λ_C.

$$\lambda_C \simeq 0.225$$

  - Are there some relations between lepton and quark flavor mixing?

$$\sin\theta_{13} \simeq \frac{\lambda_C}{\sqrt{2}}$$

2. Lepton model

- Toward a minimal model consistent
  with neutrino oscillation experiments (Texture Zero)

- They introduced two right-handed Majorana neutrinos: $(N_1,\ N_2)$

  P. H. Frampton, S. L. Glashow and T. Yanagida, Phys. Lett. B548 (2002) 119.

$$M_D = \begin{pmatrix} a & 0 \\ b & e \\ 0 & f \end{pmatrix}_{LR}, \quad M_N = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}_{RR}.$$

PMNS matrix element in NH case ➡ not consistent with experimental data

$$U_{e3} \simeq \frac{m_2}{2m_3} = \frac{\sqrt{\Delta m^2_{\rm sol}}}{2\sqrt{\Delta m^2_{\rm atm}}} \simeq 0.086$$

$$U_{e3}^{\rm exp} \simeq 0.15$$

- 4 real parameters and 1 phase parameter ➡ related to the leptogenesis

2. Lepton model

- Toward a minimal model consistent with neutrino oscillation experiments (Occam's Razor)

- They introduced two right-handed Majorana neutrinos: $(N_1,\ N_2)$

  K. Harigaya, M. Ibe and T. T. Yanagida, Phys. Rev. D86 (2012) 013002.

  The model in the IH case is consistent with experimental data:

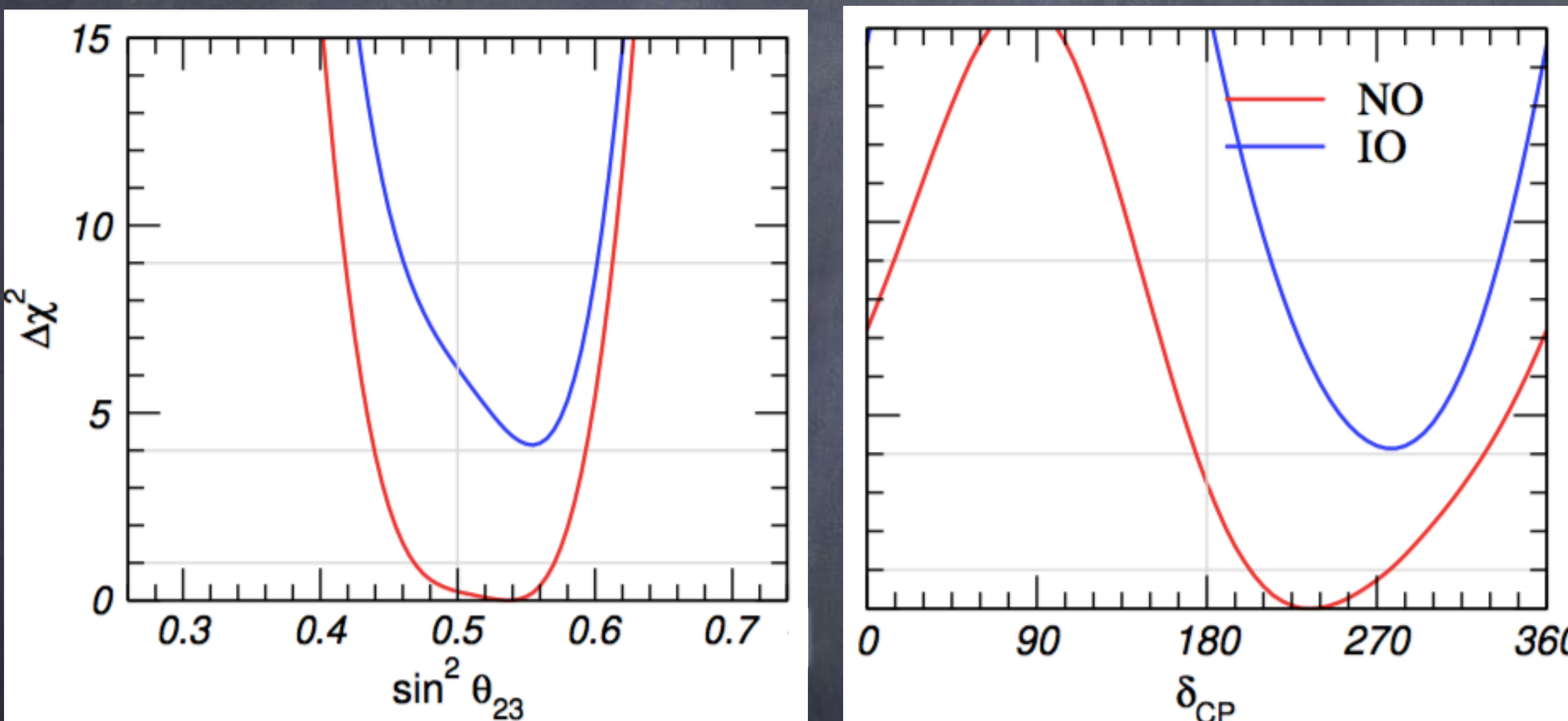
$$M_D = \begin{pmatrix} 0 & d \\ b & 0 \\ c & f \end{pmatrix}_{LR}, \quad M_N = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix}_{RR},$$

$$M_\nu = -M_D M_N^{-1} M_D^T = -\begin{pmatrix} \frac{d^2}{M_2} & 0 & \frac{df}{M_2} \\ 0 & \frac{b^2}{M_1} & \frac{bc}{M_1} \\ \frac{df}{M_2} & \frac{bc}{M_1} & \frac{c^2}{M_1} + \frac{f^2}{M_2} \end{pmatrix}$$

4 real parameters and 1 phase parameter ➡ 5 observables

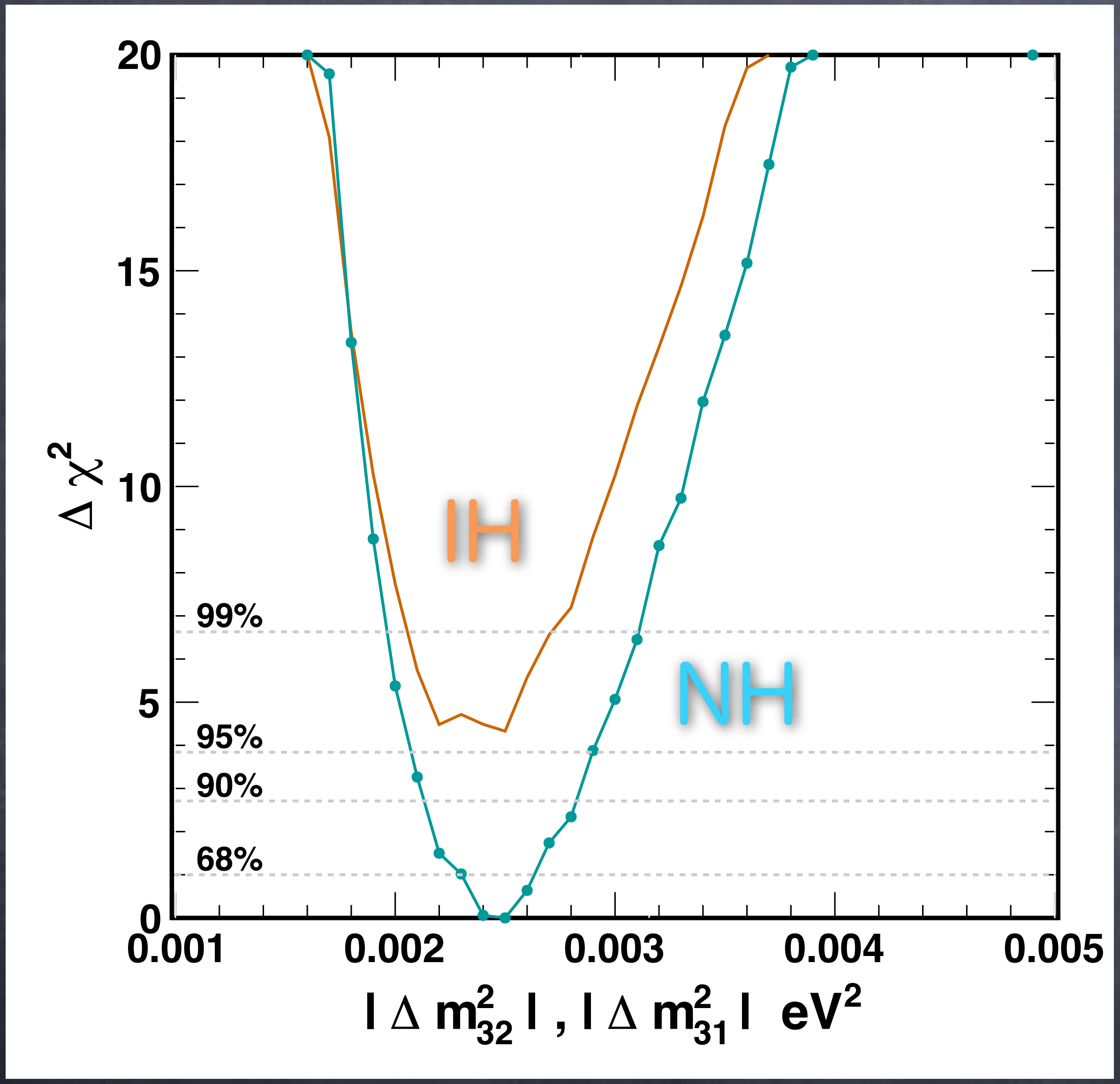
Prediction: $\delta_{CP} = \pm\frac{\pi}{2}$ ⬅ strictly

