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Testing Neutrino Mass Orderings at Colliders

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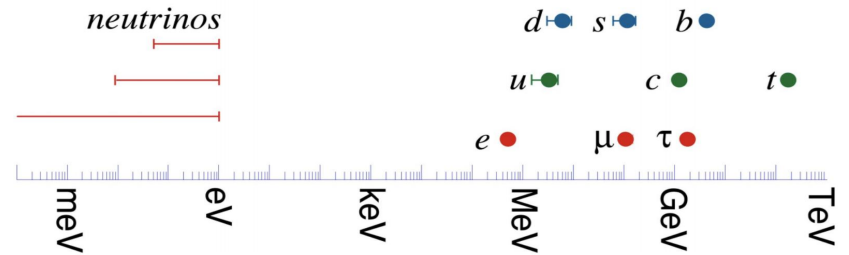
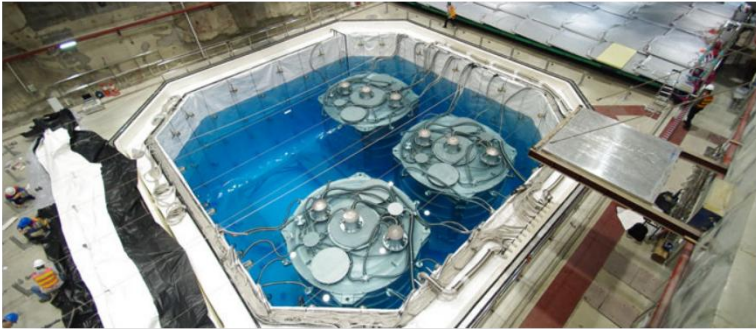
GUTPC 2026, Hangzhou, HIAS

based on 2601.10311 with Supriya Senapati, Jin Sun

Neutrino Mass Problem

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

from Planck satellite



Seesaw mechanism

$$L \supset -y_D \bar{l}_L \tilde{H} \nu_R - M_R \bar{\nu}_R c \nu_R$$

$$M = \begin{pmatrix} 0 & M_D \\ M_D & M_R \end{pmatrix}$$

$$m_1 \approx \frac{-M_D^2}{M_R}, m_2 \approx M_R.$$

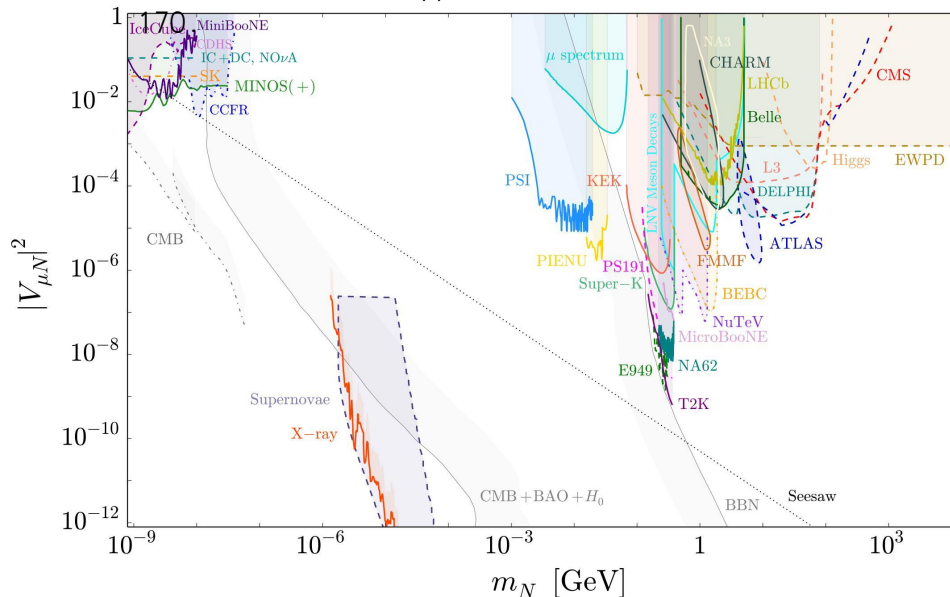
The lightness of the observed neutrinos is explained by heavy right-handed neutrinos,

Origin of Neutrino Masses

- Can we test seesaw?

Search for RHNs

P. Bolton, F. F. Deppisch, P. S. B. Dev, JHEP 03 (2020),



Limits on the seesaw parameters (m_N, V_{lN}) from the collider searches for heavy neutrinos and other probes.

We need to look for other production channels!

Our goal is to search the heavy neutrinos and test the type-I seesaw, the origin of the neutrino masses!

However, direct probes of the heavy neutrinos within the **minimal** model **cannot reach the type-I seesaw** due to the low mixing at the EW scale

$$\begin{bmatrix} \nu_L \\ \nu_R \end{bmatrix} = \begin{bmatrix} V_{LL} & V_{RL} \\ V_{LR} & V_{RR} \end{bmatrix} \begin{bmatrix} \nu \\ N \end{bmatrix}$$

$$V_{lN}^2 \approx \frac{m_\nu}{m_N} < \frac{\text{eV}}{\text{GeV}} < 10^{-10}$$

Origin of Neutrino Masses

- **B-L Gauged Model**

$$SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$$

R. N. Mohapatra, R. E. Marshak, Phys. Rev. Lett. 44 (1980) 1316

B-L number is anomaly free

- **Additional scalar singlet χ with the scalar potential**

$$V(H, \chi) = m^2 H^+ H + \mu^2 |\chi|^2 + \lambda_1 (H^+ H)^2 + \lambda_2 |\chi|^4$$

