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Collider Searches of Heavy Neutrinos to Test Neutrino Mass Orderings

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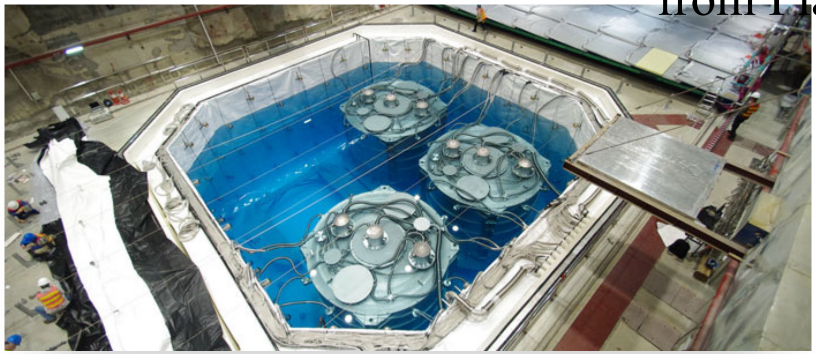
based on 2601.10311 with Supriya Senapati, Jin Sun

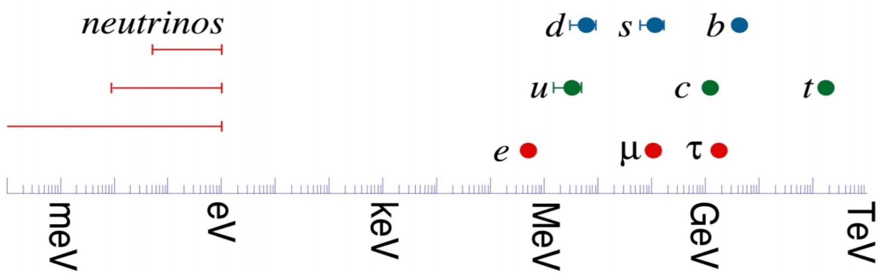
Accepted by PRD

Neutrino Mass Problem

$$\sum m_{\nu} \lesssim 0.12\ eV$$

from Planck satellite





Seesaw mechanism

$$L \supset -y_D \overline{l_L} \widetilde{H} \nu_R - M_R \overline{\nu_R{}^c} \nu_R$$
$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$
$$m_1 \approx \frac{-M_D^2}{M_R}, m_2 \approx M_R.$$

The lightness of the observed neutrinos is explained by heavy right-handed neutrinos,

Testing Neutrino Masses Ordering at Colliders?

- Collider can probe Neutrino Mass Origin
- Can we probe Mass Ordering?

