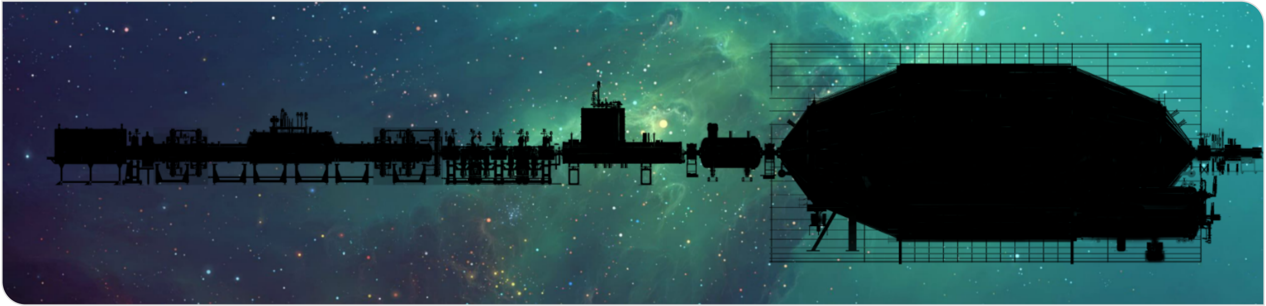
A Look at General Neutrino Interactions with KATRIN

Matter and the Universe Days 2023

Caroline Fengler for the KATRIN Collaboration | September 14th, 2023



Theory of General Neutrino Interactions (GNI)

- Generalisation of neutrino Non-Standard Interactions (NSI)
- Considers scalar, pseudoscalar, vector, axial vector or tensor interactions of neutrinos with fermions:

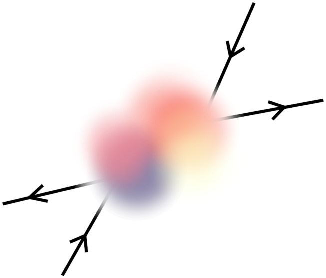
$$\mathcal{L}_{GNI}^{NC} = -\frac{G_F}{\sqrt{2}} \sum_{j=1}^{10} \overset{(\sim)}{\epsilon}_{j,f} \left(\bar{\nu}\, \mathcal{O}_j\, \nu\right) \left(\bar{f}\, \mathcal{O}_j'\, f\right)$$

$$\mathcal{L}_{GNI}^{CC} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \overset{(\sim)}{\epsilon}_{j,ud} \left(\bar{e}\, \mathcal{O}_j\, \nu\right) \left(\bar{u}\, \mathcal{O}_j'\, d\right) + h.c.$$

- Assume that GNI arise from heavy New Physics $\rightarrow$ Map low energy GNI operators onto dim 6 SM(N)EFT terms.

$$\mathcal{L}_{EFT}(\phi) = \mathcal{L}_{SM}(\phi) + \sum_{n\geq 5} \frac{1}{\Lambda^{n-4}} C_i^{(n)} \mathcal{O}_i^{(n)}(\phi)$$

$\rightarrow$ Enables broad search for New Physics through precision measurements.

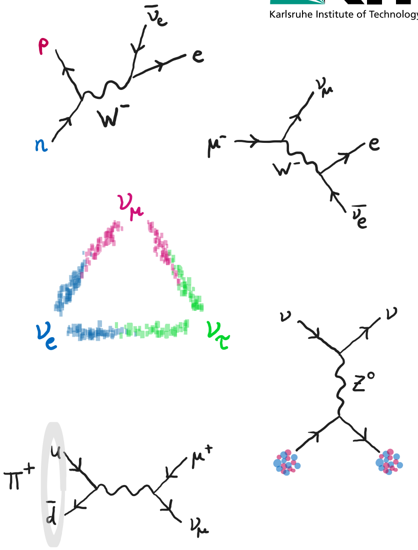


Bischer and Rodejohann, Nucl. Phys. B, 10.1016/j.nuclphysb.2019.114746

Search for General Neutrino Interactions

- **Possible interaction channels**:
  - Neutrino oscillation
  - LFV in μ- and τ-decays
  - Neutrino scatterings, e.g. CEνNS
  - π-decay
  - β-decay

- Different interaction channels are sensitive to different combinations of ϵ_i in GNI Lagrangian.

