Probing Sterile Neutrinos in Meson Decays

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Reference:
JHEP 1104 (2011) 011 [arXiv:1101.1382]

The νMSM

TA, Blanchet, Shaposhnikov '05
TA, Shposhnikov '05

- Observational Problems in the MSM
  - Neutrino masses
  - Dark Matter
  - Baryon Asymmetry of the Universe

- Right-handed Neutrinos $\boldsymbol{\nu_{R1}, \nu_{R2}, \nu_{R3}}$

$$\delta L = i\overline{\nu_{RI}}\partial_\mu \gamma^\mu \nu_{RI} - F_{\alpha I}\,\overline{L_\alpha}\nu_{RI}\Phi - \frac{M_I}{2}\overline{\nu_{RI}}\nu_{RI}^c + \text{h.c.} \qquad I = 1,2,3 \quad \alpha = e,\mu,\tau$$

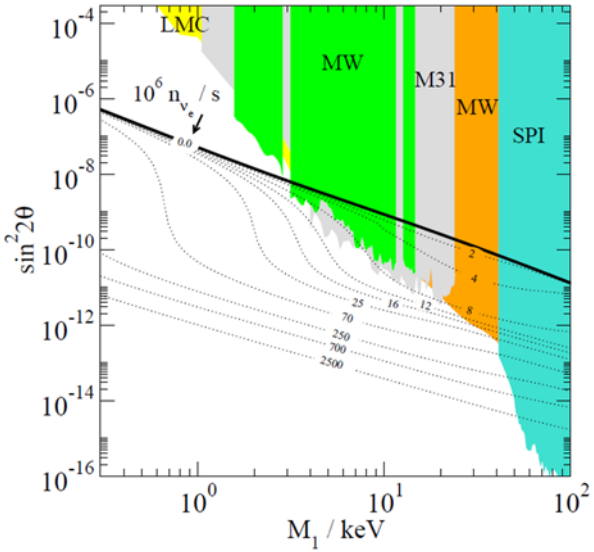
  - $\left|[M_D]_{\alpha I}\right| = \left|F_{\alpha I}\langle\Phi\rangle\right| \ll M_I < O(10^2)\,\text{GeV}$

    - Seesaw mechanism still works
      - Active neutrinos ν_1, ν_2, ν_3 : $M_\nu = -M_D M_M^{-1} M_D^T$
      - Sterile neutrinos N_1, N_2, N_3: $M_M = M_I$

Roles of three sterile (RH) neutrinos

- N_1 : Dark Matter Candidate
  - $M_1 = 4\text{-}50$ keV, $|F_{\alpha 1}| = 5 \cdot 10^{-15}\text{-}4 \cdot 10^{-13}$
  - Negligible contribution to M_ν
  - Test by cosmic X-rays from $N_1 \longrightarrow \nu\,\gamma$

[Laine, Shaposhnikov '08]



- N_2 and N_3 :
  - Neutrino Oscillation data
    Masses and mixings of active neutrinos
  - Baryon Asymmetry of the Universe (BAU)
    Mechanism via neutrino oscillation
    [Akhmedov, Rubakov, Smirnov '98]

- In this talk,
  - Direct search for $N_{2,3}$ in meson decays when $M_{2,3} < m_\pi$

Limits on light sterile neutrinos

- Flavor mixing

$$\nu_{L\alpha} = U_{\alpha i}\,\nu_i + \Theta_{\alpha I}\,N_I^c$$

$$\Theta_{\alpha I} = \frac{[M_D]_{\alpha I}}{M_I} = \frac{F_{\alpha I}\langle\Phi\rangle}{M_I}$$

- Allowed range of $\Theta_{\alpha I}$
  - Direct search experiments put
    ⇒Upper bounds on $\Theta_{\alpha I}$
  - Big Bang Nucleosynthesis puts
    ⇒Upper bounds on lifetimes [Dolgov, Hansen, Rafflet, Semikoz '00]
    $\tau_{\rm BBN}[\rm sec] = 128.7(M_N/\rm MeV)^{-1.828} - 0.04179$
    ⇒Lower bounds on $\Theta_{\alpha I}$

- Gorbunov, Shaposhnikov ('07)
  - No allowed region for $M_{2,3} < m_\pi$
- However, we find an allowed range in NH case.