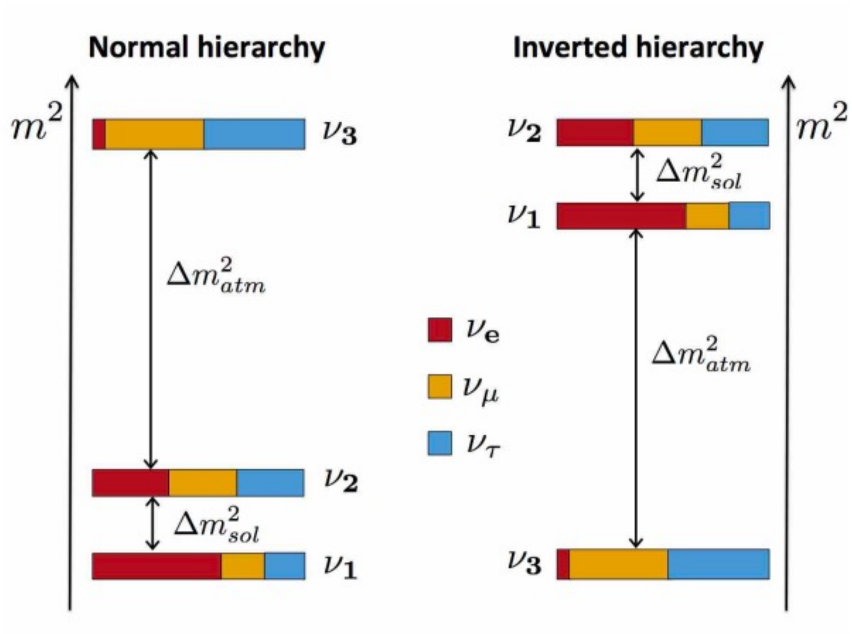
- Two Neutrino mass ordering

- Normal hierachy

$$m_3 \gg m_2, m_1 = 0$$

- Inverted hierachy

$$m_1 \approx m_2, m_3 = 0$$



Flavor Mixing of RHN

- **Casas-Ibarra**

$$Y = \frac{i}{\langle \Phi(0) \rangle} U^{PMNS} m_\nu^{1/2} \Omega m_N^{1/2},$$

- **NH and IH**

Assume two nearly degenerate RHNs

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \end{pmatrix} \quad \text{for NH,}$$

$$\Omega = \begin{pmatrix} \cos\omega & \sin\omega \\ -\xi\sin\omega & \xi\cos\omega \\ 0 & 0 \end{pmatrix} \quad \text{for IH,}$$

$$x_\omega \equiv e^{\mathrm{Im}\,\omega}$$

- **Active-sterile mixing**

$$\Theta_{\alpha I} \simeq \frac{vY_{\alpha I}}{M_I}.$$

$$\boldsymbol{m_N \approx M_{2,3}}$$

$$|U_\alpha|^2 \equiv \sum_{I=2,3} |\Theta_{I\alpha}|^2 = \frac{1}{2M}\left(|C_\alpha^+|^2 X_\omega^2 + |C_\alpha^-|^2 X_\omega^{-2} + \mathcal{O}\left(\frac{\Delta M}{M}\right)\right),$$

NH: $$C_\alpha^\pm = iU_{\alpha 2}^{PMNS}\sqrt{m_2} \pm \xi U_{\alpha 3}^{PMNS}\sqrt{m_3}$$

IH: $$C_\alpha^\pm = iU_{\alpha 1}^{PMNS}\sqrt{m_1} \pm \xi U_{\alpha 2}^{PMNS}\sqrt{m_2},$$

Flavor Mixing of RHN

- **PMNS Matrix**

$$U^{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}\mathrm{e}^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}\mathrm{e}^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}\mathrm{e}^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \mathrm{e}^{\frac{i\alpha_{21}}{2}} & 0 \\ 0 & 0 & \mathrm{e}^{\frac{i\alpha_{31}}{2}} \end{pmatrix},$$

Only one Majorana phase is free

$$|U^{PMNS}| \approx \begin{array}{cc} \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.35 & 0.58 & 0.73 \\ 0.44 & 0.60 & 0.67 \end{pmatrix} & \begin{array}{c} e3 \\ \mu 3 \\ \tau 3 \end{array} \end{array}$$

Flavor Mixing of RHN

- NH

  $m_3 \gg m_2, m_1 = 0$

$$|U_\alpha|^2 \equiv \sum_{I=2,3} |\Theta_{I\alpha}|^2 = \frac{1}{2M}\left(|C_\alpha^+|^2 X_\omega^2 + |C_\alpha^-|^2 X_\omega^{-2} + \mathcal{O}\left(\frac{\Delta M}{M}\right)\right),$$

NH: $C_\alpha^\pm = iU_{\alpha 2}^{PMNS}\sqrt{m_2} \pm \xi U_{\alpha 3}^{PMNS}\sqrt{m_3}$

$C_e^\pm \approx U_{e3}^{PMNS}\sqrt{m_3}$

$C_{\mu,\tau}^\pm \approx U_{\mu,\tau 3}^{PMNS}\sqrt{m_3}$

$|U_{e3}^{PMNS}| < |U_{\mu,\tau 3}^{PMNS}|$, δ and α_{ij} are free

- $U_{eN}^2 \ll U_{\mu,\tau N}^2$
- $U_{eN}^2 / U_{tot}^2 \approx [0.003, 0.14]$, range from phase cancellation of $\sqrt{m_2}$ term
- $U_{\mu,\tau N}^2 / U_{tot}^2 \approx [0.11(09), 0.88(0.86)]$