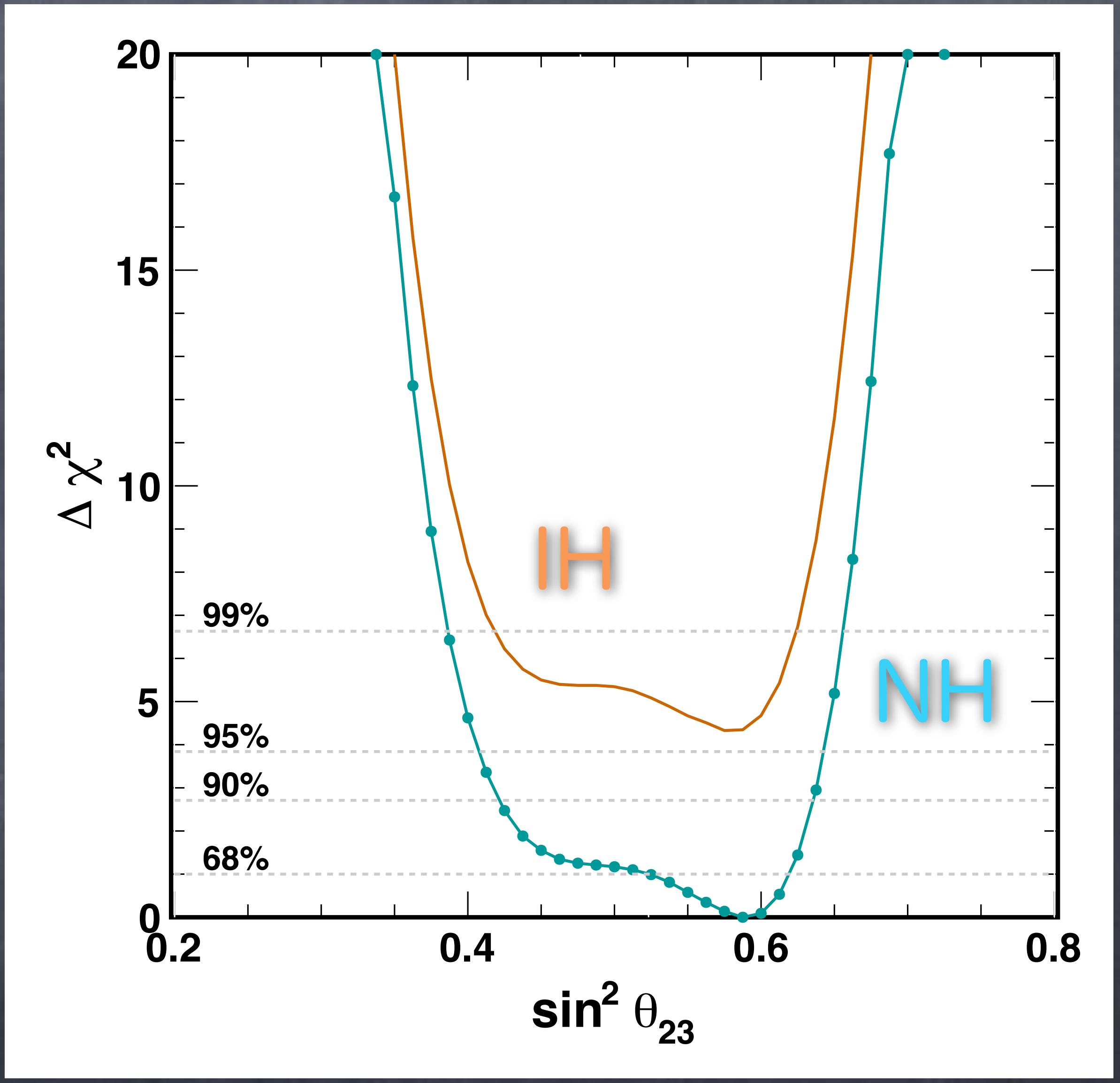
- Normal hierarchy is favored
  - Data for NuFIT 3.2 (2018):



  - $\delta_{CP} \simeq -90^\circ \ (270^\circ)$, NH
  - θ_{23} is maximal

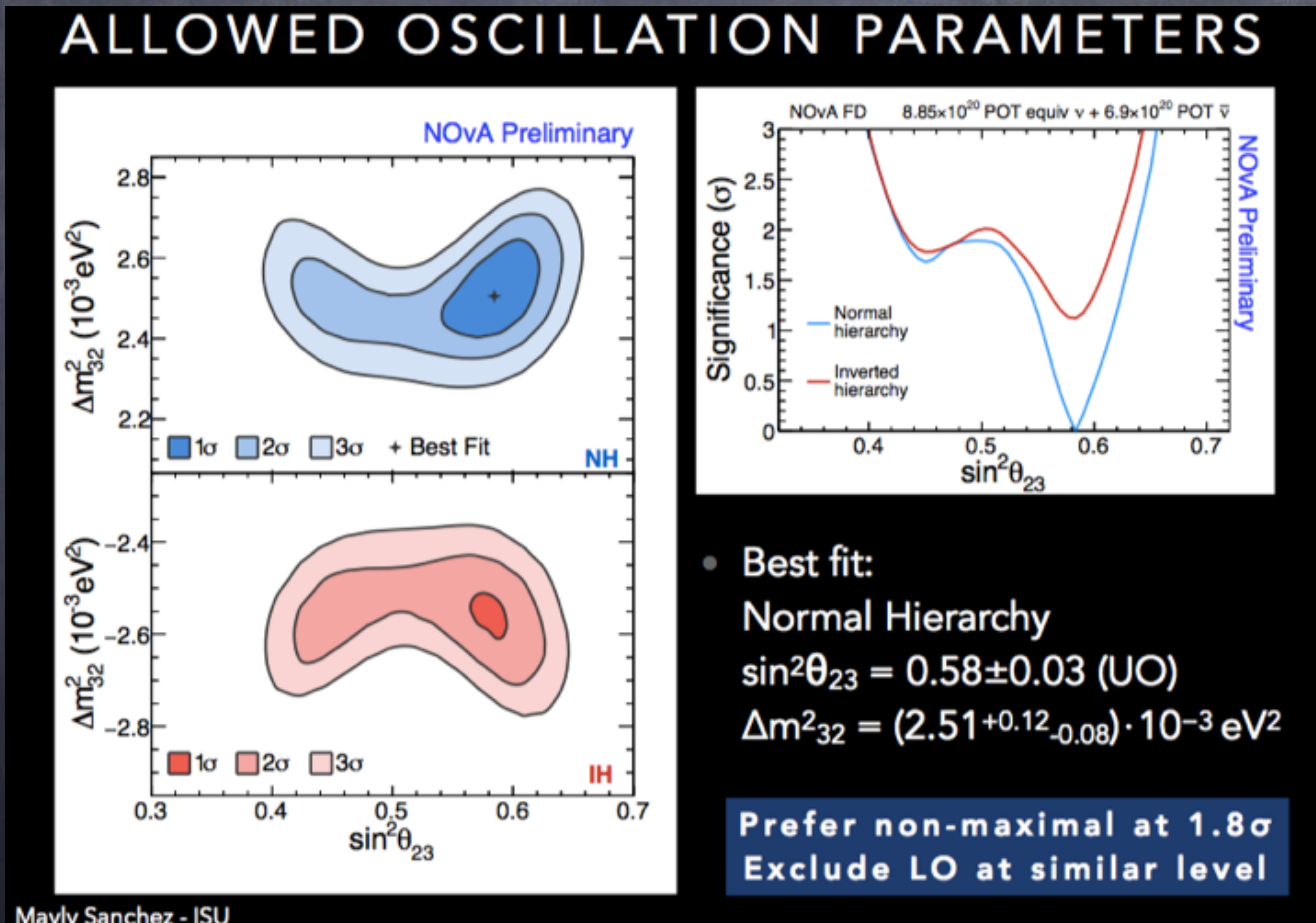
- Normal hierarchy is favored
    - Neutrino 2018: SK experiment





K. Abe et al. [Super-Kamiokande Collaboration], Phys. Rev. D 97 (2018) no.7, 072001

- Normal hierarchy is favored
  - Neutrino 2018: NOvA experiment



- We investigate a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - We take the charged lepton mass matrix diagonal
  - We introduce two right-handed Majorana neutrinos
  - The right-handed Majorana neutrino mass matrix:

$$M_N = \begin{pmatrix} M_1 & 0 \\ 0 & M_2 \end{pmatrix} = M_0 \begin{pmatrix} p^{-1} & 0 \\ 0 & 1 \end{pmatrix}$$

  - The Dirac neutrino mass matrix:

$$M_D = vY_\nu = v \begin{pmatrix} a & d \\ b & e \\ c & f \end{pmatrix}$$

- We investigate a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - We take the charged lepton mass matrix diagonal
  - We introduce two right-handed Majorana neutrinos
  - Right-handed Majorana and Dirac neutrino mass matrices

$$M_N = M_0 \begin{pmatrix} p^{-1} & 0 \\ 0 & 1 \end{pmatrix}, \quad M_D = v \begin{pmatrix} a & d \\ b & e \\ c & f \end{pmatrix}$$

  - By using seesaw mechanism, the left-handed Majorana neutrino mass matrix

$$M_\nu = -M_D M_N^{-1} M_D^T = -\frac{v^2}{M_0} \begin{pmatrix} a^2p + d^2 & abp + de & acp + df \\ abp + de & b^2p + e^2 & bcp + ef \\ acp + df & bcp + ef & c^2p + f^2 \end{pmatrix}$$

- We investigate a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - Tri-bimaximal (TBM) mixing matrix: P. F. Harrison, D. H. Perkins and W. G. Scott 2002

$$V_{\mathrm{TBM}} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

⬆ Symmetry for conserving this column:

Trimaximal (TM) mixing TM_1

C. H. Albright, A. Dueck and W. Rodejohann, Eur. Phys. J. C 70 (2010) 1099;
W. Rodejohann and H. Zhang, Phys. Rev. D 86 (2012) 093008.