Neutrino Yukawa couplings for $N_{2,3}$

$$F = U_{\rm PMNS}\, D_\nu^{1/2}\, \Omega\, D_N^{1/2} / \langle \Phi \rangle$$ **(in NH)**

[Casas, Ibarra '01]

- Parameters of active neutrinos

$D_\nu^{1/2} = \mathrm{diag}(\sqrt{m_1} = 0, \sqrt{m_2}, \sqrt{m_3})$: active ν masses

$$U_{\rm PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -c_{23}s_{12} - s_{23}c_{12}s_{13}e^{i\delta} & c_{23}c_{12} - s_{23}s_{12}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{23}s_{12} - c_{23}c_{12}s_{13}e^{i\delta} & -s_{23}c_{12} - c_{23}s_{12}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \begin{pmatrix} 1 & & \\ & e^{i\eta} & \\ & & 1 \end{pmatrix}$$

Dirac phase δ

Majorana phase η

- Parameters of sterile neutrinos

$D_N^{1/2} = \mathrm{diag}(\sqrt{M_2}, \sqrt{M_3})$: sterile ν masses

$$\Omega = \begin{pmatrix} 0 & 0 \\ \cos\omega & -\sin\omega \\ \xi\sin\omega & \xi\cos\omega \end{pmatrix}$$

ω: complex number

$\xi = \pm 1$

Imω

- **For $\mathrm{Im}\omega \gg 1$, $\Omega \propto e^{\mathrm{Im}\omega}$**

$$F, \Theta \propto e^{\mathrm{Im}\omega} \equiv X_\omega$$

Mixing elements in NH case

- μ and τ types

$$\left|\Theta_{\mu I}\right|^2 \simeq \left|\Theta_{\tau I}\right|^2 \simeq X_\omega^2 \frac{m_{\rm atm}}{8\,M_I} = 6\times 10^{-11} X_\omega^2 \left(\frac{100{\rm MeV}}{M_I}\right)^2 \qquad r_m = \frac{m_{\rm atm}}{m_{\rm sol}} \simeq 0.18$$

- e type

$$|\Theta_{eI}|^2 = X_\omega^2 \frac{m_{\rm atm}}{4\,M_I} \cos^2\theta_{13}\left[\tan^2\theta_{13} + 2\,\xi\,\sin(\delta+\eta)\sqrt{r_m}\sin\theta_{12}\tan\theta_{13} + r_m\sin^2\theta_{12}\right]$$

  - $O(X_\omega^2)$ and $O(X_\omega^0)$ terms in $|\Theta_{eI}|^2$ vanish, when

$$\tan\theta_{13}^{cr} = \sqrt{r_m}\sin\theta_{12}$$
$$\xi\,\sin(\delta+\eta) = -1$$

$\sin^2\theta_{13}^{cr} = 0.041\sim0.070\ (3\sigma),\ 0.046\sim0.065\ (2\sigma)$

$\sin^2\theta_{13} < 0.053\ \ (3\sigma),\ 0.039\ (2\sigma)$

[Schwetz, Tortola, Valle '08]

$$|\Theta_{eI}|^2 \simeq 3\times 10^{-11}\frac{1}{X_\omega^2}\left(\frac{100{\rm MeV}}{M_I}\right)^2$$