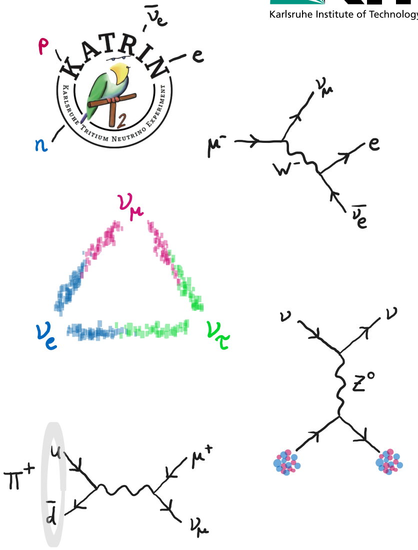


Search for General Neutrino Interactions

- **Possible interaction channels**:
  - Neutrino oscillation
  - LFV in μ- and τ-decays
  - Neutrino scatterings, e.g. CEνNS
  - π-decay
  - β-decay

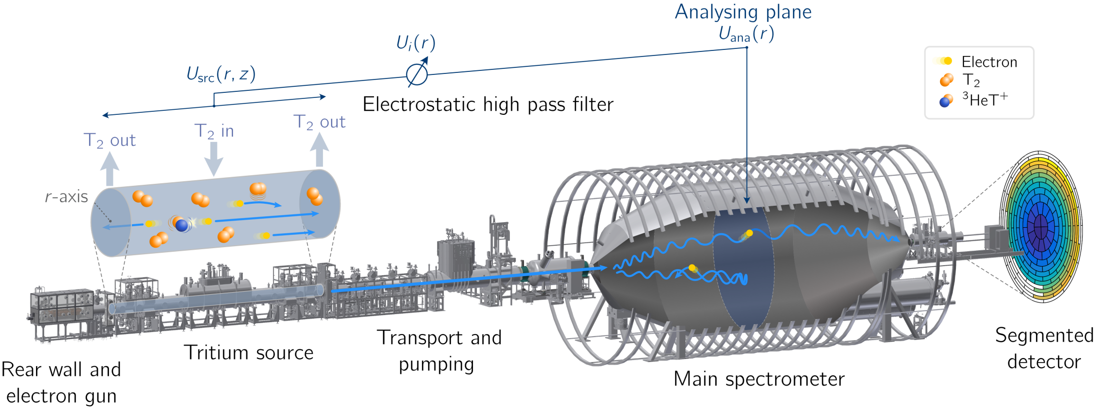
- Different interaction channels are sensitive to different combinations of ϵ_i in GNI Lagrangian.

- GNI cause modifications to the β-spectrum.
  → **Energy-dependent contributions to the rate** in KATRIN
  → First proof of principle study!



The KATRIN Experiment: Overview

70 m long set-up: a gaseous tritium source & high resolution MAC-E filter

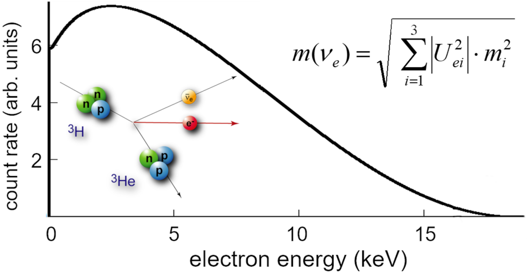


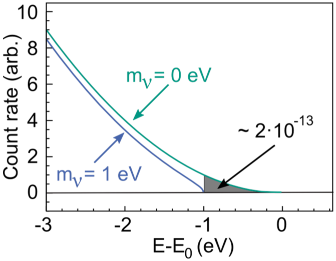
Tritium β-decay

Continuous β-spectrum described by Fermi's Golden Rule, measurement of effective mass $m(\nu_e)$ based on kinematic parameters & energy conservation.

$$\boxed{\frac{d\Gamma}{dE} \propto (E_0 - E)\sqrt{(E_0 - E)^2 - m^2(\nu_e)}\,\Theta(E_0 - E - m_i)}$$

$$m(\nu_e) = \sqrt{\sum_{i=1}^{3} \left|U_{ei}^2\right| \cdot m_i^2}$$





GNI @ KATRIN

Karlsruhe Institute of Technology

$$\boxed{\frac{d\Gamma_{\mathrm{GNI}}}{dE} = \frac{d\Gamma_{\mathrm{SM}}}{dE} \sum_{k=\beta,\, N} \sqrt{(E_0 - E)^2 - m_k^2} \cdot \xi_k \left[1 - b'_k \frac{m_k}{E_0 - E}\right] \Theta(E_0 - m_k - E)}$$

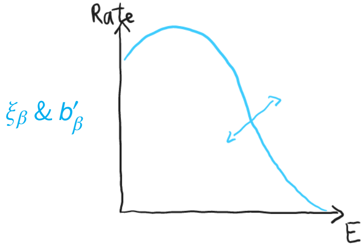
- Total differential decay rate for left-handed neutrino and right-handed neutrino
- Dimensionless coefficients ξ_k and b'_k defined in terms of factors $\epsilon,\ \hat{\epsilon},\ U_{e4}$ and nuclear form factors $g_V,\ g_S,\ g_T$ and g_A.
- Recover SM for $\xi_N = b'_k = 0$.