  - Dirac neutrino mass matrix

$$M_D = v \begin{pmatrix} \frac{b+c}{2} & \frac{e+f}{2} \\ b & e \\ c & f \end{pmatrix}$$

4 real and 2 phase parameters

- We investigate a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - Dirac neutrino mass matrix

$$M_D = v \begin{pmatrix} \frac{b+c}{2} & \frac{e+f}{2} \\ b & e \\ c & f \end{pmatrix}$$

  - Neutrino mass matrix

$$\hat{M}_\nu = -\frac{v^2}{M_0} \begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{3}{4}\left((b+c)^2 p + (e+f)^2\right) & \frac{1}{2}\sqrt{\frac{3}{2}}\left((c^2-b^2)p - e^2 + f^2\right) \\ 0 & \frac{1}{2}\sqrt{\frac{3}{2}}\left((c^2-b^2)p - e^2 + f^2\right) & \frac{1}{2}\left((b-c)^2 p + (e-f)^2\right) \end{pmatrix}$$

  - The lightest neutrino mass m_1 is zero

- We present a minimal model of the NH case for neutrino masses

We introduce S_4 flavor symmetry (Indirect approach)

Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

$$\mathcal{L}_Y = y_{\rm atm}\phi_{\rm atm}\bar{L}HN_1/\Lambda + y_{\rm sol}\phi_{\rm sol}\bar{L}HN_2/\Lambda$$

$\phi_{\rm atm}, \phi_{\rm sol}$: S_4 3' scalar fields (flavons)

L : S_4 3' lepton doublet

H : S_4 singlet Higgs doublet

N_1, N_2 : S_4 and gauge singlets right-handed Majorana neutrinos

Λ : Cut-off scale for the model

S_4 breaks down to Z_2 $(1, SU)$

$$\langle\phi_{\rm atm}\rangle \sim \begin{pmatrix} \frac{b+c}{2} \\ c \\ b \end{pmatrix}, \quad \langle\phi_{\rm sol}\rangle \sim \begin{pmatrix} \frac{e+f}{2} \\ f \\ e \end{pmatrix}, \quad SU = US = \frac{1}{3}\begin{pmatrix} -1 & 2 & 2 \\ 2 & -1 & 2 \\ 2 & 2 & -1 \end{pmatrix}$$

Multiplication rule for S_4 group: $\phi(3')\bar{L}(3') = \phi_1\bar{L}_1 + \phi_2\bar{L}_3 + \phi_3\bar{L}_2$

- We present a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - In order to get a minimal scheme, we reduce parameters

$$(\mathrm{I})\ b+c=0, \quad (\mathrm{II})\ c=0, \quad (\mathrm{III})\ b=0$$

$$M_D = vY_\nu = \begin{cases} v\begin{pmatrix} 0 & \frac{e+f}{2} \\ b & e \\ -b & f \end{pmatrix} & (\mathrm{I})\ b+c=0 \\ v\begin{pmatrix} \frac{b}{2} & \frac{e+f}{2} \\ b & e \\ 0 & f \end{pmatrix} & (\mathrm{II})\ c=0 \\ v\begin{pmatrix} \frac{c}{2} & \frac{e+f}{2} \\ 0 & e \\ c & f \end{pmatrix} & (\mathrm{III})\ b=0 \end{cases}$$

3 real parameters and 1 phase parameter ➡ CP phase is predicted

- We present a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - In order to get a minimal scheme, we reduce parameters

$$(\mathrm{I})\ b + c = 0 : \quad M_D = vY_\nu = v\begin{pmatrix} 0 & \frac{e+f}{2} \\ b & e \\ -b & f \end{pmatrix}$$

Neutrino mass matrix after rotating TBM matrix: $\hat{M}_\nu$

$$\hat{M}_\nu = -\frac{f^2 v^2}{M_0}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{3}{4}(k+1)^2 & -\frac{1}{2}\sqrt{\frac{3}{2}}(k^2-1) \\ 0 & -\frac{1}{2}\sqrt{\frac{3}{2}}(k^2-1) & 2B^2 p e^{2i\phi_B} + \frac{1}{2}(k-1)^2 \end{pmatrix}$$

$$\frac{e}{f} = k, \quad \arg[b] = \phi_B, \quad \frac{b}{f} = Be^{i\phi_B}$$

k, B : real parameters

- We present a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

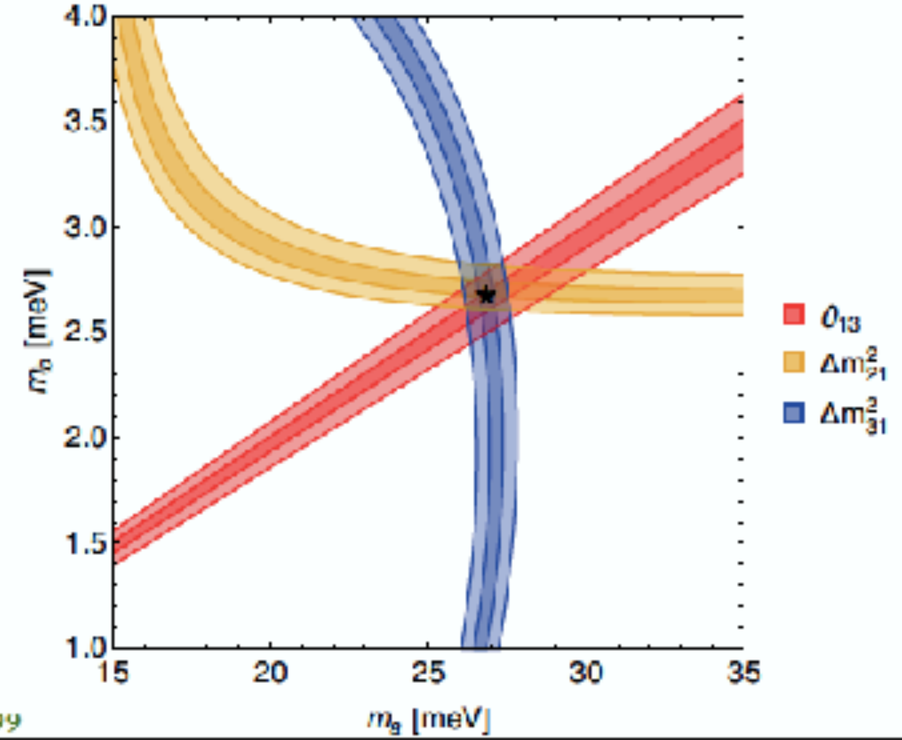
  - FLASY2018: King's talk (k=-3)

SFK 1304.6264

The Littlest Seesaw

Google → ↓ 1512.07531

$$m_\nu = m_a \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 1 \\ 0 & 1 & 1 \end{pmatrix} + m_b \begin{pmatrix} 1 & 3 & 1 \\ 3 & 9 & 3 \\ 1 & 3 & 1 \end{pmatrix} e^{i2\pi/3}$$



Ballett, SFK, Pascoli, Prouse, Wang 1612.01999

m_a (meV)	m_b (meV)	η (rad)	θ_{12} (°)	θ_{13} (°)	θ_{23} (°)	δ_{CP} (°)	m_1 (meV)	m_2 (meV)	m_3 (meV)
26.57	2.684	$\frac{2\pi}{3}$	34.3	8.67	45.8	86.7	0	8.59	49.8
Value	from	[25]	$33.48^{+0.78}_{-0.75}$	$8.50^{+0.20}_{-0.21}$	$42.3^{+3.0}_{-1.6}$	54^{+39}_{-70}	0	$8.66+0.10$	$49.57+0.47$

2 input parameters

Predicts:

3 neutrino masses,
3 mixing angles,
1 Dirac CP phase,
2 Majorana phases
= *9 observables*

Currently measured 5 observables

Very predictive!