Flavor Mixing of RHN

- IH

$$m_1 \approx m_2, m_3 = 0$$

$$|U_\alpha|^2 \equiv \sum_{I=2,3} |\Theta_{I\alpha}|^2 = \frac{1}{2M}\left(|C_\alpha^+|^2 X_\omega^2 + |C_\alpha^-|^2 X_\omega^{-2} + \mathcal{O}\left(\frac{\Delta M}{M}\right)\right),$$

IH: $$C_\alpha^\pm = iU_{\alpha 1}^{PMNS}\sqrt{m_1} \pm \xi U_{\alpha 2}^{PMNS}\sqrt{m_2},$$

$$C_e^\pm \approx U_{e1}^{PMNS}\sqrt{m_1} + U_{e2}^{PMNS}\sqrt{m_2}$$
$$C_{\mu,\tau}^\pm \approx U_{\mu,\tau 1}^{PMNS}\sqrt{m_1} + U_{\mu,\tau 2}^{PMNS}\sqrt{m_2}$$

$|U_{e1}^{PMNS}|$ is the largest

- $U_{eN}^2 / U_{tot}^2 \approx [0.021, 0.96]$, $\sqrt{m_{1,2}}$ term can cancel totally
- $U_{\mu N}^2 / U_{tot}^2 \approx [0, 0.57]$
- $U_{\tau N}^2 / U_{tot}^2 \approx [0, 0.61]$