- In IH case, no cancellation in $\Theta_{\alpha I}$ is possible

Search for light sterile neutrinos

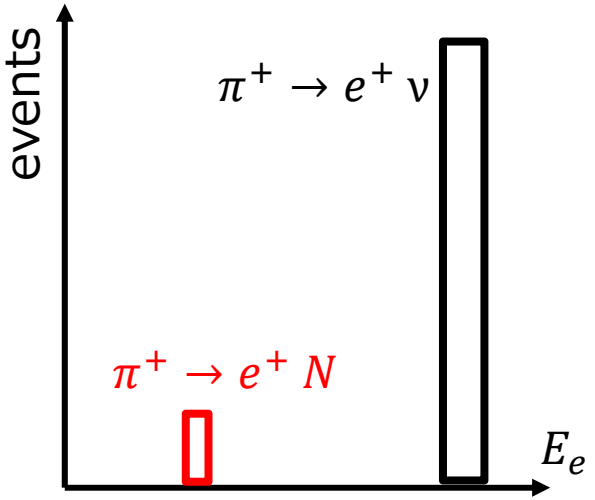
- Productions by meson decays

$\pi^+ \to e^+ N$

$K^+ \to e^+ N,\ K^+ \to \mu^+ N$

- **Peak search** [Shrock '80]
  - Measure E_e in $\pi^+ \to e^+ N$

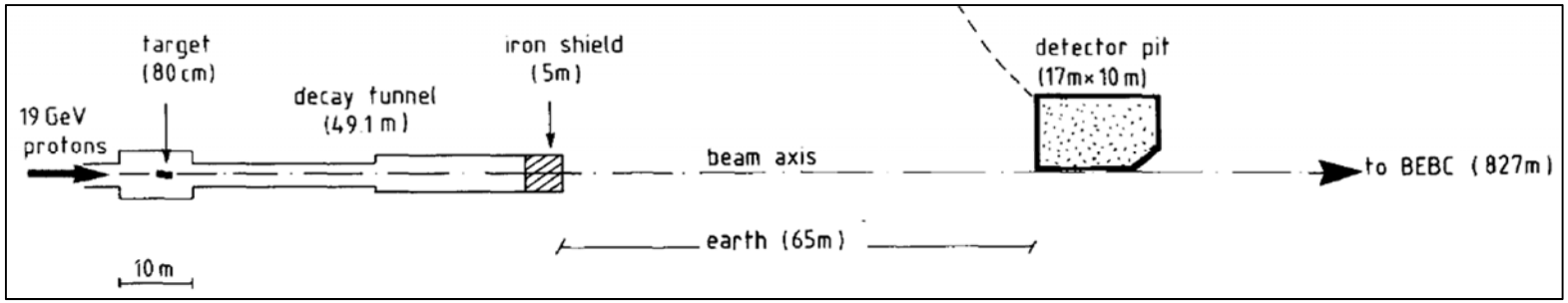
$$E_e = \frac{m_\pi^2 - m_e^2 - M_N^2}{2\, m_\pi}$$