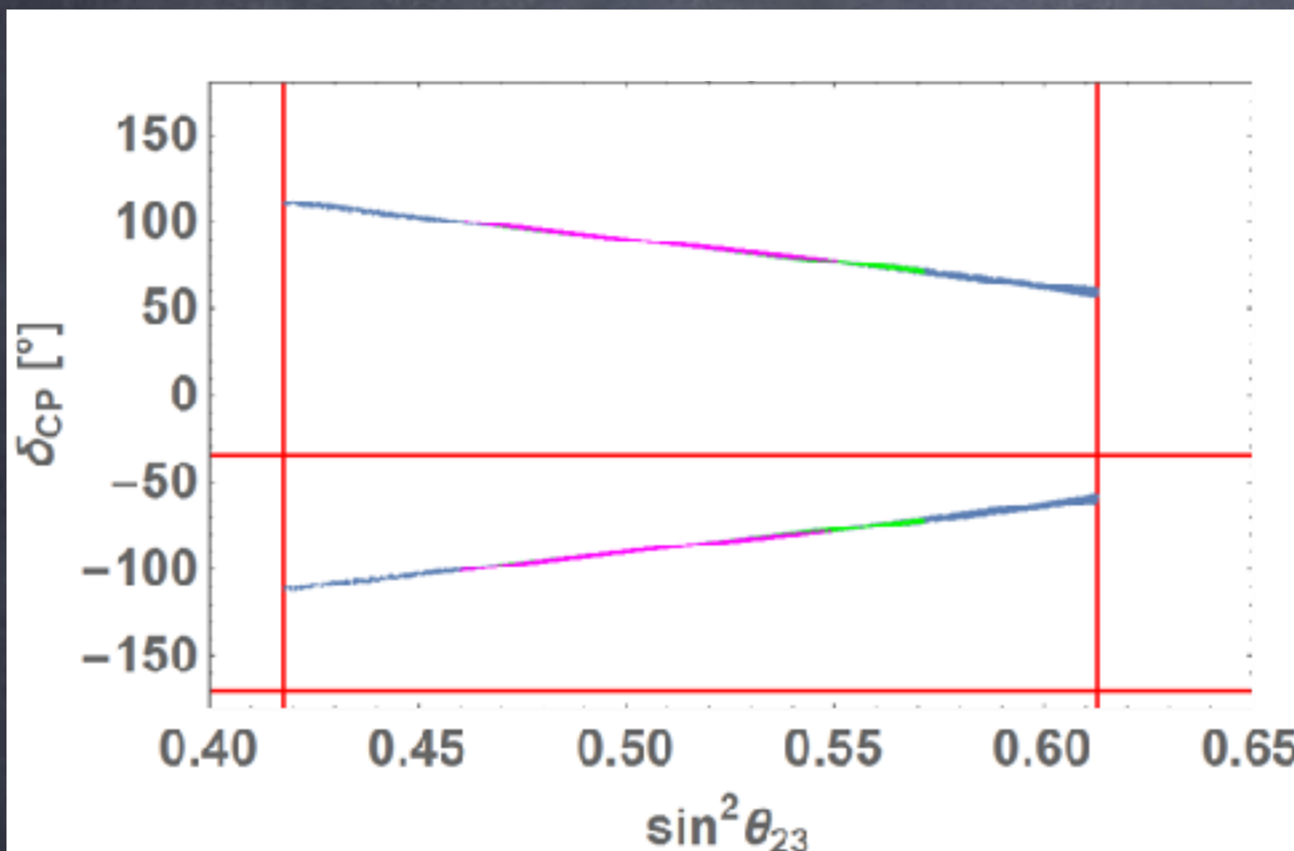
e.g. max. atm & max. CPV due to approx. mu-tau sym SFK, Nishi 1807.00023

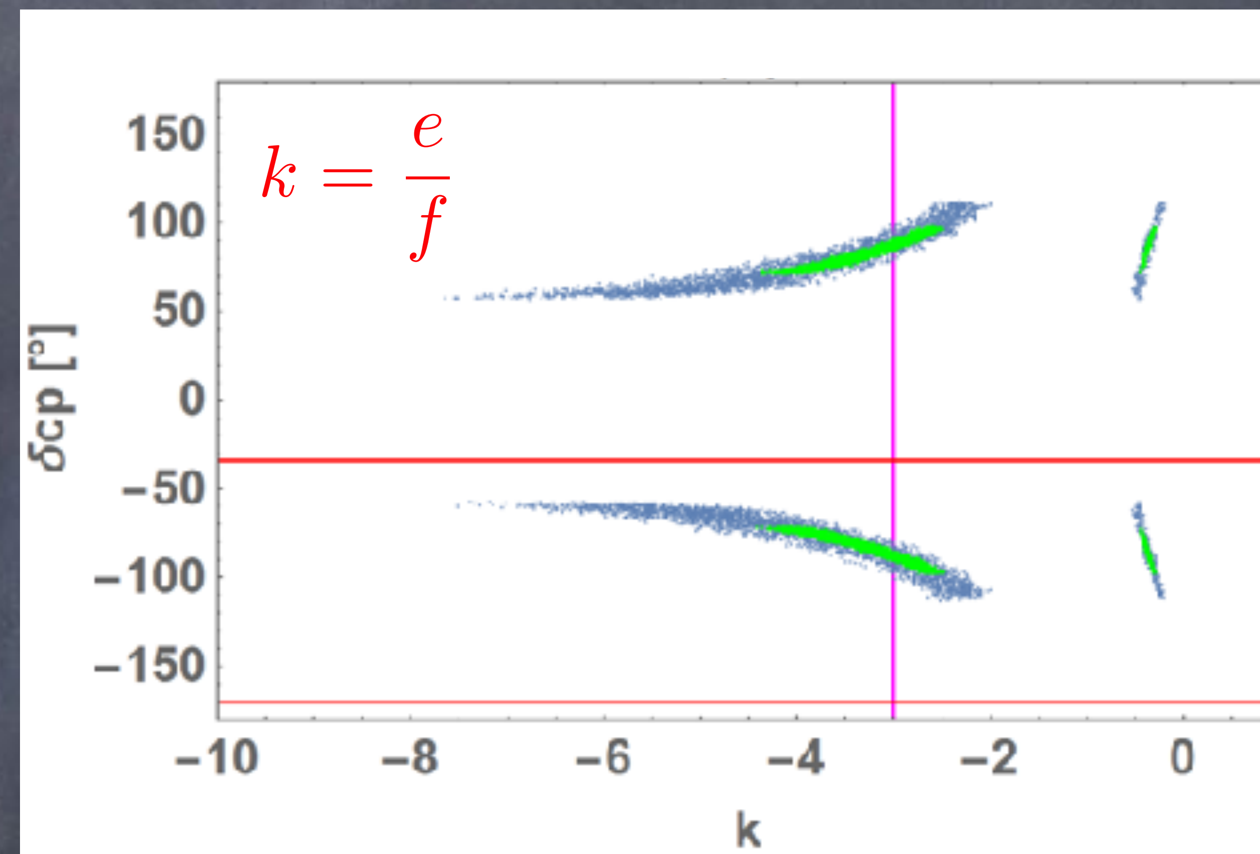
Good agreement!

- We present a minimal model of the NH case for neutrino masses

Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - Numerical analyses:





blue: 3σ green: 1σ purple: mode of King et. al. (k=-3)

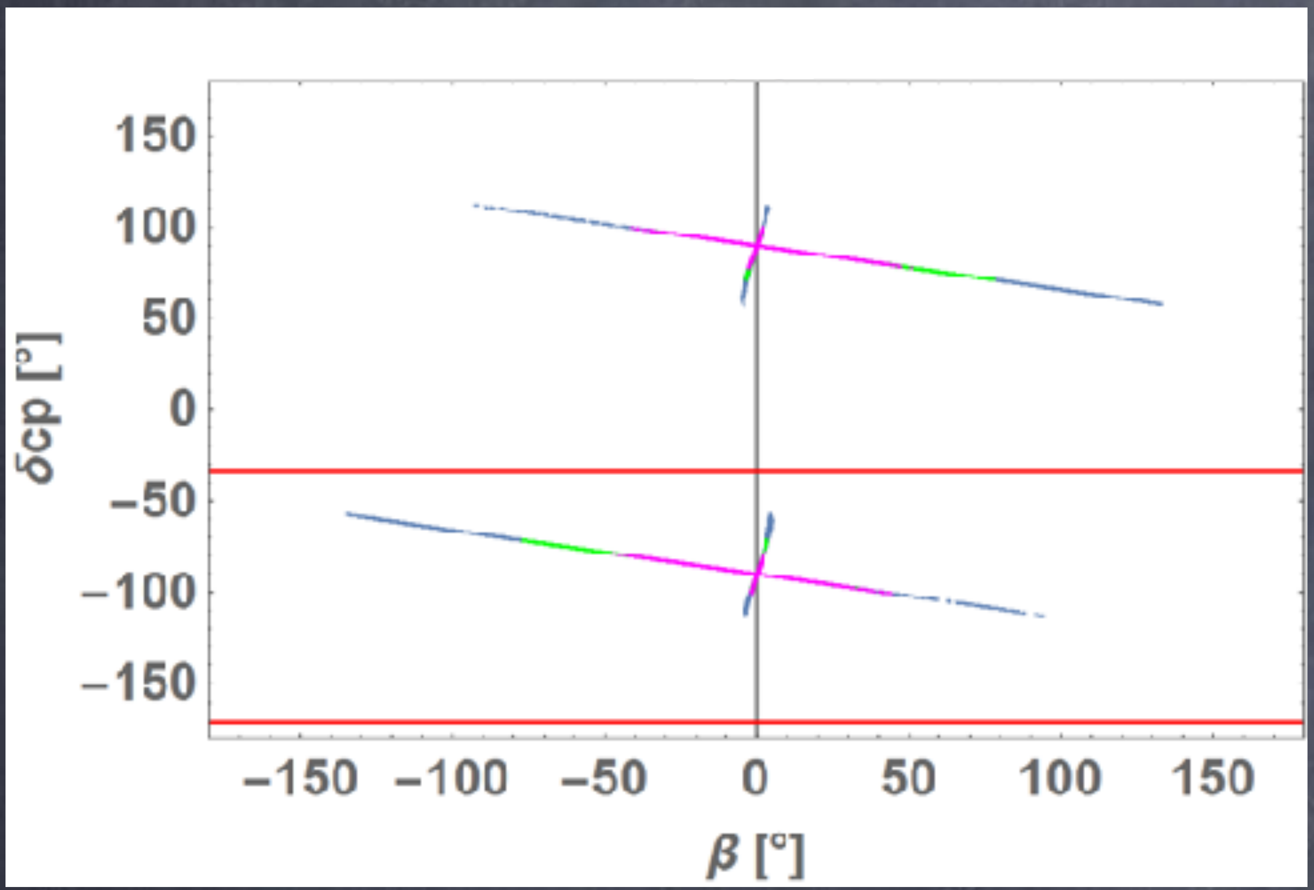
vertical red line: 3σ horizontal red line: 2σ (T2K experiment)