Bischer and Rodejohann, Nucl. Phys. B, 10.1016/j.nuclphysb.2019.114746

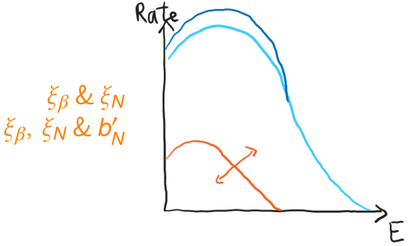
GNI @ KATRIN

$$\boxed{\frac{d\Gamma_{\mathrm{GNI}}}{dE} = \frac{d\Gamma_{\mathrm{SM}}}{dE} \sum_{k=\beta,\,N} \sqrt{(E_0 - E)^2 - m_k^2} \cdot \xi_k \left[1 - b'_k \frac{m_k}{E_0 - E}\right] \Theta(E_0 - m_k - E)}$$

Only left-handed neutrino



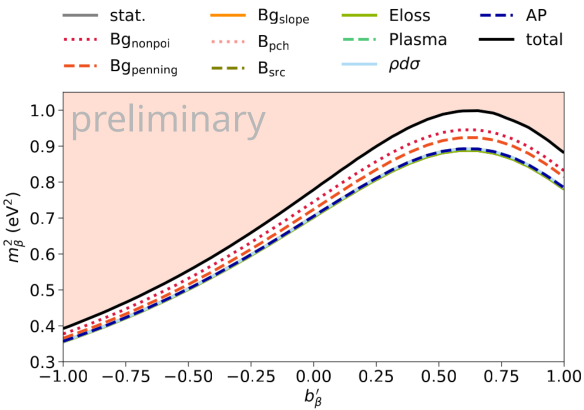
With right-handed neutrino



Sensitivity of GNI for left-handed neutrino

- Can exclude large m_β^2 values (red shaded region).
- Ordering of systematic effects of GNI agrees with ordering from neutrino mass analysis.
  $\longrightarrow$ Proof of principle worked!
- Mild influence of GNI contributions b'_β on neutrino mass sensitivity.
  $\longrightarrow$ Possible to probe different GNI scenarios!
- Sensitivity is dominated by statistics.
  $\longrightarrow$ Further improvement by adding more data.

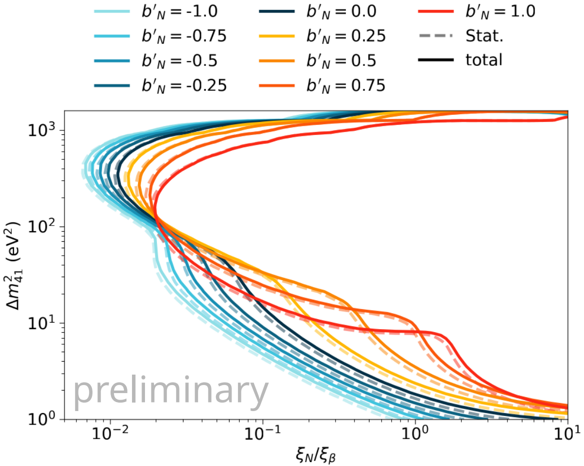
Preliminary Study on KNM2 MC at 95 % CL



Sensitivity of GNI for right-handed neutrino

- Able to probe sterile neutrino parameter space with GNI model using $b'_N = 0$ and $\xi_N = \tan^2\theta \cdot (g_A^2 + 3g_V^2)$.
  $\longrightarrow$ Allows cross-check between GNI and $3 + 1\ \nu$ model.
- Obtained expected sensitivity shapes, excluding large mixing angles.
- Ordering of systematic effects of GNI agrees with ordering from sterile neutrino mass analysis.
  $\longrightarrow$ Proof of principle worked!