- **Majorana Mass Terms from symmetry breaking of B-L**

$$\mathcal{L} \supset -y_D \bar{l}_L \tilde{H} \nu_R - y_M \overline{\nu_R^c} \chi \nu_R.$$

$$m_N \approx y_M v_\chi \sim \text{GeV} - \text{TeV}$$

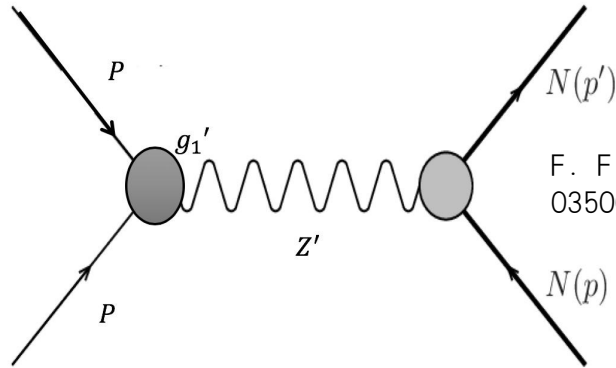
- **Additional $B - L$ gauge boson Z' with interactions**

$$\mathcal{L} \supset \sum ig_{B-L} Y_{B-L} Z' f \bar{f}$$

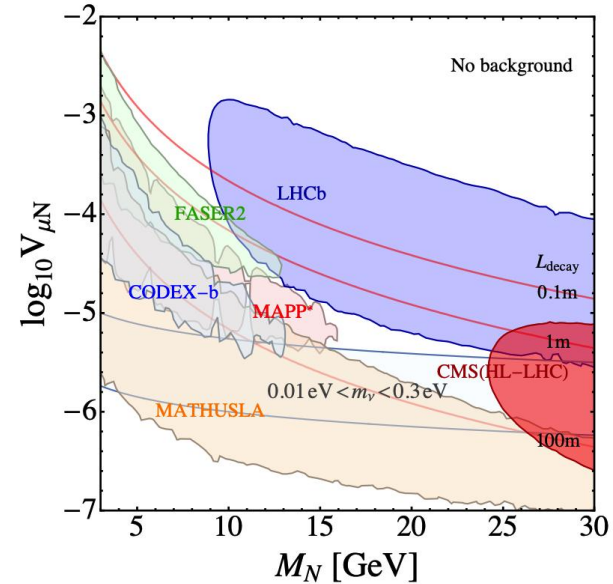
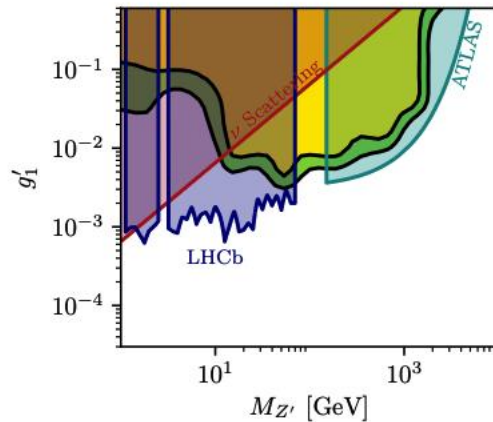
- **Additional RHN production from Z' , S , H decays.**