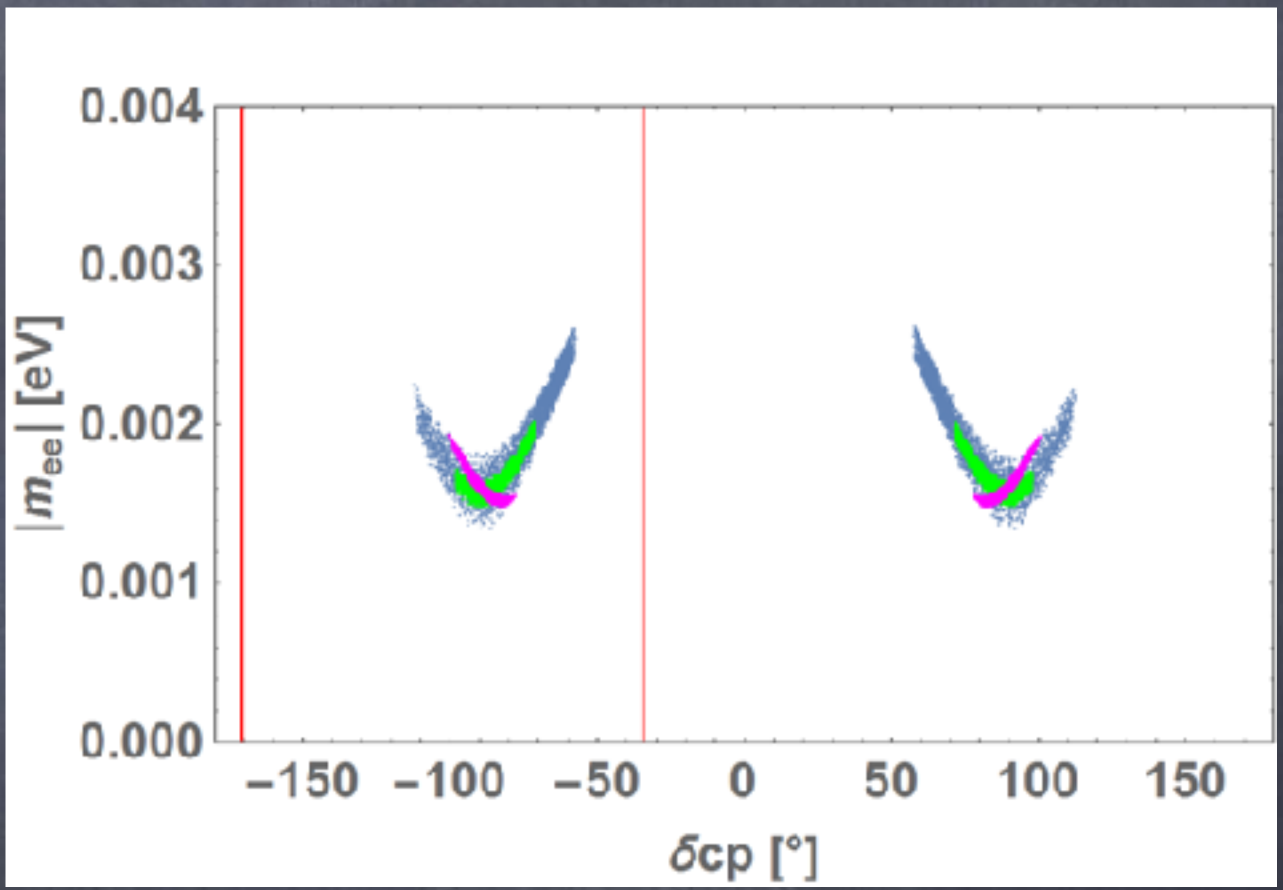
$\delta_{CP} \simeq \pm\frac{\pi}{2}$ ➡ sign cannot be fixed ➡ leptogenesis

- We present a minimal model of the NH case for neutrino masses

Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - Numerical analyses:





blue: 3σ green: 1σ purple: mode of King et. al. (k=-3)

red line: 2σ (T2K experiment)

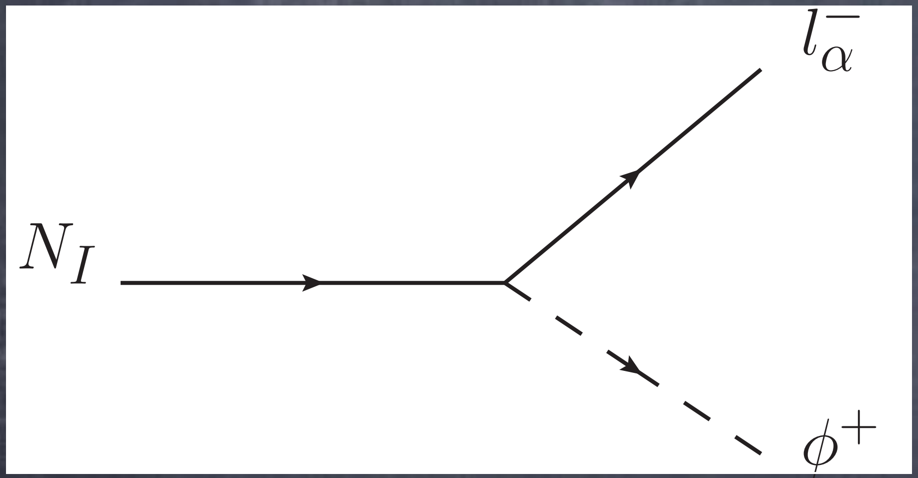
Dirac phase and Majorana phase are related each other because there is only 1 phase in our model

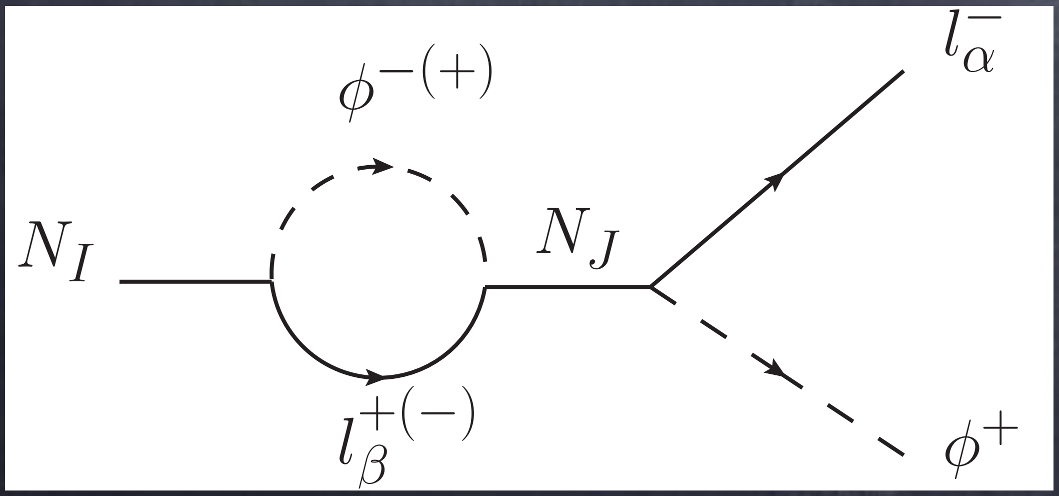
- CP violation and leptogenesis
  - Lagrangian including right-handed Majorana neutrinos

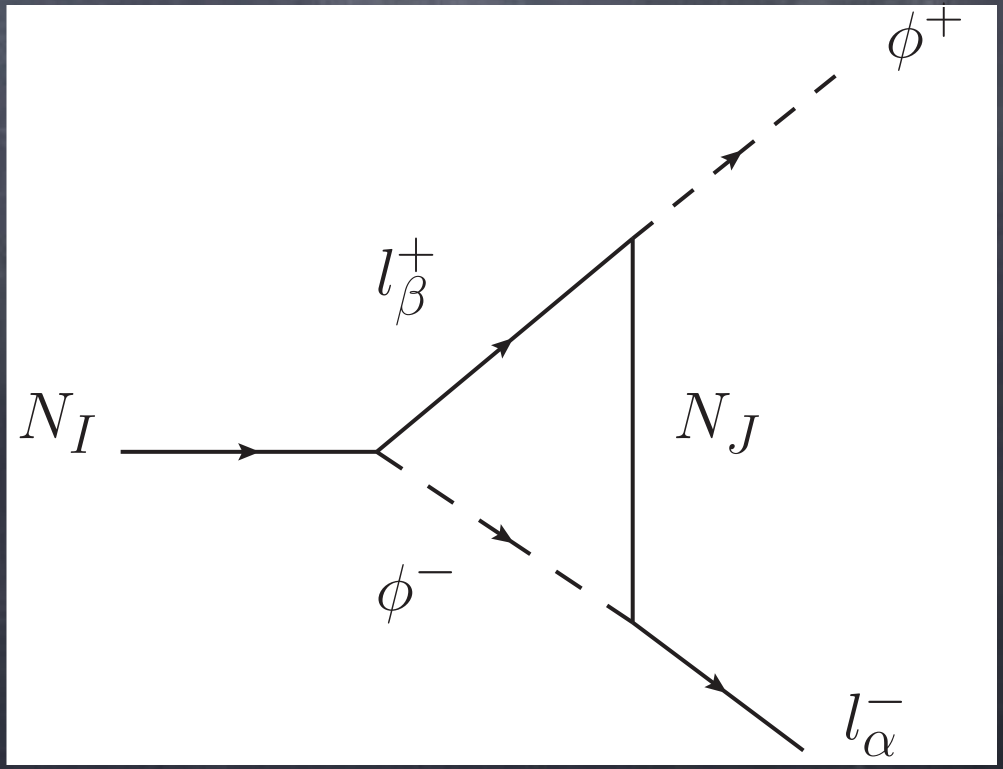
$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_I\gamma^\mu\partial_\mu N_I - \left((Y_\nu)_{\alpha I}\bar{L}_\alpha\tilde{H}N_I + \frac{M_I}{2}\bar{N}_I^c N_I + h.c.\right)$$