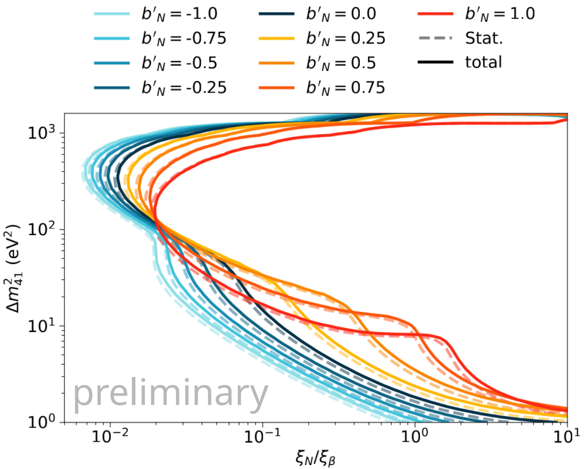
Preliminary Study on KNM2 MC at 95 % CL



Sensitivity of GNI for right-handed neutrino

- Able to probe different GNI scenarios:
  - **Single type of interaction**:
    ϵ_T gives strongest constraints at $\mathcal{O}(10^{-2})$.
    Constraints for similar parameters from other experiments (LHC, neutron decay) up to $\mathcal{O}(10^{-3})$.
  - **Right-handed W boson**:
    Only consider vector-like interactions.
  - **Leptoquark**:
    Different combinations of interactions possible, dependent on Leptoquark model.
  - **Charged Higgs**:
    Only consider scalar interactions.
- Sensitivity is dominated by statistics.
  $\longrightarrow$ Further improvement by adding more data.

Preliminary Study on KNM2 MC at 95 % CL

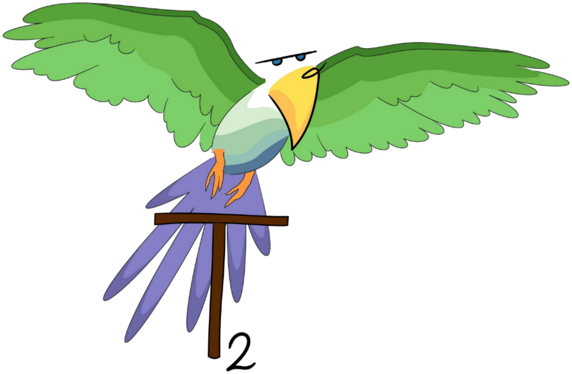


10.1016/j.ppnp.2018.08.002, 10.1002/andp.201300072

Summary & Outlook

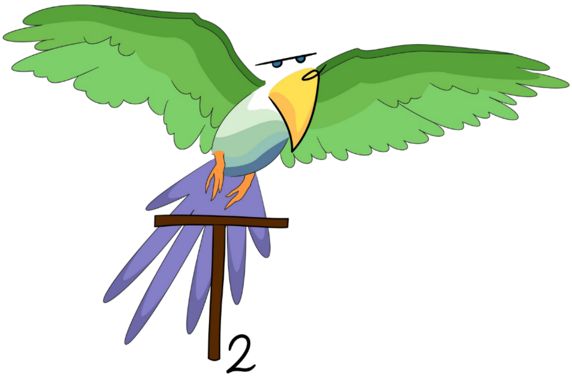
- Theory of General Neutrino Interactions is a **powerful tool** in the search for New Physics.
- KATRIN's high-precision measurement of the β-spectrum allows to **constrain combinations of GNI** contributions.
- More concrete constraints are possible when considering **specific New Physics models**.
- **Sensitivity will continuously improve** by adding more data.
- Analysis on data is almost finalized and will be **released soon**!

Thank you for your attention!



We acknowledge the support of Helmholtz Association (HGF); Ministry for Education and Research BMBF (05A17PM3, 05A17PX3, 05A17VK2, 05A17PDA, 05A17WO3, 05A20VK3, 05A20PMA and 05A20PX3); Helmholtz Alliance for Astroparticle Physics (HAP); the doctoral school KSETA at KIT; Helmholtz Young Investigator Group (VH-NG-1055); Max Planck Research Group (MaxPlanck@TUM); Deutsche Forschungsgemeinschaft DFG (Research Training Group grant nos. GRK 1694 and GRK 2149); Graduate School grant no. GSC 1085-KSETA, SFB-1258, and Excellence Cluster ORIGINS in Germany; Ministry of Education, Youth and Sport (CANAM-LM2015056, LTT19005) in the Czech Republic; the Department of Energy through grants DE-FG02-97ER41020, DE-FG02-94ER40818, DE-SC0004036, DE-FG02-97ER41033, DE-FG02-97ER41041, DE-SC0011091 and DE-SC0019304; and the Federal Prime Agreement DE-AC02-05CH11231 in the USA. This project has received funding from the European Research Council (ERC) under the European Union Horizon 2020 research and innovation programme (grant agreement no. 852845). We thank the computing cluster support at the Institute for Astroparticle Physics at Karlsruhe Institute of Technology, Max Planck Computing and Data Facility (MPCDF), and National Energy Research Scientific Computing Center (NERSC) at Lawrence Berkeley National Laboratory.