Origin of Neutrino Masses

- **RHNs from Z' Decay**



F. F. Deppisch, S. Kulkarni, **WL**, Phys.Rev.D 100 (2019) 3, 035005

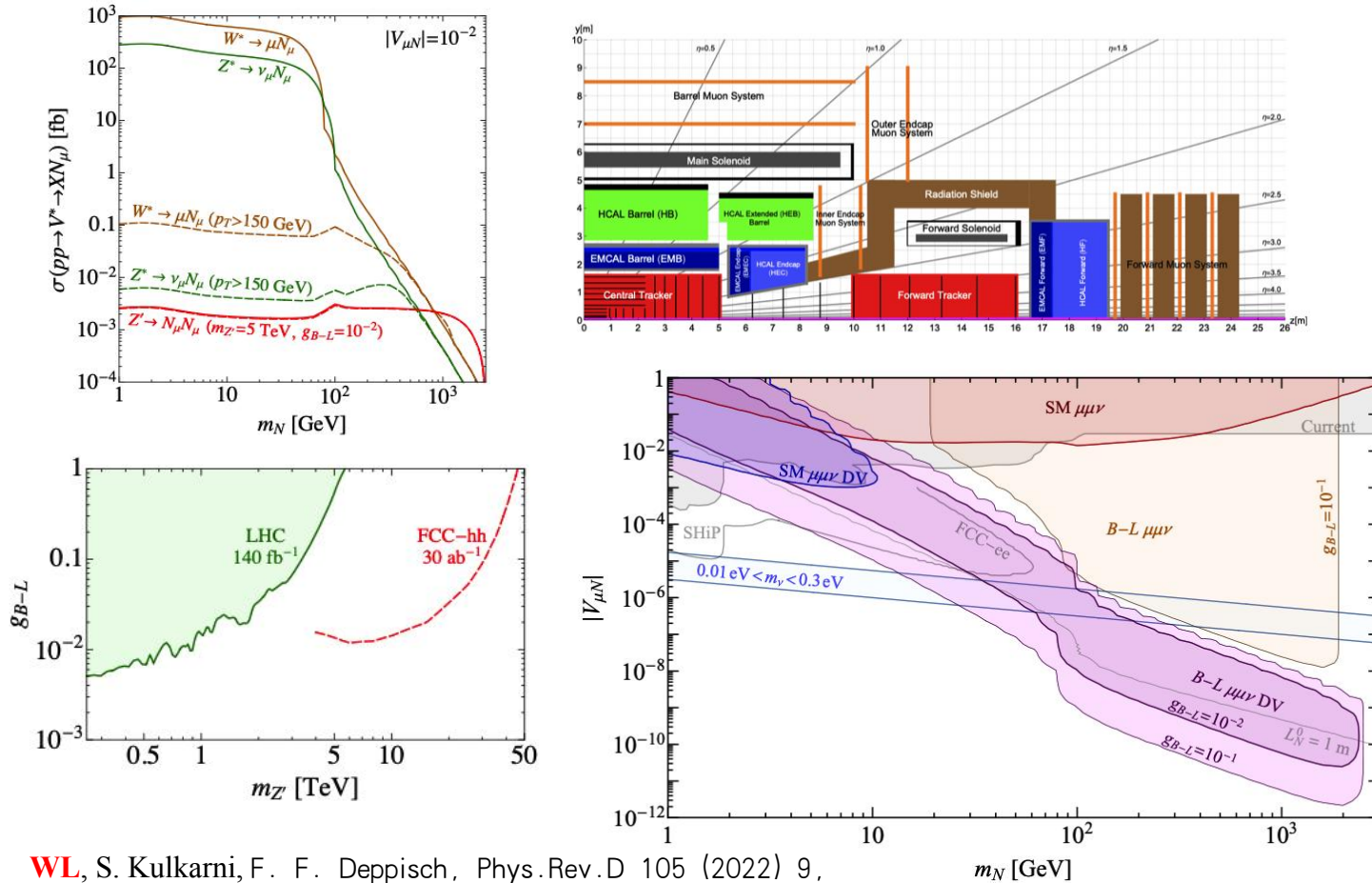


S. Amrith, J.M.Butterworth, F. F. Deppisch, **WL** et al, JHEP 05

- $g_{B-L}^{(2019), 154} = 10^{-3}$, $M_N = 0.3 M_{Z'}$, Seesaw mechanism can be tested by MATHUSLA and CMS.

Origin of Neutrino Masses

- RHNs from Z' Decay, FCC-hh

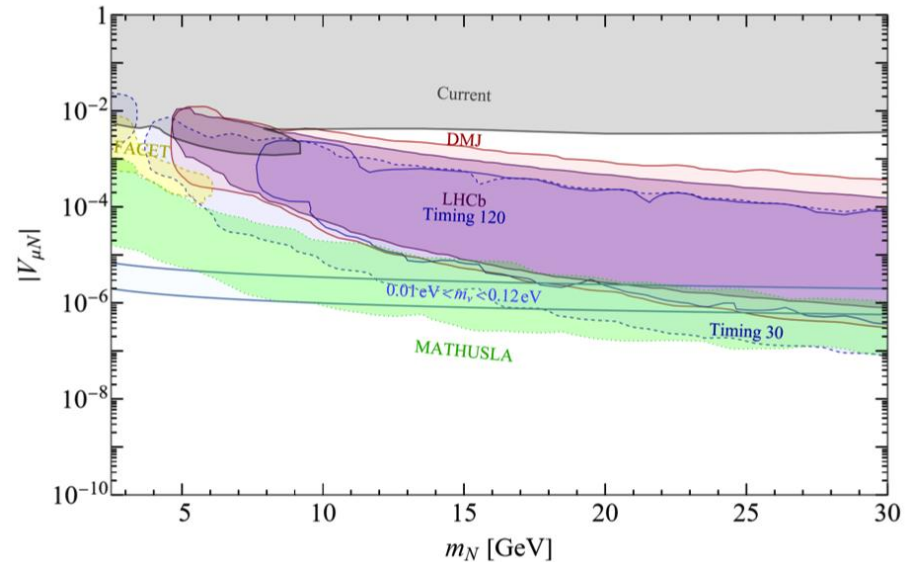
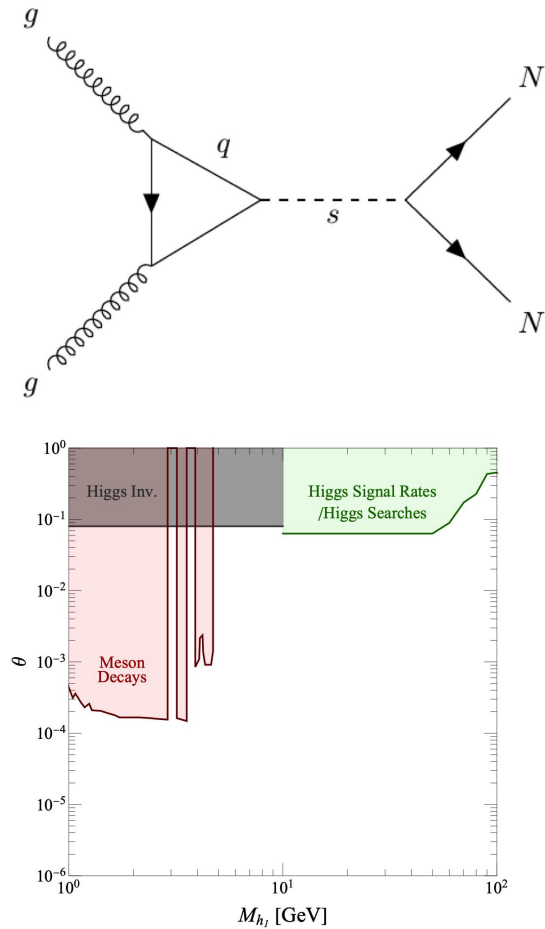


WL, S. Kulkarni, F. F. Deppisch, Phys.Rev.D 105 (2022) 9,

- $g_{B-L} = 10^{-2}$, $M_{Z'} = 5$ TeV, Seesaw mechanism can be tested by FCC-hh.