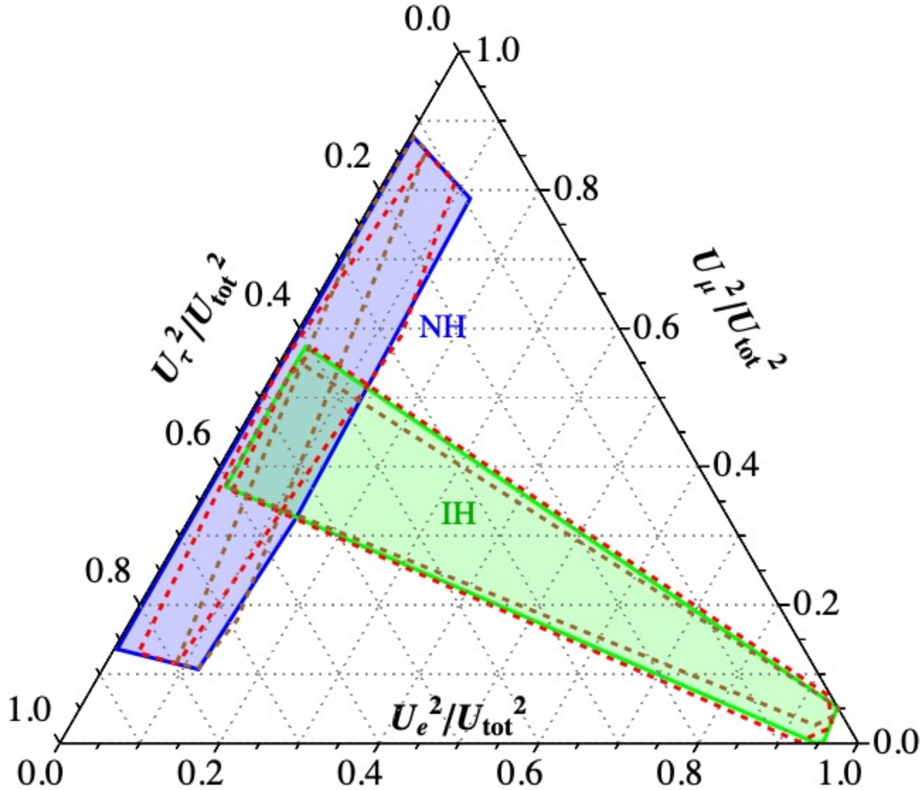
Flavor Mixing of RHN

- NH/IH RHNs have different flavor mixing pattern

NH: $U^2_{eN} \ll U^2_{\mu,\tau N}$

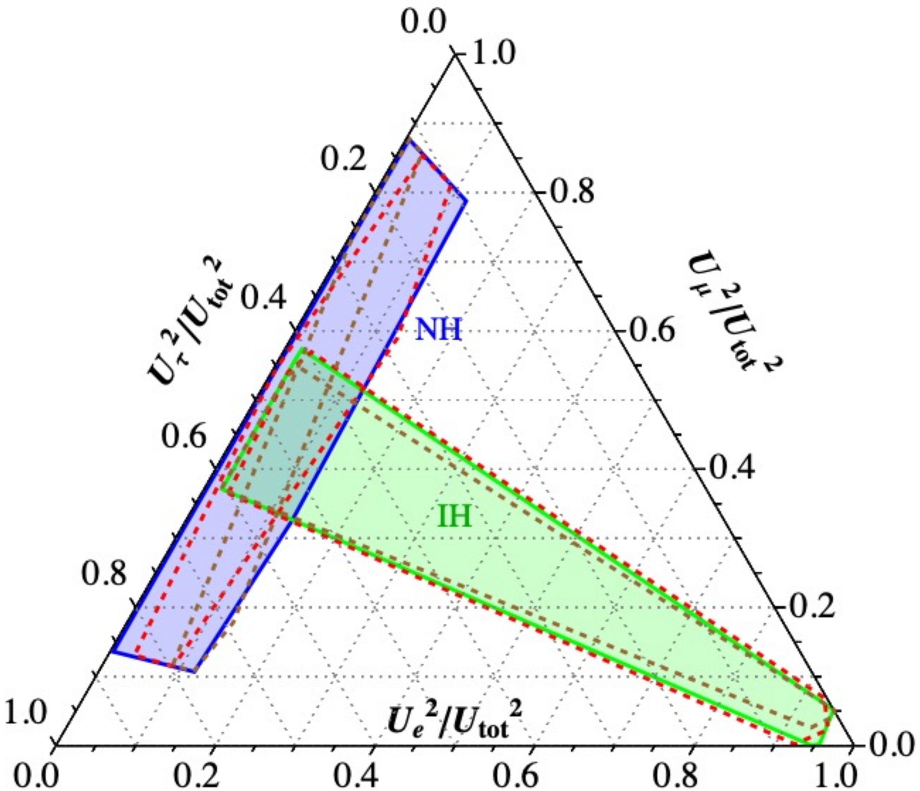
IH: $U^2_{e,\mu,\tau N}$ can be similar

- Independent of Mass and total mixing
- also See M. Drewes, Eur.Phys.J.C 82 (2022) 12, 1176



Flavor Mixing of RHN

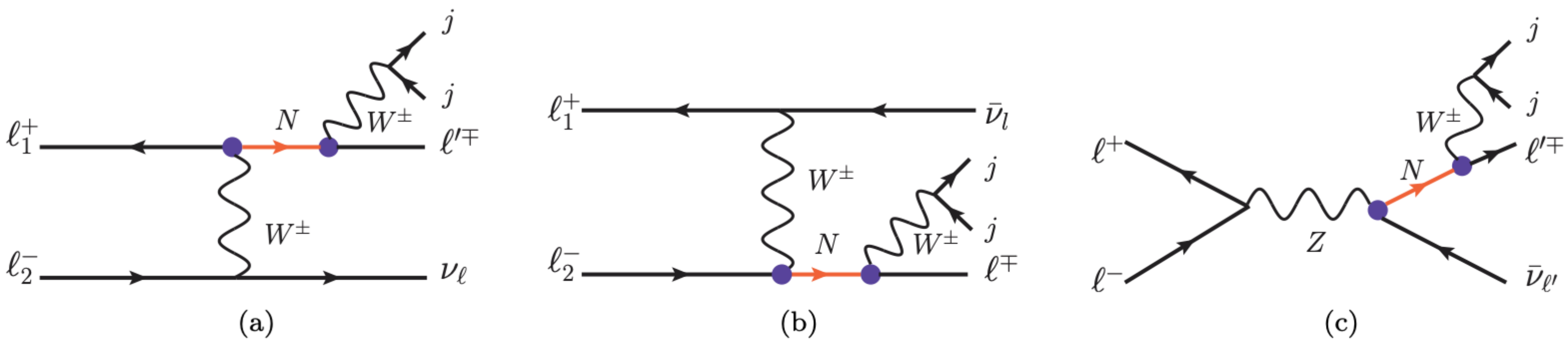
- **Narrow down from Dirac CP phase $\boldsymbol{\delta}$**
- **T2K center (Red): $\boldsymbol{\delta}$=-$\boldsymbol{\pi}/2$, assume ± 8 *degree***
- **Nova center (Brown): $\boldsymbol{\delta}$=148 Degree, assume ± 7 *degree***