  - Decays of the right-handed Majorana neutrinos

$$L_\alpha = \begin{pmatrix} \nu_\alpha \\ l_\alpha^- \end{pmatrix}, \quad H = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}, \quad \tilde{H} = i\tau_2 H = \begin{pmatrix} \phi^{0*} \\ -\phi^- \end{pmatrix}$$





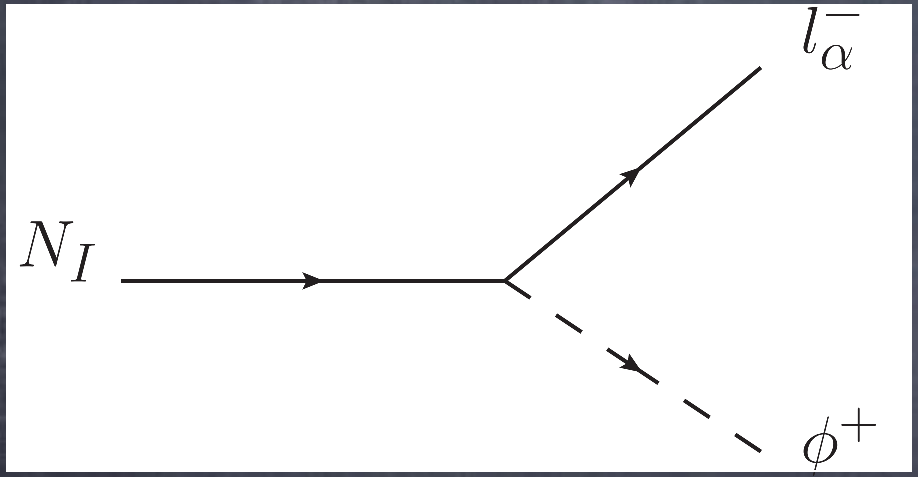


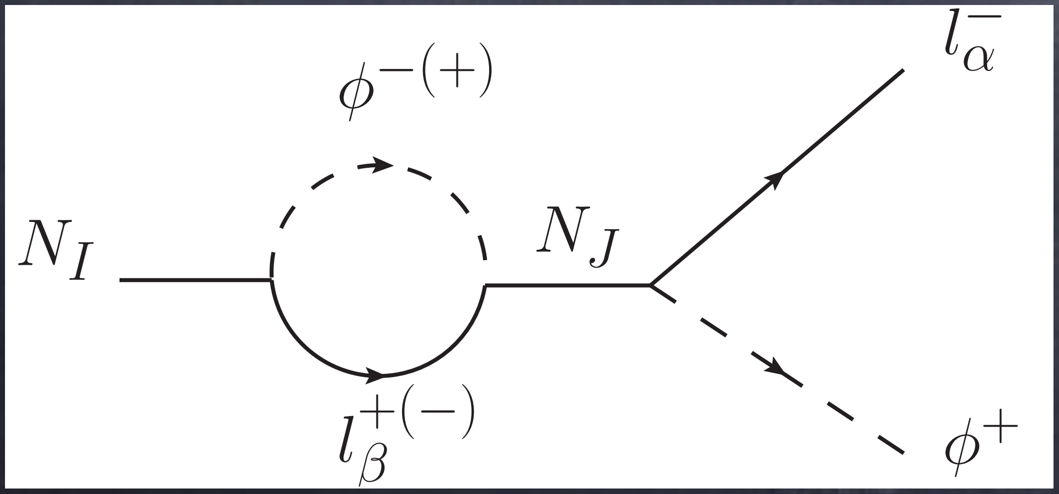
- CP violation and leptogenesis

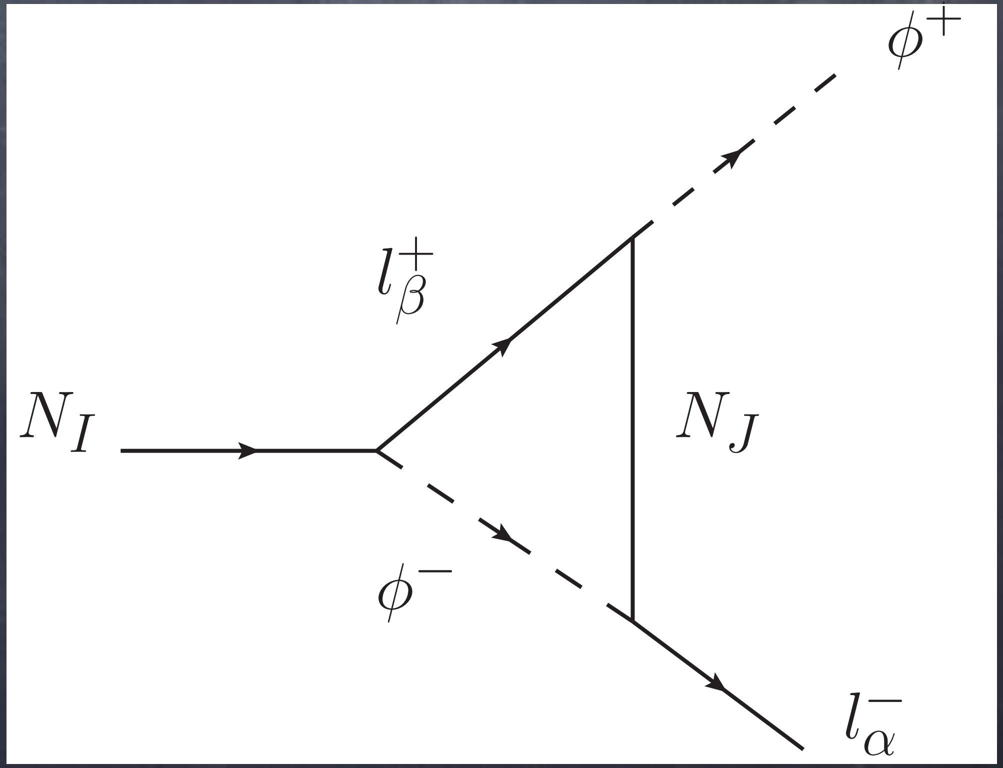
  - CP Asymmetry: $$\epsilon_1 = \frac{\Gamma(N_1 \to HL) - \Gamma(N_1 \to \bar{H}\bar{L})}{\Gamma(N_1 \to HL) + \Gamma(N_1 \to \bar{H}\bar{L})}$$

$$= \frac{1}{8\pi} \sum_{i=2,3} \frac{\mathrm{Im}\left[(Y_\nu^\dagger Y_\nu)^2_{i1}\right]}{(Y_\nu^\dagger Y_\nu)_{11}} f\left(\frac{M_i^2}{M_1^2}\right)$$

$$f(x) = \sqrt{x}\left[\frac{x-2}{x-1} - (1+x)\ln\left(\frac{1+x}{x}\right)\right]$$







- CP violation and leptogenesis
  - Baryon asymmetry of the universe:

$$\eta_B \equiv \frac{n_B}{n_\gamma} = 7.04 \times \frac{28}{79} Y_{B-L}$$

$$Y_{B-L} = -\epsilon_1 \kappa Y_{N_1}^{\mathrm{eq}} \qquad g^* = 106.75 \ (\mathrm{SM}) \qquad Y_{N_1}^{\mathrm{eq}} = \frac{135\zeta(3)}{4\pi g^*}$$

κ : suppression factor

G. F. Giudice, A. Notari, M. Raidal, A. Riotto and A. Strumia, Nucl. Phys. B685 (2004) 89

$$\frac{1}{\kappa} \simeq \frac{3.3 \times 10^{-3}}{\tilde{m}_1} + \left(\frac{\tilde{m}_1}{5.5 \times 10^{-4} \mathrm{eV}} \right)^{1.16}, \qquad \tilde{m}_1 = \frac{v^2}{M_1} (Y_\nu^\dagger Y_\nu)_{11}$$

- CP violation and leptogenesis
  - Baryon asymmetry of the universe:

$$\epsilon_1 \simeq -\frac{3}{16\pi}\frac{\mathrm{Im}[\{(Y_\nu^\dagger Y_\nu)_{21}\}^2]}{(Y_\nu^\dagger Y_\nu)_{11}}\frac{M_1}{M_2}$$

$$\frac{\mathrm{Im}[\{(Y_\nu^\dagger Y_\nu)_{21}\}^2]}{(Y_\nu^\dagger Y_\nu)_{11}} = \frac{1}{2}f^2(k-1)^2\sin 2\phi_B$$

$$J_{CP} = \frac{3}{8}\frac{f^{12}}{(M_1M_2)^3}B^6(1-k^2)(k+1)^4\sin 2\phi_B\frac{v^{12}}{(\Delta m_{13}^2-\Delta m_{12}^2)\Delta m_{13}^2\Delta m_{12}^2}$$

$$\sin\delta_{CP} = \frac{J_{CP}}{s_{23}c_{23}s_{12}c_{12}s_{13}c_{13}^2}, \quad J_{CP} = \mathrm{Im}\left[U_{e1}U_{\mu 2}U_{\mu 2}^*U_{\mu 1}^*\right]$$