Origin of Neutrino Masses

- **RHNs from light scalar S decay**

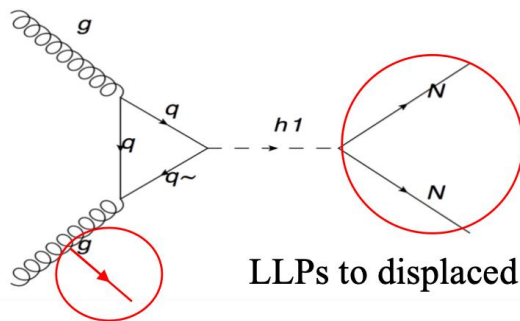
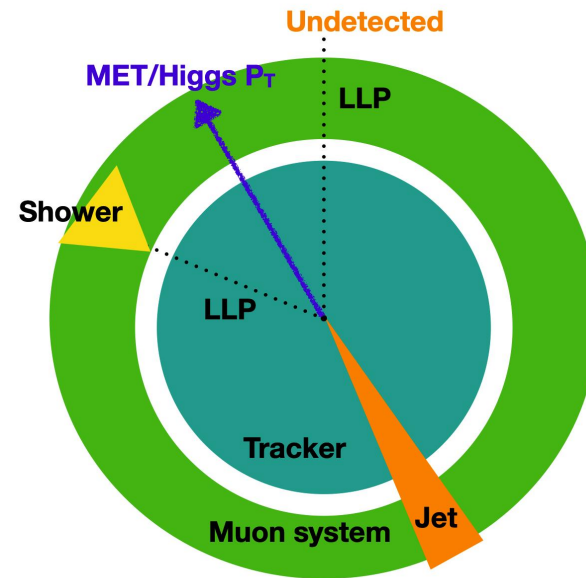
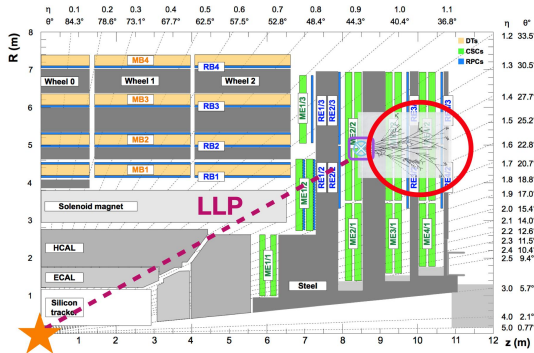


WL, J. Li, J. Li, H. Sun, Phys.Rev.D 106 (2022) 1, 015019

- $\theta = 0.06$, $M_S = 4 M_N$, Seesaw mechanism can be tested by MATHUSLA.

Origin of Neutrino Masses

- RHNs from SM Higgs Decay, Recast CMS Displaced Shower Search



LLPs to displaced shower

ISR jets to **trigger** MET

CMS-EXO-20-015

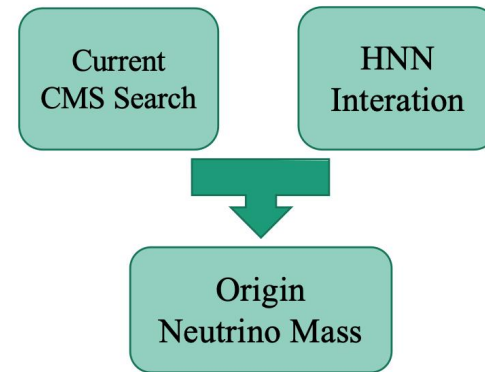
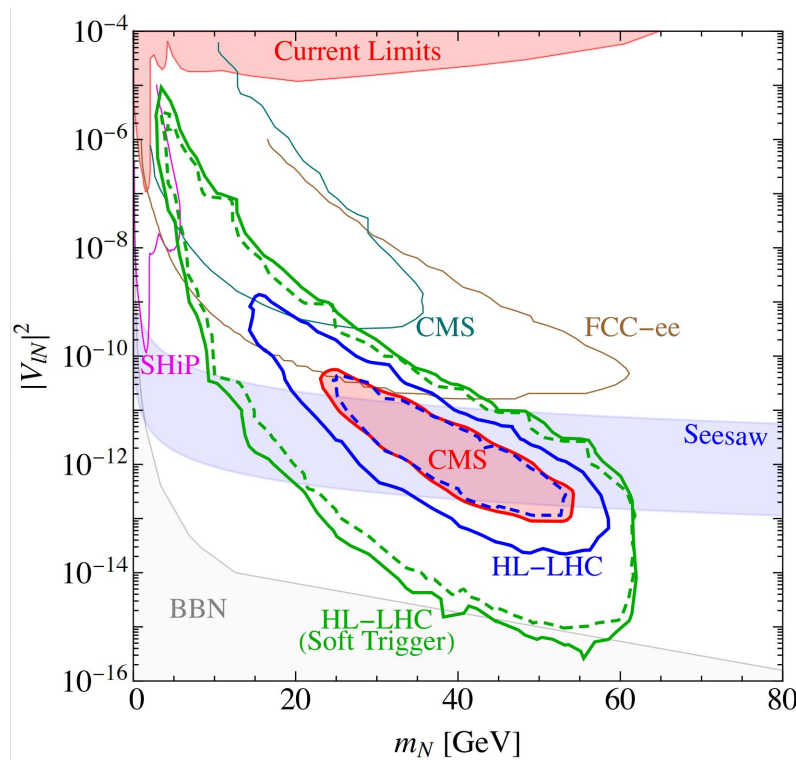
CMS-EXO-22-017

WL, F. F. Deppisch, S. Kulkarni,
Phys.Rev.D 111 (2025) 9, 093003

- We focus on heavy N s LLP
- LLP can also be searched with **CMS muon system** since **Run2**.
- No Dedicated trigger, require **high MET** to trigger, $MET > 200$ GeV
- New trigger since Run3, higher efficiency.