- **Still a lot freedom in Majorana CP, $\boldsymbol{\delta + \alpha_{ij}}$**

Colliders Observables

- **Probing flavor mixing at lepton colliders, CEPC/FCC-ee**



- **Lepton flavor violation signatures**

However small cross section

- **Z decay dominanting**

$$e^+e^- \to N\nu\ (\bar{\nu}), \qquad N \to \ell_\alpha jj\,,$$

Colliders Observables

- **Map into Observables**

$$N_{S,\alpha} = \sigma(Z) \times \mathrm{Br}(Z \to N\nu\ (\bar{\nu})) \times \mathrm{Br}(N \to \ell_\alpha jj) \times \mathcal{L} \times \epsilon,$$

$$\mathrm{Br}(Z \to N\nu\ (\bar{\nu})) \propto U_{\mathrm{tot}}^2$$

$$\mathrm{Br}(N \to \ell_\alpha jj) \propto U_{\alpha N}^2 / U_{\mathrm{tot}}^2. \qquad R_\alpha \equiv U_{\alpha N}^2 / U_{\mathrm{tot}}^2$$

- **We can measure the flavor mixing to probe mass orderings**

$$N_{S,\alpha} \simeq \mathcal{O}(10^{11}) \times U_{\mathrm{tot}}^2 \times R_\alpha \equiv N_0 \times R_\alpha,$$

Statistical Analysis

- **Lepton Flavor final states can determine $\boldsymbol{R_{\alpha}^{obs}}$**
- **NH/IH predicted $\boldsymbol{R_{\alpha}^{NH/IH}}$**
- **We need large number of events to falsify NH/IH**
- χ^2 analysis is employed

$$\chi^2_{\mathrm{NH/IH}} = \sum_{\alpha=e,\mu} \frac{\left[N_0\left(R_{\alpha}^{\mathrm{obs}} - R_{\alpha}^{\mathrm{NH/IH}}\right)\right]^2}{N_0 R_{\alpha}^{\mathrm{NH/IH}} + N_{B,\alpha}},$$

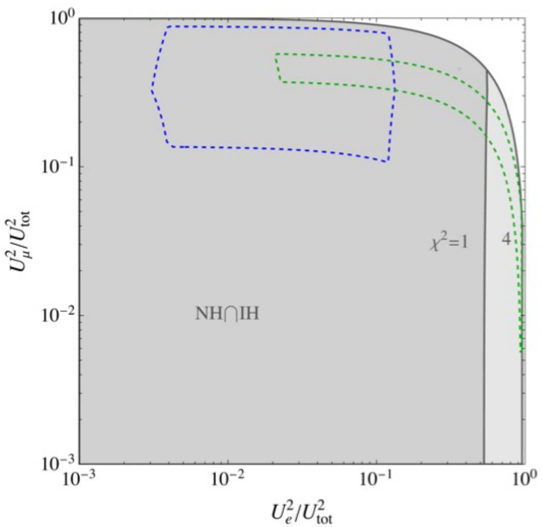
- The smallest χ^2 is taken to tell whether **NH/IH is disfavored**