Backup



Flavour Space Tensor

j	ϵ_j	$\mathcal{O}_j$	$\mathcal{O}'_j$
1	ϵ_L	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
2	$\tilde{\epsilon}_L$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1-\gamma^5)$
3	ϵ_R	$\gamma_\mu(1-\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
4	$\tilde{\epsilon}_R$	$\gamma_\mu(1+\gamma^5)$	$\gamma^\mu(1+\gamma^5)$
5	ϵ_S	$(1-\gamma^5)$	1
6	$\tilde{\epsilon}_S$	$(1+\gamma^5)$	1
7	$-\epsilon_P$	$(1-\gamma^5)$	γ^5
8	$-\tilde{\epsilon}_P$	$(1+\gamma^5)$	γ^5
9	ϵ_T	$\sigma_{\mu\nu}(1-\gamma^5)$	$\sigma^{\mu\nu}(1-\gamma^5)$
10	$\tilde{\epsilon}_T$	$\sigma_{\mu\nu}(1+\gamma^5)$	$\sigma^{\mu\nu}(1+\gamma^5)$

$$\mathcal{L}_{GNI}^{CC} = -\frac{G_F V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,ud} \right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha \mathcal{O}_j \nu_\beta\right) \left(\bar{u}_\gamma \mathcal{O}'_j d_\delta\right) + h.c.$$

- $\epsilon_{L/R}$: Coupling for left-/right-handed vector-like interactions
- ϵ_S: Coupling for scalar interactions
- ϵ_P: Coupling for pseudo-scalar interactions
- ϵ_T: Coupling for tensor-like interactions

GNI - ϵ and ϵ^2

- For different ϵ-parameters we get slightly different transformations
- $q \geq C \cdot |\epsilon|^2$ with
  - $C = \frac{1}{1 - \frac{1}{2}|\epsilon|^2}$ for ϵ_L^N or ϵ_R^N
  - $C = 1$ for $\widetilde{\epsilon_L^N}$ or $\widetilde{\epsilon_R^N}$
  - $C = \frac{g_S^2}{g_V^2 + 3g_A^2} \approx 0.17945$ for ϵ_S^N or $\widetilde{\epsilon_S^N}$
  - $C = \frac{48 g_T^2}{g_V^2 + 3g_A^2} \approx 8.06537$ for ϵ_T^N or $\widetilde{\epsilon_T^N}$
- See results on the next slides!

$$\begin{aligned}
\xi_\beta &= g_V^2 \left(|\widehat{\epsilon}_L + \epsilon_R|^2 + |\widetilde{\epsilon}_L + \widetilde{\epsilon}_R|^2\right) + g_S^2 \left(|\epsilon_S|^2 + |\widetilde{\epsilon}_S|^2\right) \\
&\quad + 3g_A^2 \left(|\widehat{\epsilon}_L - \epsilon_R|^2 + |\widetilde{\epsilon}_L - \widetilde{\epsilon}_R|^2\right) + 48 g_T^2 \left(|\epsilon_T|^2 + |\widetilde{\epsilon}_T|^2\right), \\
\xi_\beta b_\beta &= g_V g_S \, 2\mathrm{Re}\left[(\widehat{\epsilon}_L + \epsilon_R)\epsilon_S + (\widetilde{\epsilon}_L + \widetilde{\epsilon}_R)(\widetilde{\epsilon}_S)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(\widehat{\epsilon}_L - \epsilon_R)(\epsilon_T)^* - (\widetilde{\epsilon}_L - \widetilde{\epsilon}_R)(\widetilde{\epsilon}_T)^*\right], \\
\xi_\beta b'_\beta &= g_V g_S \, 2\mathrm{Re}\left[(\widehat{\epsilon}_L + \epsilon_R)\widetilde{\epsilon}_S + \epsilon_S(\widetilde{\epsilon}_L + \widetilde{\epsilon}_R)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(\widehat{\epsilon}_L - \epsilon_R)(\widetilde{\epsilon}_T)^* - (\widetilde{\epsilon}_L - \widetilde{\epsilon}_R)(\epsilon_T)^*\right], \\
\xi_\beta c_\beta &= 2\mathrm{Re}\left[g_V^2(\widehat{\epsilon}_L + \epsilon_R)(\widetilde{\epsilon}_L + \widetilde{\epsilon}_R) + g_S^2 \epsilon_S (\widetilde{\epsilon}_S)^*\right] \\
&\quad + 2\mathrm{Re}\left[-3g_A^2(\widehat{\epsilon}_L - \epsilon_R)(\widetilde{\epsilon}_L - \widetilde{\epsilon}_R)^* + 48 g_T^2 \epsilon_T (\widetilde{\epsilon}_T)^*\right].
\end{aligned}$$