Origin of Neutrino Masses

- **RHNs from SM Higgs Decay, Recast CMS Displaced Shower Search**



WL, F. F. Deppisch, S. Kulkarni, Phys.Rev.D 111 (2025) 9, 093003

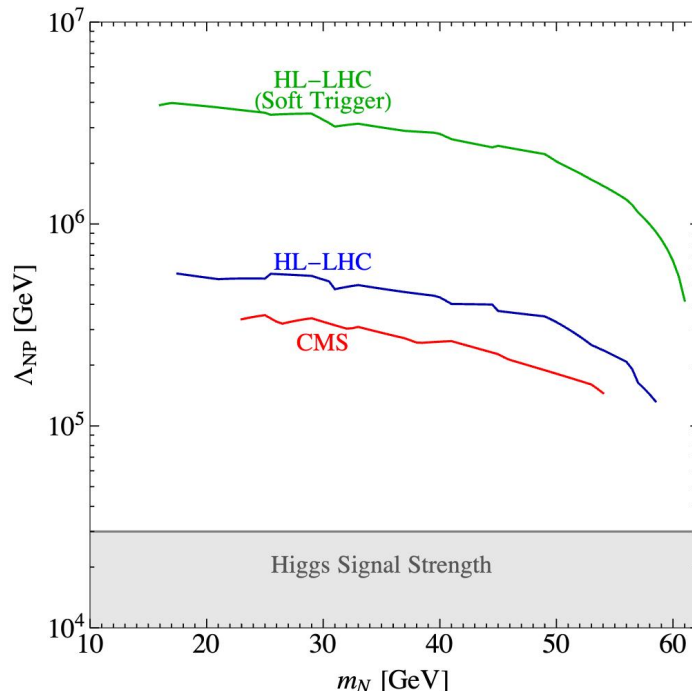
- Higgs mixing at current limits
- **Existing** CMS Search **can test Seesaw!**
- Dedicated trigger since Run3, **better** sensitivity expected
- **$\text{Br}(\text{H} \rightarrow \text{NN}) \approx 10^{-5}$** is required to test seesaw.

Origin of Neutrino Masses

- **RHNs from SM Higgs Decay, Recast CMS Displaced Shower Search**
- **More General Description in N_R SMEFT(0806.0876).**

$$\mathcal{L}_5 = \frac{(\alpha_W^\dagger)_{ab}}{\Lambda} (\bar{L}_a \tilde{\phi})(\phi^\dagger \tilde{L}_b^c) + \frac{(\alpha_{N\phi})_{ss'}}{\Lambda} (\phi^\dagger \phi) \bar{\nu}_{Rs} \nu_{Rs'}^c + \frac{(\alpha_{NB})_{ss'}}{\Lambda} \bar{\nu}_{Rs} \sigma^{\mu\nu} \nu_{Rs'}^c B_{\mu\nu} + h.c.$$

- **Only three in Dim-5**
- **Weinberg Operator for Neutrino Mass, Dipole for W/Z decay to N**



- **Anisimov-Graesser Operator** for HNN
- **Current limits from Higgs signal strength (2210.16279, 2304.06772)**
 $\Lambda \geq 30$ TeV
- **Large parameter space in EFTs to probe seesaw**
- **Limits from this work surpass current limits by more than 10 times**

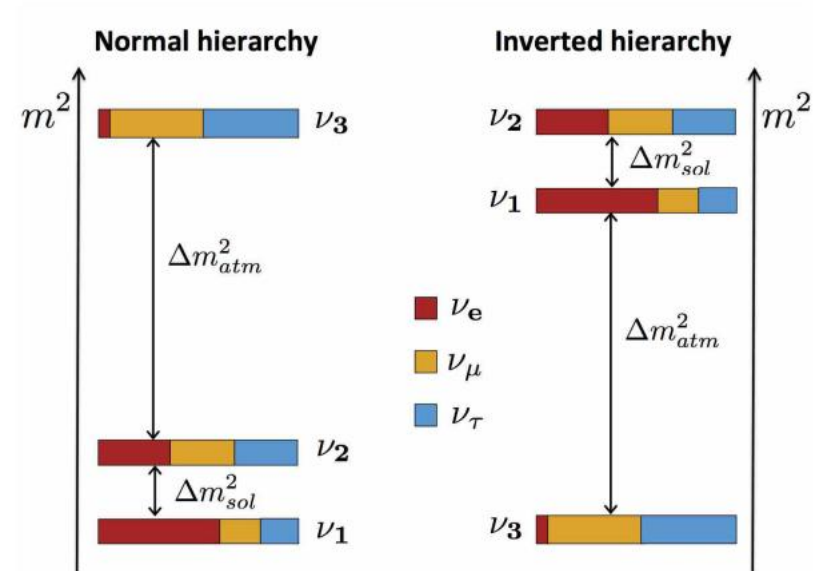
Testing Neutrino Masses Ordering at Colliders?