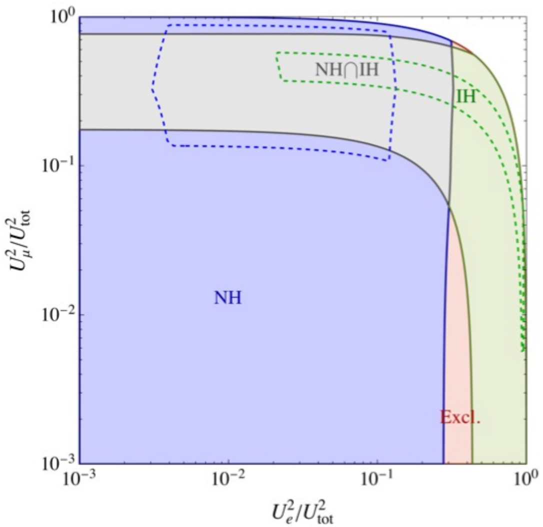
Test Mass Ordering

- **Color Scheme**

Region	Color	$\min(\chi^2_{NH})$	$\min(\chi^2_{IH})$
NH Favor	Blue	< 4	> 4
IH Favor	Green	> 4	< 4
NH $\cap$ IH Favor	Gray	< 4	< 4
Excluded	Red	> 4	> 4

- $\boldsymbol{U^2_{tot}}$**=**$\boldsymbol{4\times10^{-9}}$**,** $\boldsymbol{m_N}$ **=50 GeV;** $\boldsymbol{U^2_{tot}}$**=**$\boldsymbol{10^{-8}}$**,** $\boldsymbol{m_N}$ **=50 GeV**





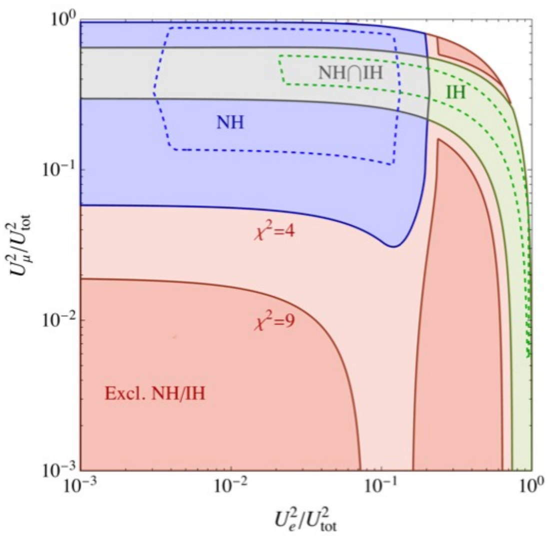
- **No test** **Only small fraction**

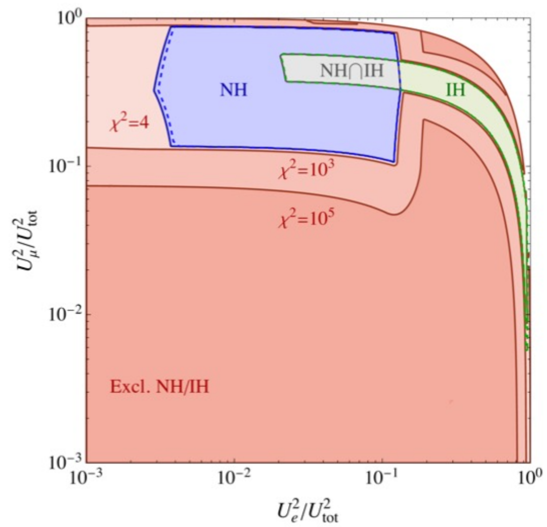
Test Mass Ordering

- **Color Scheme**

Region	Color	$\min(\chi^2_{NH})$	$\min(\chi^2_{IH})$
NH Favor	Blue	< 4	> 4
IH Favor	Green	> 4	< 4
NH $\cap$ IH Favor	Gray	< 4	< 4
Excluded	Red	> 4	> 4

- $\boldsymbol{U^2_{tot}=10^{-7}}$, $\boldsymbol{M_N}$ **=50 GeV;** $\boldsymbol{U^2_{tot}=10^{-5}}$, $\boldsymbol{M_N}$ **=50 GeV**