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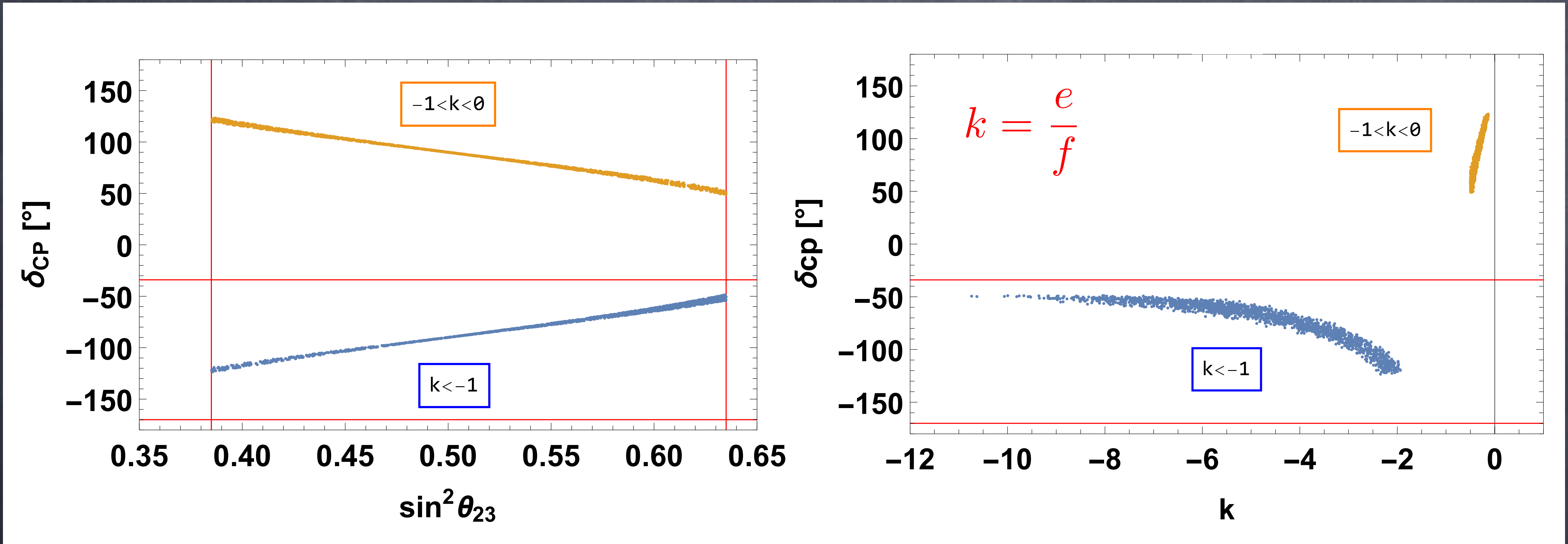
- We present a minimal model of the NH case for neutrino masses

Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - Numerical analyses: $\eta_B = (5.8 - 6.6) \times 10^{-10}$ (95% C.L.), $M_2 = 10^{14}$ GeV



blue: k<-1 orange: -1<k<0

vertical red line: 3 σ horizontal red line: 2 σ (T2K experiment)

k<-1: $\delta_{CP} \sim -\frac{\pi}{2}$ ➡ sign is fixed

3. Summary

- We presented the minimal model of the NH case for neutrino masses

  - We introduced two right-handed Majorana neutrinos

  - S_4 symmetry

$$M_D = vY_\nu = v\begin{pmatrix} 0 & \frac{e+f}{2} \\ b & e \\ -b & f \end{pmatrix}$$

  - CP phase is predicted because of 3 real and 1 phase parameters

  - The sign of CP phase for PMNS matrix is fixed by considering the baryon asymmetry of the universe through leptogenesis

Buck Up

- Neutrino oscillation and lepton mixing

- Eigenvalues of neutrino for flavors and masses, time evolution

$$|\nu_\alpha\rangle = \sum_i U_{\alpha j}|\nu_j\rangle, \quad |\nu_\alpha(t)\rangle = \sum_i U_{\alpha j}|\nu_j\rangle e^{-iE_j t}$$

- 2 generation case (mixing angle: θ)

$$|\nu_e(t)\rangle = \cos\theta|\nu_1\rangle e^{-iE_1 t} + \sin\theta|\nu_2\rangle e^{-iE_2 t}$$
$$|\nu_\mu(t)\rangle = -\sin\theta|\nu_1\rangle e^{-iE_1 t} + \cos\theta|\nu_2\rangle e^{-iE_2 t}$$

- Transition probability for $\nu_e \to \nu_\mu$

$$P(\nu_e \to \nu_\mu; t) = |\langle\nu_\mu|\nu_e(t)\rangle|^2 = \sin^2 2\theta \sin^2 \frac{E_2 - E_1}{2} t$$
$$\simeq \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E}, \quad \Delta m^2 = m_2^2 - m_1^2$$
$$E_j = \sqrt{p^2 + m_j^2} \simeq p + \frac{m_j^2}{2E}$$

- We investigate a minimal model of the NH case for neutrino masses

  Y. S., K. Takagi and M. Tanimoto, JHEP 1711 (2017) 201; Phys. Lett. B778 (2018) 6.

  - After rotating tri-bimaximal (TBM) mixing matrix

$$\hat{M}_\nu \equiv V_{\rm TBM}^T M_\nu V_{\rm TBM} = -\frac{v^2}{M_0}\begin{pmatrix} \frac{A_\nu^2 p + D_\nu^2}{6} & \frac{A_\nu B_\nu p + D_\nu E_\nu}{3\sqrt{2}} & \frac{A_\nu C_\nu p + D_\nu F_\nu}{2\sqrt{3}} \\ \frac{A_\nu B_\nu p + D_\nu E_\nu}{3\sqrt{2}} & \frac{B_\nu^2 p + E_\nu^2}{3} & \frac{B_\nu C_\nu p + E_\nu F_\nu}{\sqrt{6}} \\ \frac{A_\nu C_\nu p + D_\nu F_\nu}{2\sqrt{3}} & \frac{B_\nu C_\nu p + E_\nu F_\nu}{\sqrt{6}} & \frac{C_\nu^2 p + F_\nu^2}{2} \end{pmatrix}$$

$$A_\nu \equiv 2a - b - c, \quad B_\nu \equiv a + b + c, \quad C_\nu \equiv c - b,$$
$$D_\nu \equiv 2d - e - f, \quad E_\nu \equiv d + e + f, \quad F_\nu \equiv f - e$$

$$V_{\rm TBM} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

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Conditions of (1,1), (1,2), (2,1), (1,3), (3,1) components to be zero:

$$A_\nu = 2a - b - c = 0, \quad D_\nu = 2d - e - f = 0$$

  - Neutrino mass matrix

$$\hat{M}_\nu = -\frac{v^2}{M_0}\begin{pmatrix} 0 & 0 & 0 \\ 0 & \frac{3}{4}\left((b+c)^2 p + (e+f)^2\right) & \frac{1}{2}\sqrt{\frac{3}{2}}\left((c^2-b^2)p - e^2 + f^2\right) \\ 0 & \frac{1}{2}\sqrt{\frac{3}{2}}\left((c^2-b^2)p - e^2 + f^2\right) & \frac{1}{2}\left((b-c)^2 p + (e-f)^2\right) \end{pmatrix}$$

  - The lightest neutrino mass m_1 is zero

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  - Neutrino mass matrix $\hat{M}_\nu$ is diagonalized by

$$V_{23} = \frac{1}{\mathcal{A}} \begin{pmatrix} \mathcal{A} & 0 & 0 \\ 0 & 1 & \mathcal{V} \\ 0 & -\mathcal{V}^* & 1 \end{pmatrix}, \quad \mathcal{A} = \sqrt{1 + |\mathcal{V}|^2}$$

$\mathcal{V}$ is in terms of the model parameters b, c, e, f, p

  - PMNS matrix: $U_{\rm PMNS} = V_{\rm TBM} V_{23}$

$$V_{\rm TBM} = \begin{pmatrix} \frac{2}{\sqrt{6}} & \frac{1}{\sqrt{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & -\frac{1}{\sqrt{2}} \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{3}} & \frac{1}{\sqrt{2}} \end{pmatrix}$$

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  - Lepton mixing angles

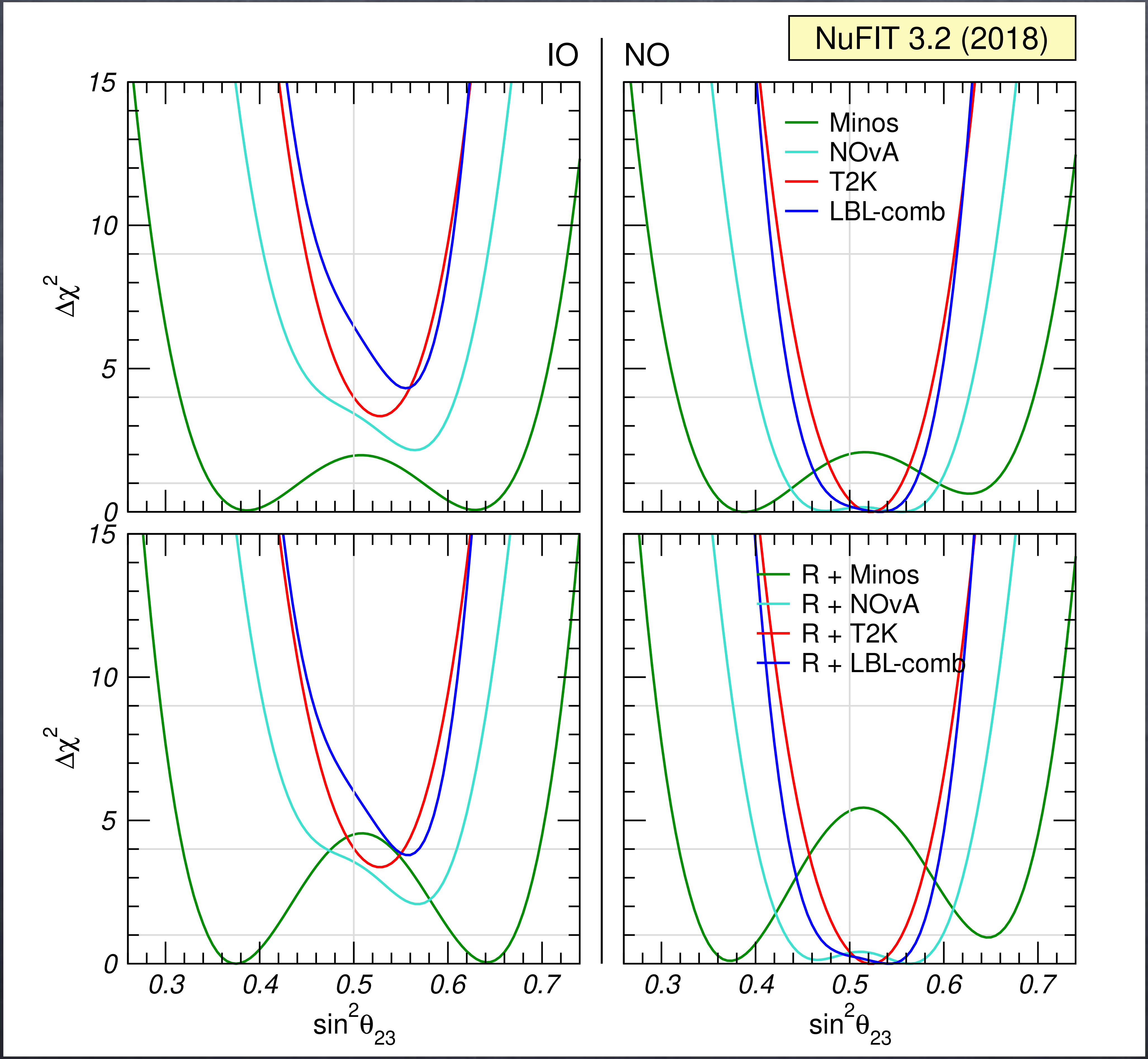
$$s_{12}^2 \equiv \sin^2\theta_{12} = \frac{|U_{e2}|^2}{1-|U_{e3}|^2}\,, \quad s_{23}^2 \equiv \sin^2\theta_{23} = \frac{|U_{\mu 3}|^2}{1-|U_{e3}|^2}\,, \quad s_{13}^2 \equiv \sin^2\theta_{13} = |U_{e3}|^2$$