- 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

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

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

$$x_\omega \equiv e^{\text{Im } \omega}$$

- Active-sterile mixing

$$\Theta_{\alpha I} \simeq \frac{v Y_{\alpha I}}{M_I}, \quad \mathbf{m}_N \approx \mathbf{M}_{2,3}$$

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

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

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

Flavor Mixing of RHN

- **PMNS Matrix**

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

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

Only one Majorana phase is free

$$|U^{PMNS}| \approx \begin{pmatrix} 0.82 & 0.55 & 0.15 \\ 0.35 & 0.58 & 0.73 \\ 0.44 & 0.60 & 0.67 \end{pmatrix} \begin{matrix} e3 \\ \mu3 \\ \tau3 \end{matrix}$$

Flavor Mixing of RHN

- NH

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

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

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

$$|U_{e3}^{PMNS}| < |U_{\mu,\tau 3}^{PMNS}|, \delta \text{ and } \eta(\alpha_{ij}) \text{ are free}$$

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

Flavor Mixing of RHN

- IH

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

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

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

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

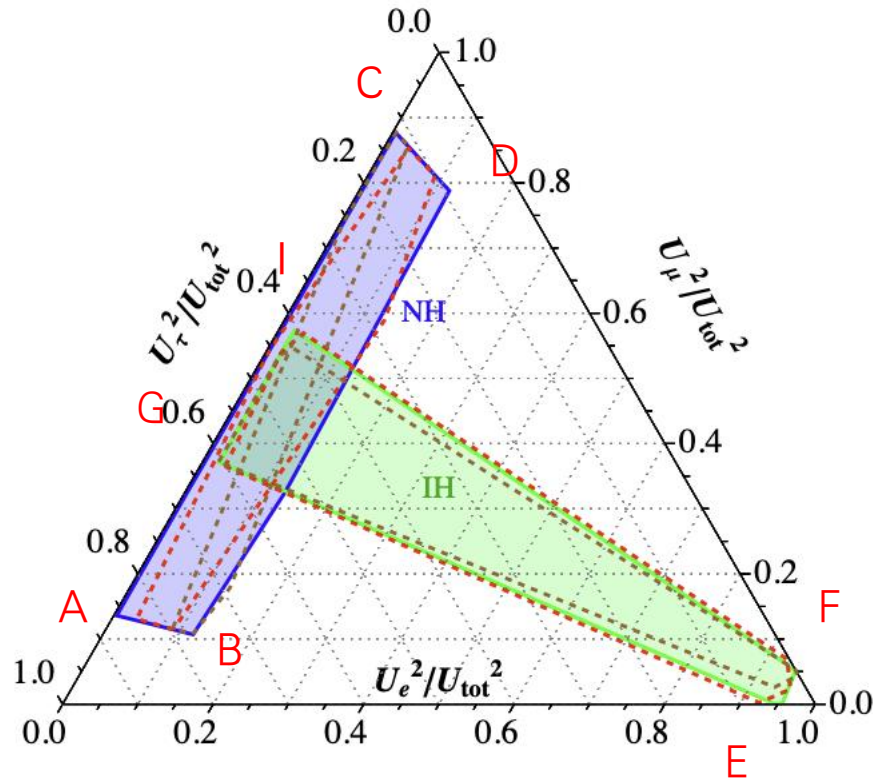
Flavor Mixing of RHN

- NH/IH RHNs have different flavor mixing pattern

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

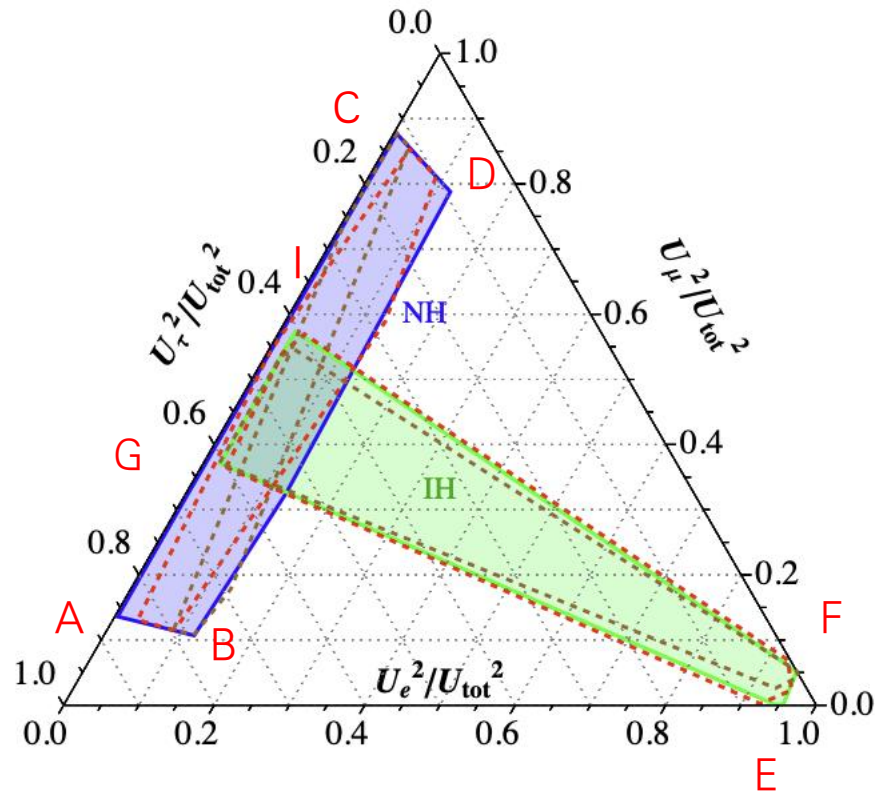
IH: $U_{e,\mu,\tau N}^2$ can be similar

- Independent of Mass and total mixing



Flavor Mixing of RHN