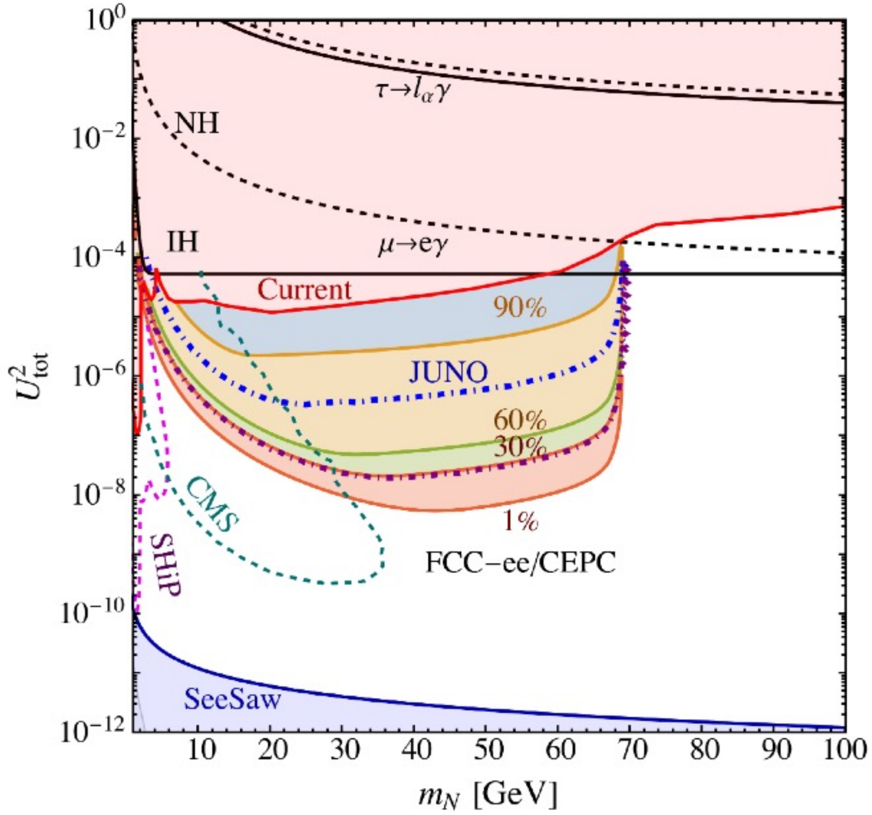
- **Half of parameter space can be identified; Nearly best to test NH/IH**