  - Jarlskog invariant parameter

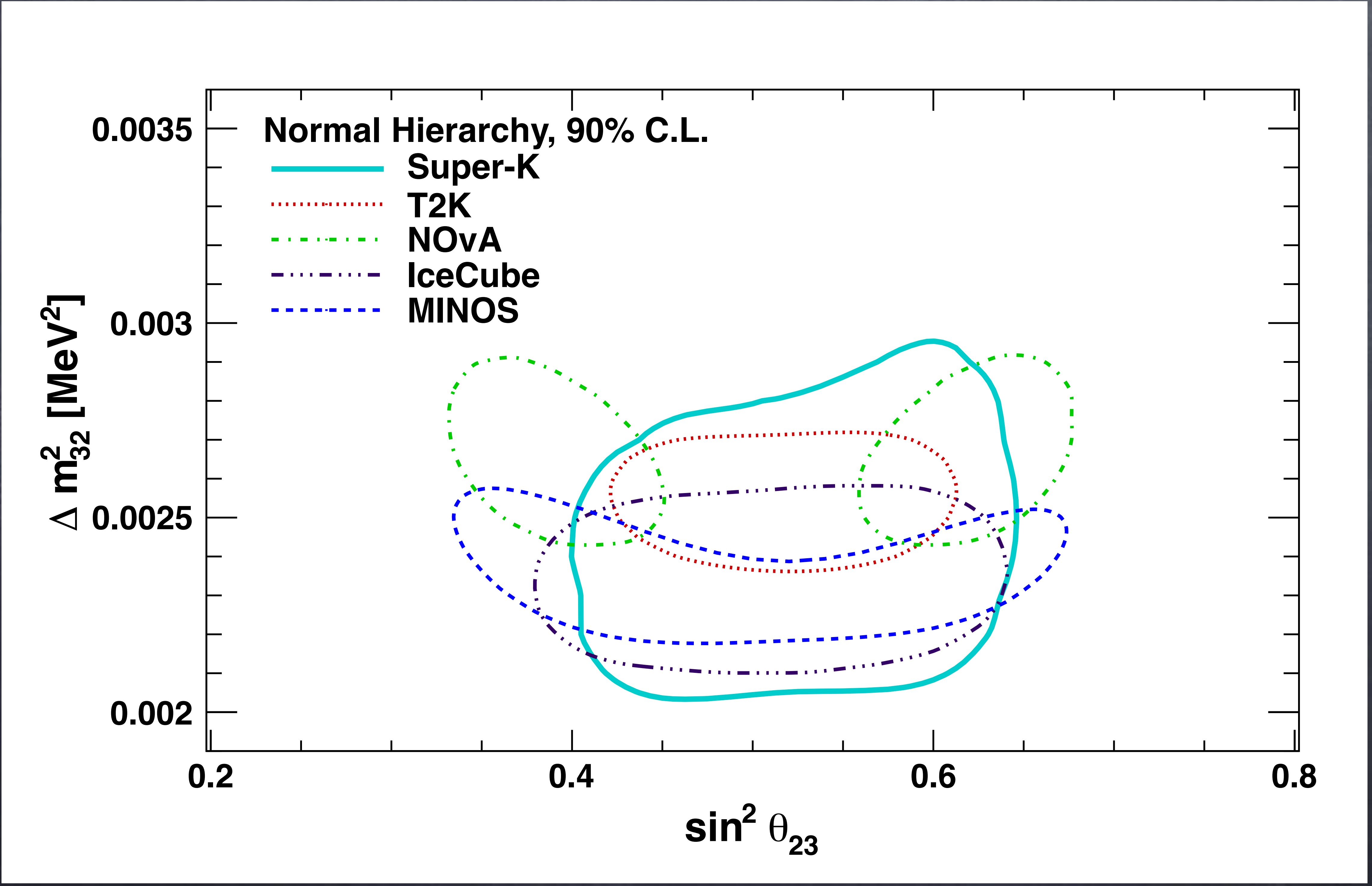
$$\sin\delta_{CP} = \frac{J_{CP}}{s_{23}c_{23}s_{12}c_{12}s_{13}c_{13}^2}, \quad J_{CP} = \mathrm{Im}\left[U_{e1}U_{\mu 2}U_{\mu 2}^{*}U_{\mu 1}^{*}\right]$$

  - Effective mass for Neutrino less double beta decay

$$|m_{ee}| = \left|m_1 U_{e1}^2 + m_2 U_{e2}^2 + m_3 U_{e3}^2\right|$$


NuFIT 3.2 (2018)
IO
NO
Minos
NOvA
T2K
LBL-comb
R + Minos
R + NOvA
R + T2K
R + LBL-comb
Δχ²
sin²θ₂₃
0
5
10
15
0.3
0.4
0.5
0.6
0.7

- Neutrino 2018: SK experiment



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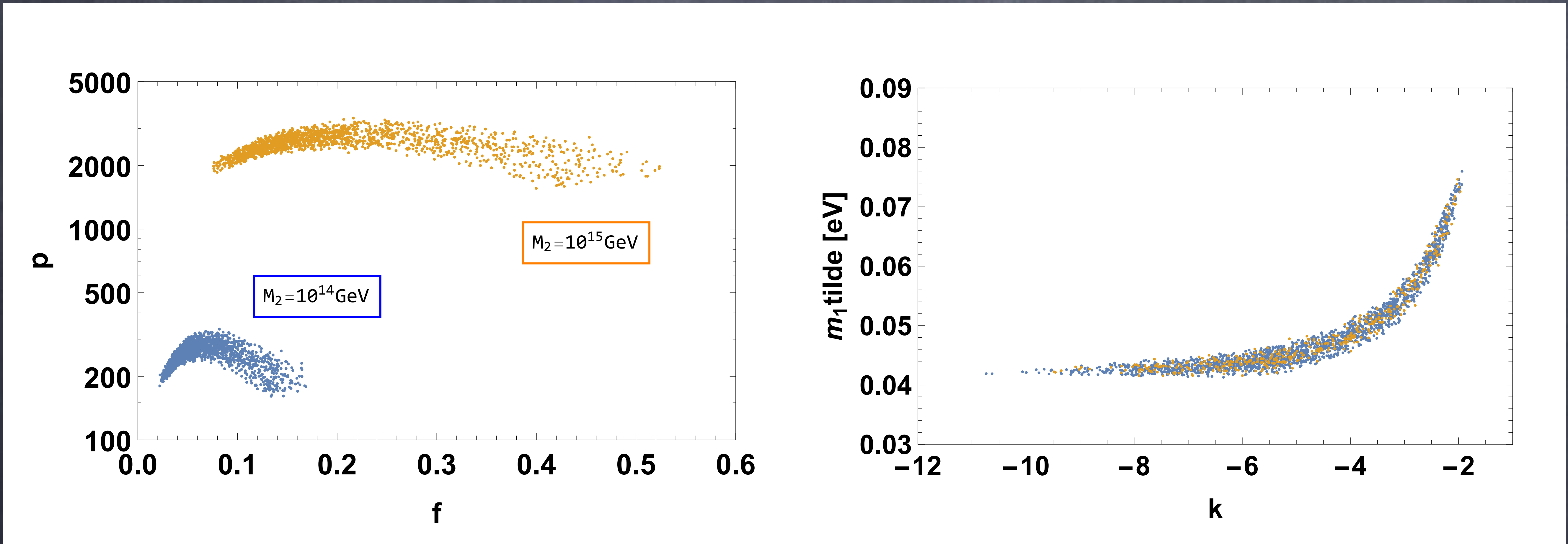
  - Numerical analyses:



blue: $M_2 = 10^{14}$ GeV   orange: $M_2 = 10^{15}$ GeV