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



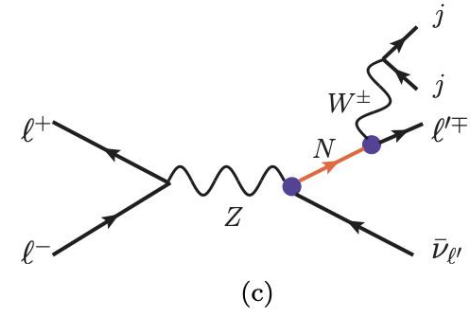
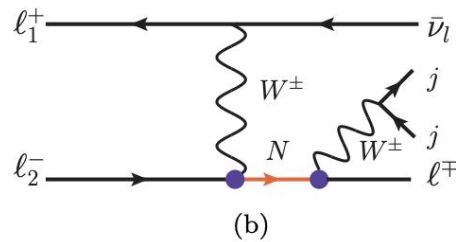
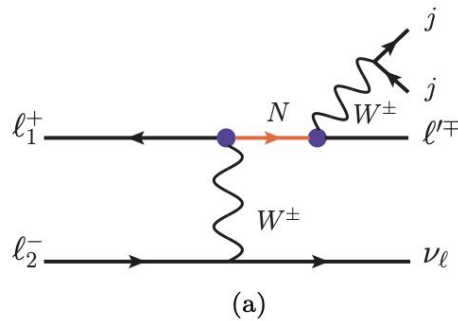
- Still a lot freedom in Majorana CP, $\delta - \eta$

Model Parameters

- 4 Free Parameters
- Mass of the **RHNs** m_N , mass splitting (not considered)
- Total Active Sterile Mixing U_{tot}^2 , controlled by Ω matrix
- Dirac/Majorana CP Phase δ, η , control $U_{\alpha N}^2 / \mathcal{U}_{tot}^2$
- Input Parameters
neutrino oscillation data into PMNS, small variation to $U_{\alpha N}^2 / \mathcal{U}_{tot}^2$

Colliders Observables

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



- Lepton flavor violation signatures

However small cross section

- Z decay dominating

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

Colliders Observables

- **Map into Observables**

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

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

$$\text{Br}(N \rightarrow \ell_{\alpha}jj) \propto U_{\alpha N}^2 / U_{\text{tot}}^2. \quad R_{\alpha} \equiv U_{\alpha N}^2 / U_{\text{tot}}^2$$

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

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

Statistical Analysis

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

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

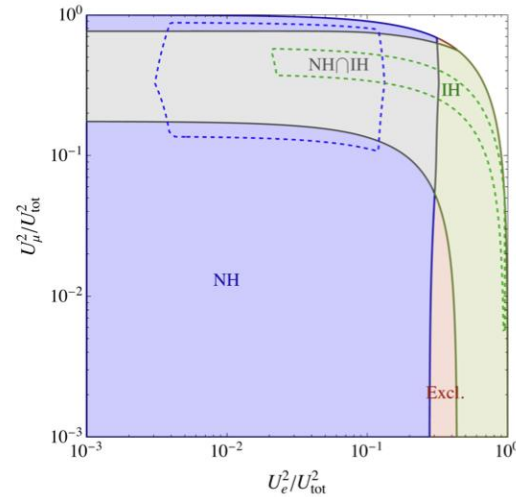
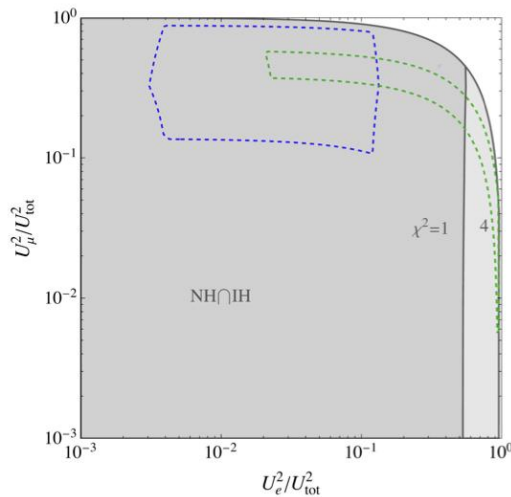
- The smallest χ^2 is taken to tell whether NH/IH is disfavored

Test Mass Ordering

- Color Scheme

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

- $U_{tot}^2 = 4 \times 10^{-9}$, $m_N = 50$ GeV; $U_{tot}^2 = 10^{-8}$, $m_N = 50$ GeV



- No test

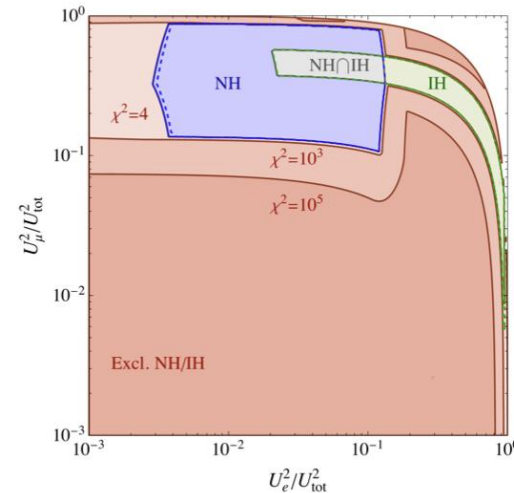
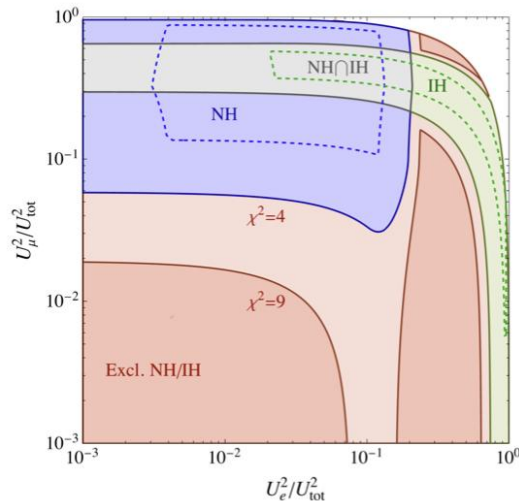
Only small fraction