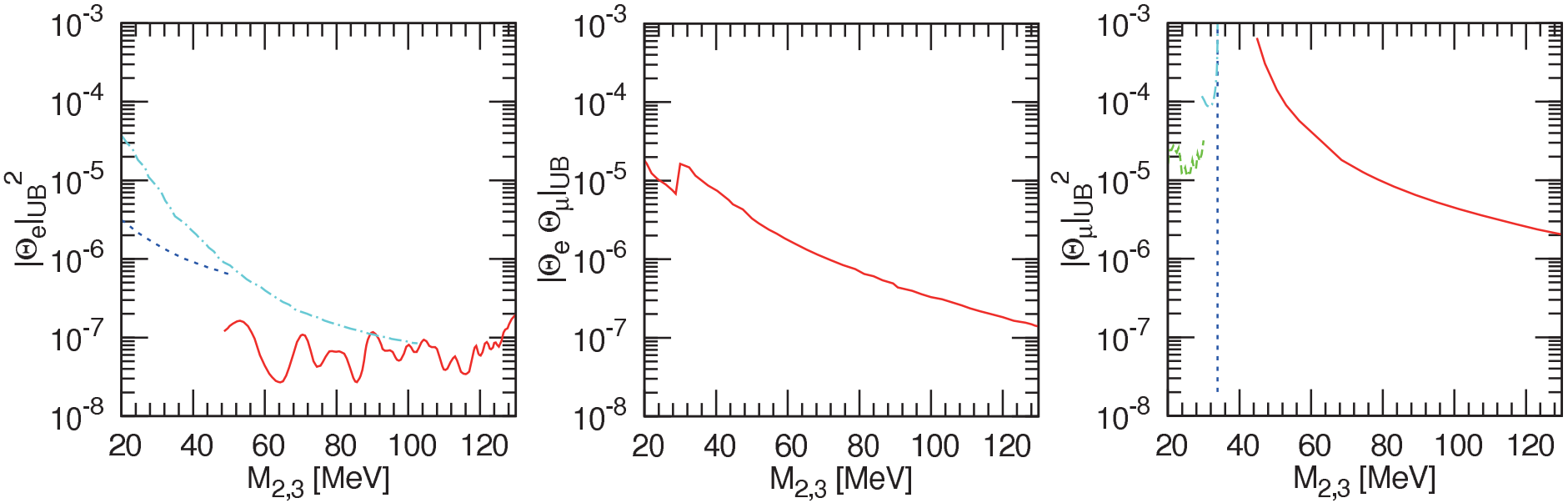
- **Decays inside the detector**

$\pi^+ \to e^+ N$ $\qquad$ $N \longrightarrow \ell^+ \ell^- \nu + c.c.$

CERN PS191



Experimental Upper bounds $\Theta_{\alpha I}$

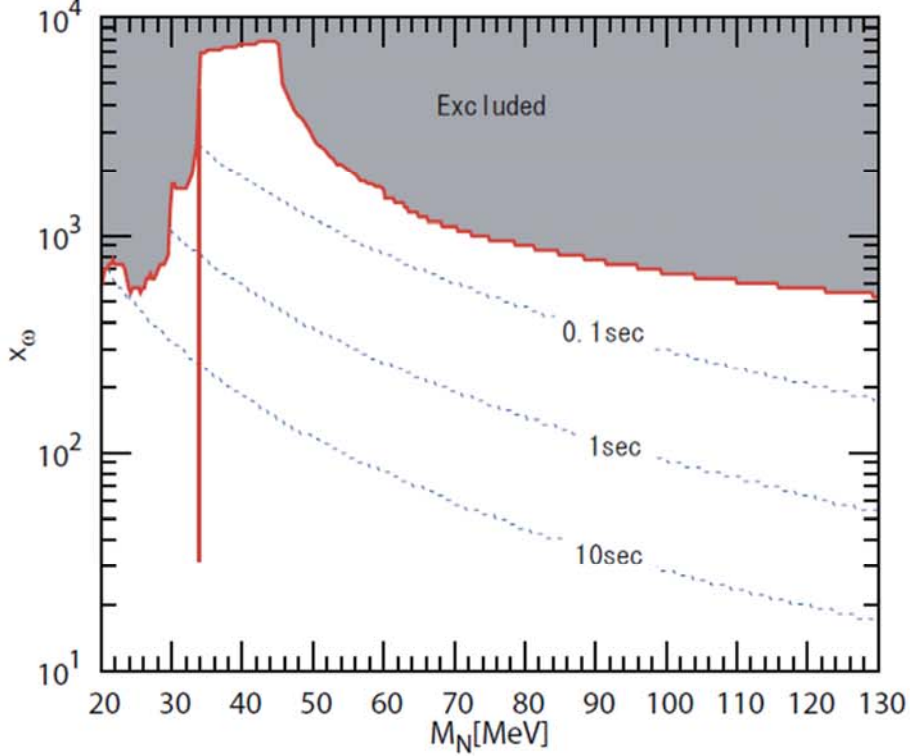


- Bounds on $\Theta_{\tau I}$ are much weaker and irrelevant
- Bound on $|\Theta_{eI}|^2$ is severer than others

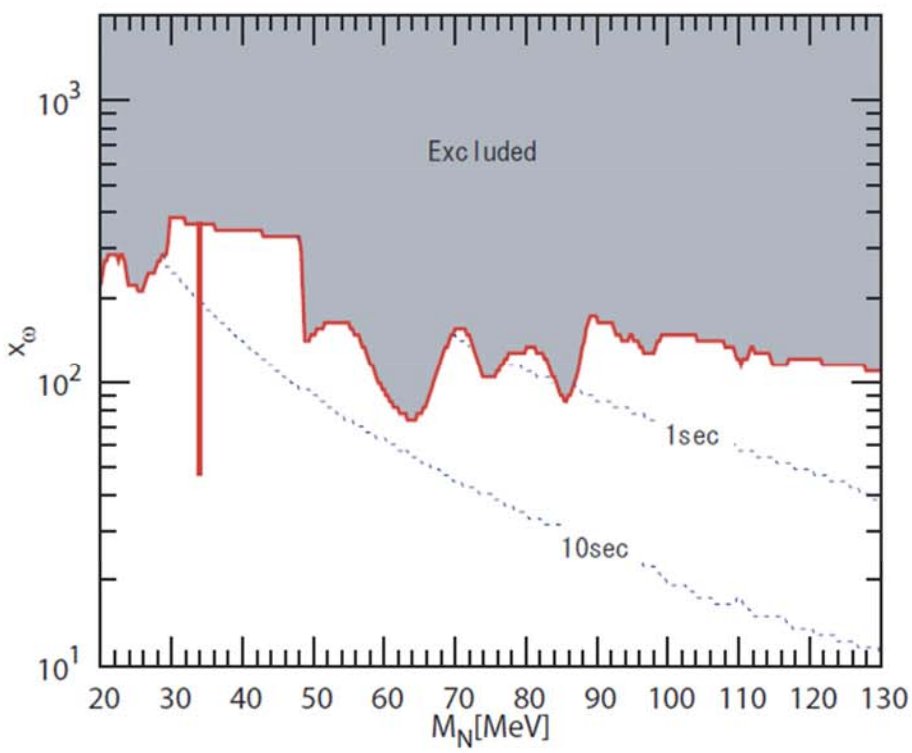
- $|\Theta_{\alpha I}| \propto X_\omega \implies$ Upper bound on X_ω