Test Mass Ordering

- **Quantify the distinguishability**
  The area in Log10 scale

$$K = 1 - \frac{S_{\mathrm{NH}\cap\mathrm{IH}}}{S_{\mathrm{tot}}} ,$$

- **Contours of K in of FCC-ee/CEPC**

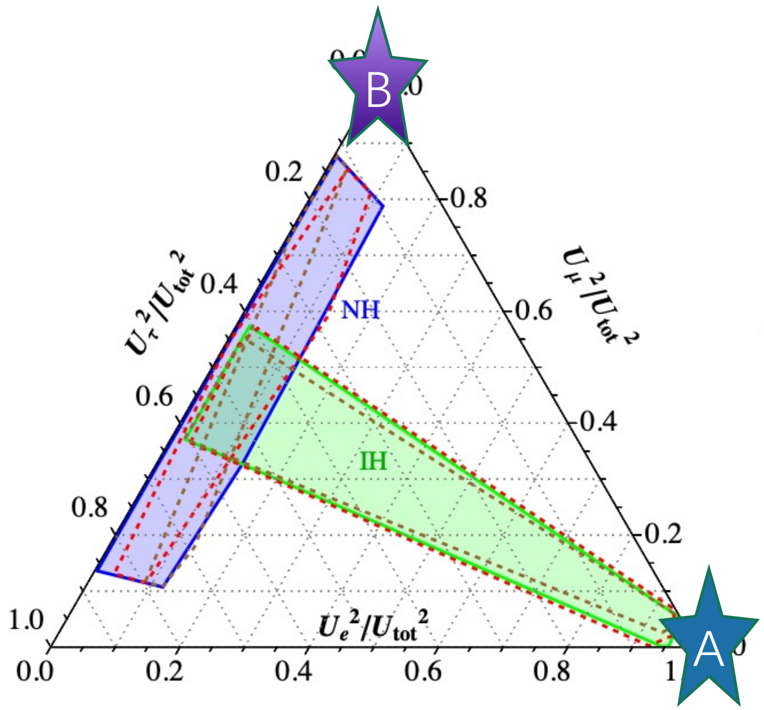


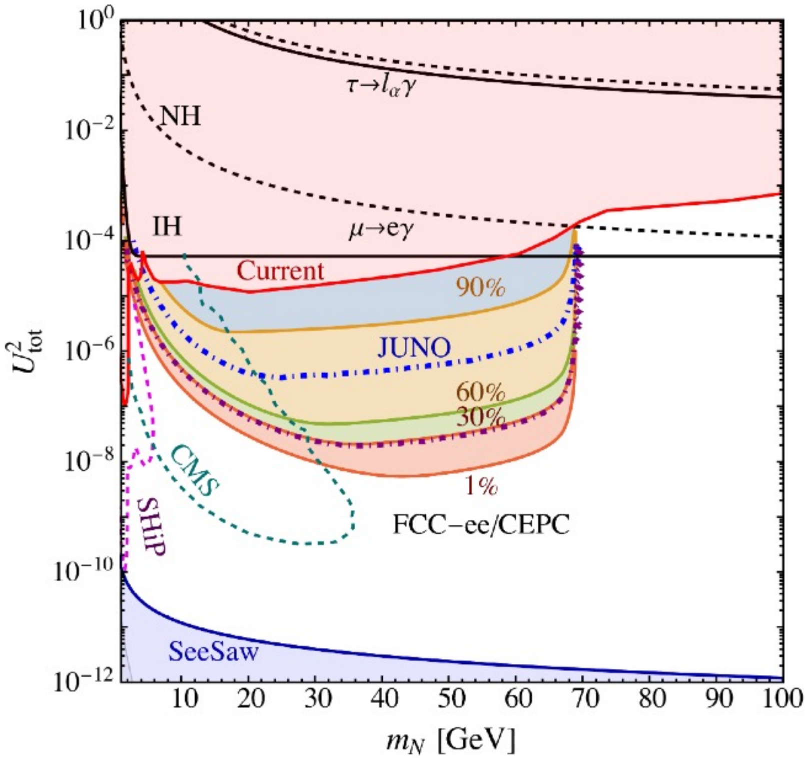
Synergy with JUNO

- **JUNO can determine mass orderings before colliders!**
- **It is still worth to perfrom such studies at Colliders**
- **Conflicts between the two means 3RHNs or NSI, See 2407.13620**

Scenario	JUNO	CEPC/FCC-ee
A	NH Favor	$R_e = (N_0 + N_{B,e})/(N_0 + \sum N_{B,\alpha})$
B	IH Favor	$R_\mu = (N_0 + N_{B,\mu})/(N_0 + \sum N_{B,\alpha})$

Blue, furthest from NH
Purple, furthest from IH





Conclusion

- Collider can test origin of the neutrino masses
- NH/IH mass orderings lead to different $U^2_{\alpha N}$ /U^2_{tot}
- We can test mass orderings by measuring the lepton final states of RHNs

- Flaws:
- We need to assume that RHNs can be produced at colliders
- JUNO can probe neutrino mass orderings before that

- Outlook:
- If JUNO and Colliders conflict, there can be 3 RHNs, instead of 2
- Collider searches of RHNs lepton final states, can help deterimine the CP phase $\delta + \alpha_{ij}$

Model Parameters

- **4 Free Parameters**
- **Mass of the RHNs $\mathbf{m_N}$, mass splitting (not considered)**

- **Total Active Sterile Mixing U^2_{tot}, controlled by Ω matrix**
- **Dirac/Majorana CP Phase δ, α_{ij}, control $U^2_{\alpha N}$ /U^2_{tot}**

- **Input Parameters**
  neutrino oscillation data into PMNS, small variation to $U^2_{\alpha N}$ /U^2_{tot}