Test Mass Ordering

- Color Scheme

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

- $U_{tot}^2=10^{-7}$, $M_N = 50$ GeV; $U_{tot}^2=10^{-5}$, $M_N = 50$ GeV



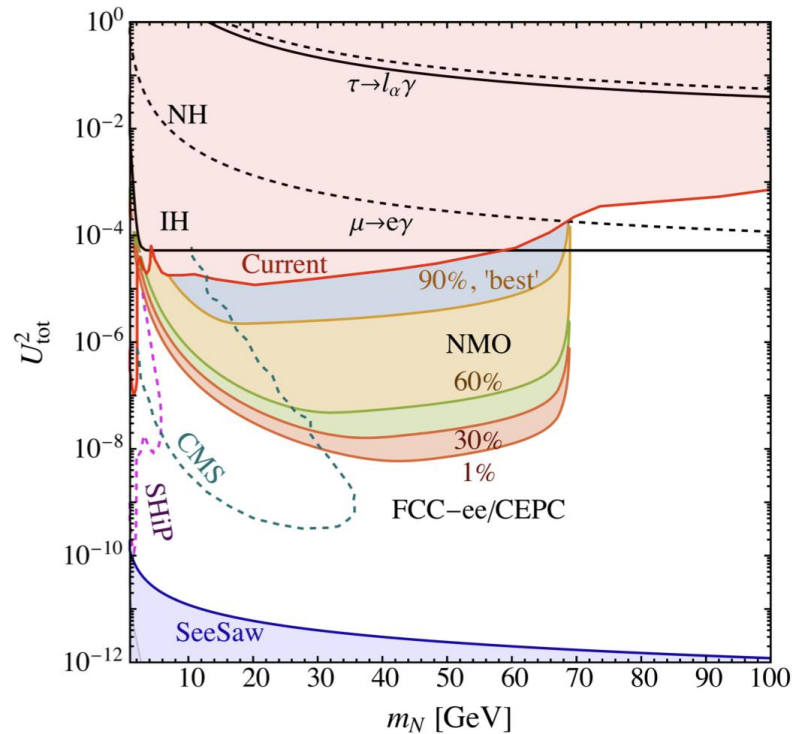
- Half of parameter space can be identified; Nearly best to test NH/IH

Test Mass Ordering

- Quantify the distinguishability
The area in Log10 scale

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

- Contours of K in of FCC-ee/CEPC

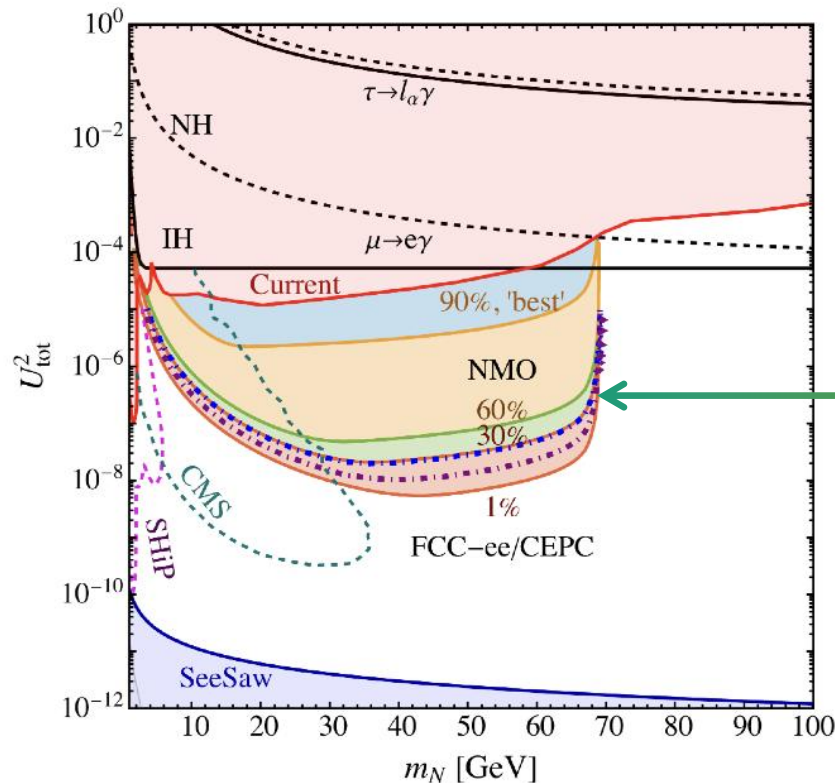


Synergy with JUNO

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

Scenario	JUNO	CEPC/FCC-ee
A	NH Favor	$R_\alpha = 1/3$
B	IH Favor	$R_\mu = 1$

Blue
Purple



Conflicts with
JUNO

Conclusion

- Collider can test origin of the neutrino masses
- NH/IH mass orderings lead to different $U_{\alpha N}^2 / U_{tot}^2$
- 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 determine the CP phase $\delta - \eta$