Upper bounds on Xω

NH case

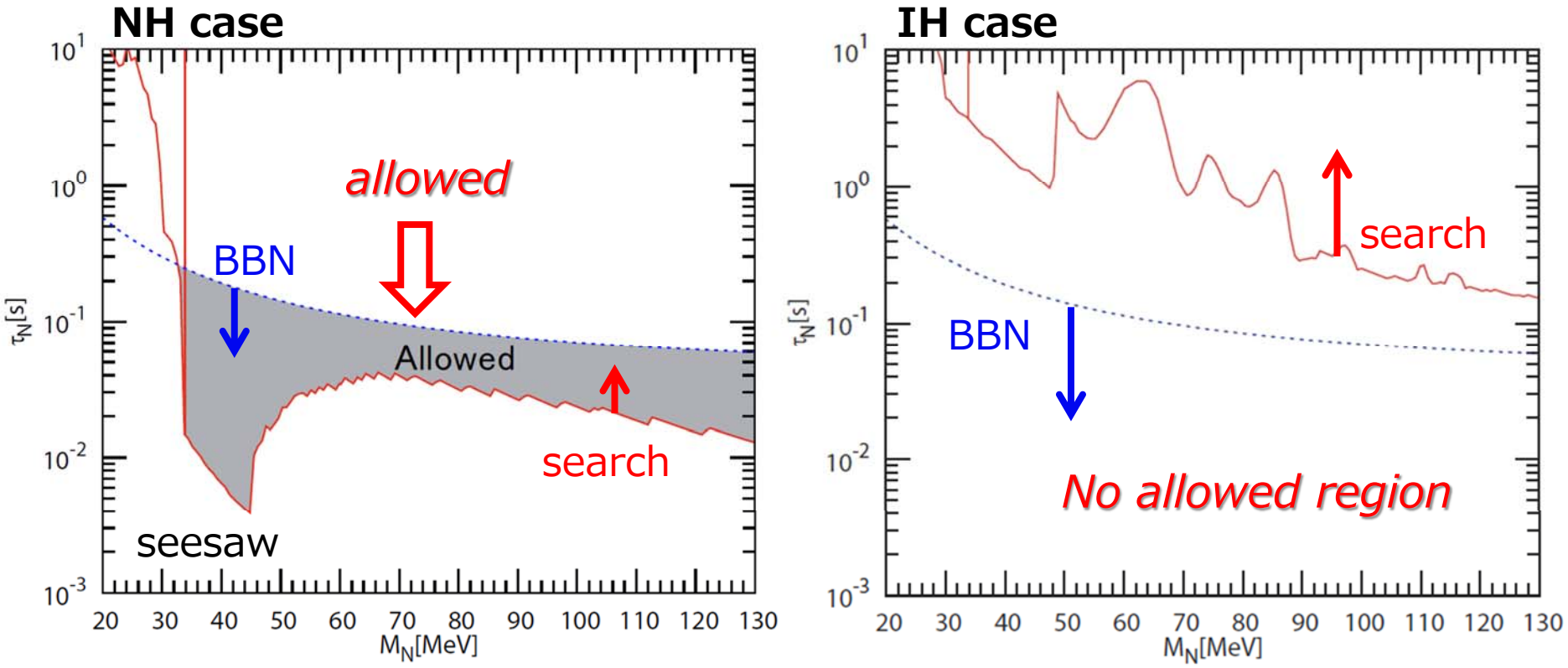


IH case



- Due to cancellation in $|\Theta_{eI}|$ for the NH case, bound in NH is much weaker than IH
- $N_{2,3}$ are long-lived particles $\Longrightarrow$ BBN constraint!

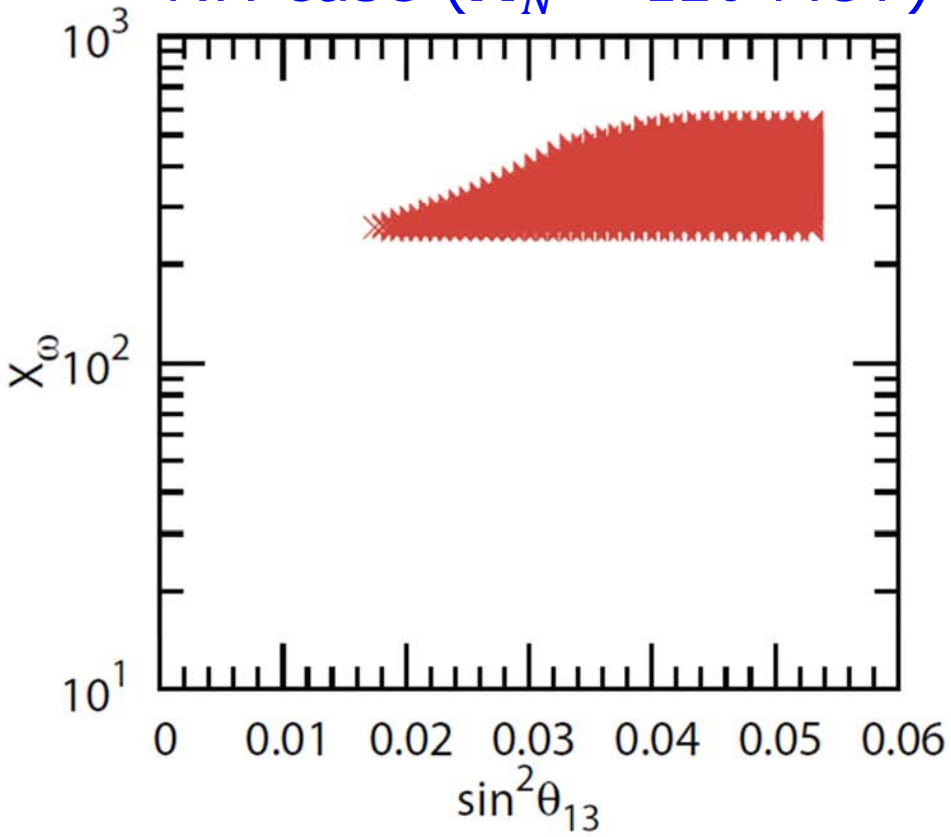
Bounds on lifetime

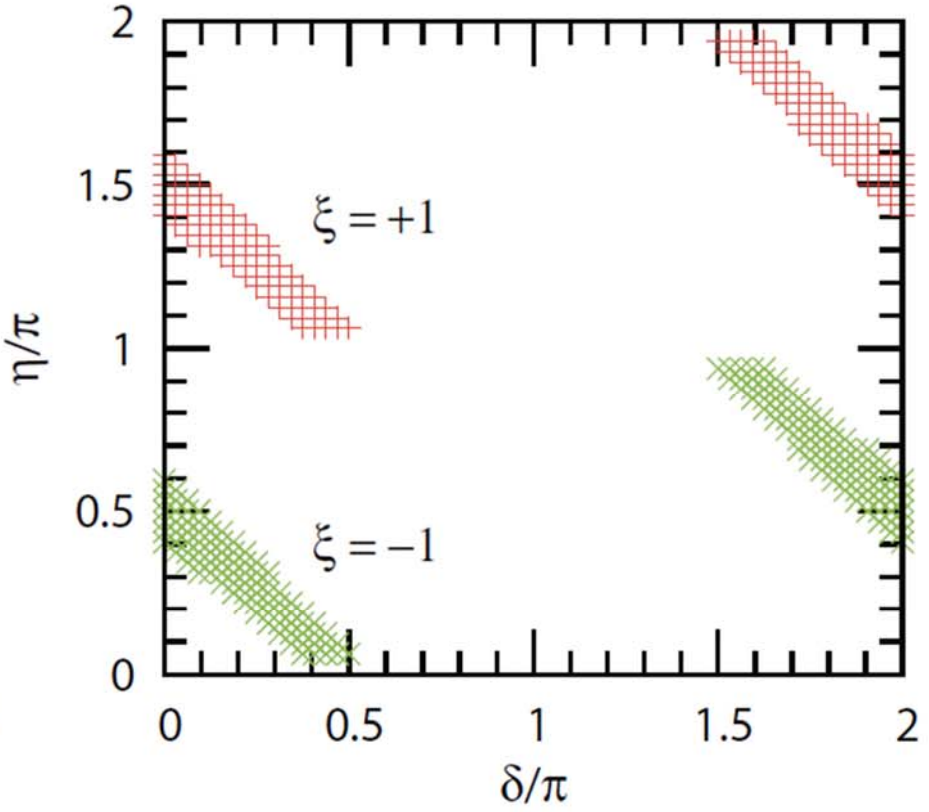


- Allowed region $M_N = 34\text{MeV} \sim m_\pi$ in the NH case.
- The suppression of Θ_{eI} in the NH is crucial !

Allowed regions (search & BBN)

NH case ($M_N = 120$ MeV)





Large X_ω

Large θ_{13}

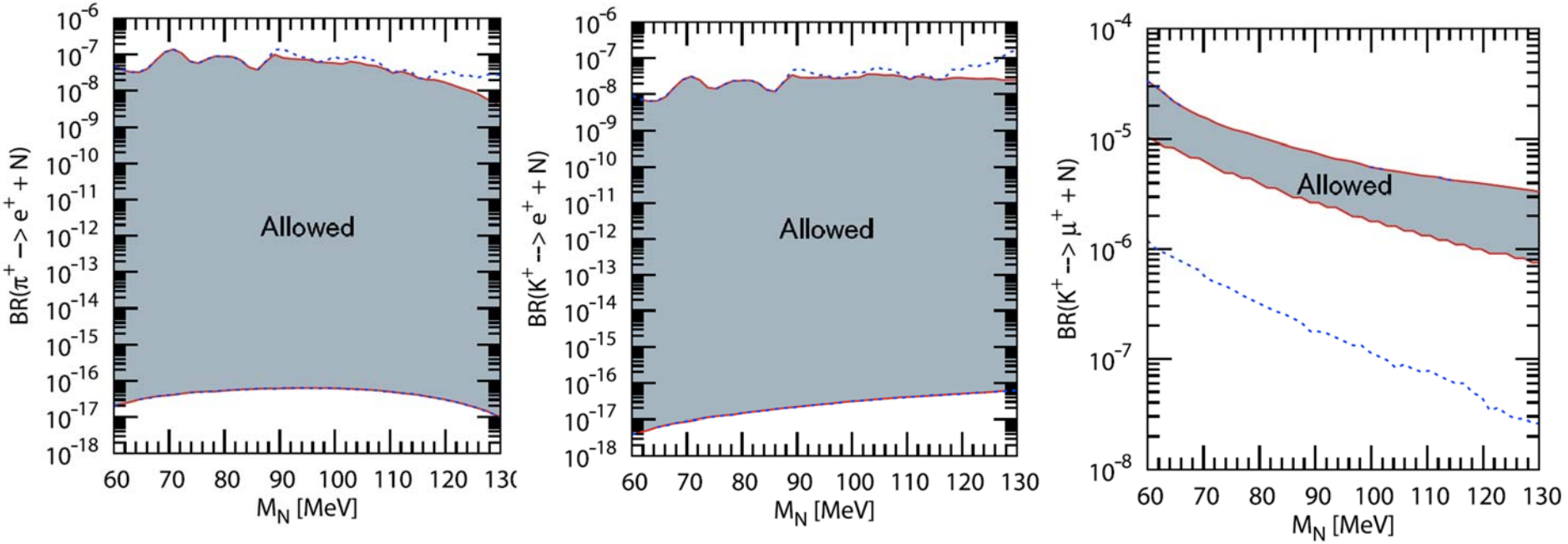
CP phases are aligned as

$\xi \sin(\delta + \eta) \approx -1$

$\xi \sin\eta < 0$

Branching ratios in NH case

$\pi^+ \to e^+ N$ $K^+ \to e^+ N$ $K^+ \to \mu^+ N$



- Cancellation of Θ_{eI}
  - Br($\pi^+ \longrightarrow e^+ N_{2,3}$) and Br($K^+ \longrightarrow e^+ N_{2,3}$) may be very small
  - May miss $N_{2,3}$ in future experiments
- $K^+ \longrightarrow \mu^+ N_{2,3}$ is promising to test
  - Improvement by a factor ~ 5 covers the whole range

Summary

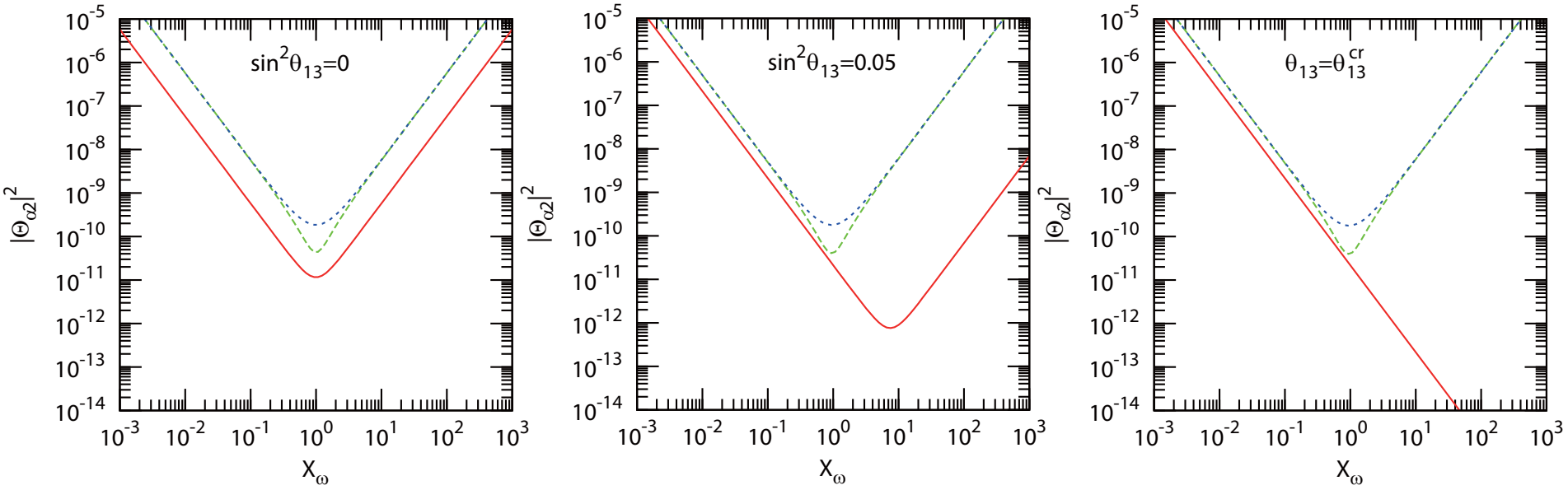
- **We considered the νMSM**
  - The MSM + 3 RH neutrinos with $M_N < O(10^2)$ GeV
    - N_1 : dark matter
    - N_2 and N_3 : seesaw + BAU
  - Mixing elements $\Theta_{\alpha 2}$ and $\Theta_{\alpha 3}$
    - $|\Theta_{\alpha I}|$ can be very large for large X_ω
    - Cancellation of $|\Theta_{eI}|$ is possible in NH

- **Search for N_2 and N_3 with $M_{2,3} < m_\pi$**
  - Allowed region ($M_{2,3} \simeq 34\text{MeV} \sim m_\pi$) in NH
  - θ_{13} should be large
  - $K^+ \longrightarrow \mu^+ N_{2,3}$ is promising to test
  - Br($\pi^+ \longrightarrow e^+ N_{2,3}$) and Br($K^+ \longrightarrow e^+ N_{2,3}$) may be very small

NH case

[TA, Eijima, Ishida '11]

θ_{13} and CP phases are important !



- For Im$\omega \gg 1$, we can obtain
  - Very Large $|\Theta_{\mu I}|^2 \simeq |\Theta_{\tau I}|^2$
  - Very suppressed $|\Theta_{eI}|^2$

Cancellation in $|\Theta_{eI}|$ occurs if

$$\tan\theta_{13}^{cr} = \sqrt{r_m}\sin\theta_{12}$$
$$\xi\sin(\delta+\eta) = -1$$