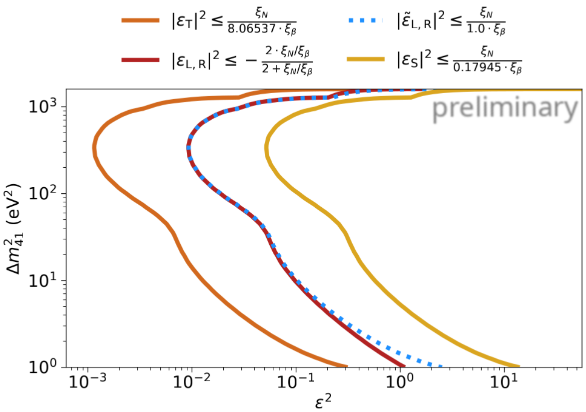
$$\begin{aligned}
\xi_N &= g_V^2 \left(|U_{e4} + \epsilon_L + \epsilon_R|^2 + |\widetilde{\epsilon}_L + \widetilde{\epsilon}_R|^2\right) + g_S^2 \left(|\epsilon_S|^2 + |\widetilde{\epsilon}_S|^2\right) \\
&\quad + 3g_A^2 \left(|U_{e4} + \epsilon_L - \epsilon_R|^2 + |\widetilde{\epsilon}_L - \widetilde{\epsilon}_R|^2\right) + 48 g_T^2 \left(|\epsilon_T|^2 + |\widetilde{\epsilon}_T|^2\right), \\
\xi_N b_N &= g_V g_S \, 2\mathrm{Re}\left[(U_{e4} + \epsilon_L + \epsilon_R)(\epsilon_S)^* + (\widetilde{\epsilon}_L + \widetilde{\epsilon}_R)(\widetilde{\epsilon}_S)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(U_{e4} + \epsilon_L - \epsilon_R)(\epsilon_T)^* - (\widetilde{\epsilon}_L - \widetilde{\epsilon}_R)(\widetilde{\epsilon}_T)^*\right], \\
\xi_N b'_N &= g_V g_S \, 2\mathrm{Re}\left[(U_{e4} + \epsilon_L + \epsilon_R)(\widetilde{\epsilon}_S)^* + \epsilon_S(\widetilde{\epsilon}_L + \widetilde{\epsilon}_R)^*\right] \\
&\quad - 3 g_A g_T \, 8\mathrm{Re}\left[(U_{e4} + \epsilon_L - \epsilon_R)(\widetilde{\epsilon}_T)^* - (\widetilde{\epsilon}_L - \widetilde{\epsilon}_R)(\epsilon_T)^*\right], \\
\xi_N c_N &= 2\mathrm{Re}\left[g_V^2(U_{e4} + \epsilon_L + \epsilon_R)(\widetilde{\epsilon}_L + \widetilde{\epsilon}_R)^* + g_S^2 \epsilon_S (\widetilde{\epsilon}_S)^*\right] \\
&\quad + 2\mathrm{Re}\left[-3g_A^2(U_{e4} + \epsilon_L - \epsilon_R)(\widetilde{\epsilon}_L - \widetilde{\epsilon}_R)^* + 48 g_T^2 \epsilon_T (\widetilde{\epsilon}_T)^*\right].
\end{aligned}$$

Sensitivity of GNI for right-handed neutrino

- Draw conclusions from sensitivity on $\frac{\xi_N}{\xi_\beta}$ to sensitivity on ϵ-parameters.
- Most sensitive to ϵ_T at $\mathcal{O}(10^{-2})$
- Constraints for similar parameters from other experiments (LHC, neutron decay) at $\mathcal{O}(10^{-3})$

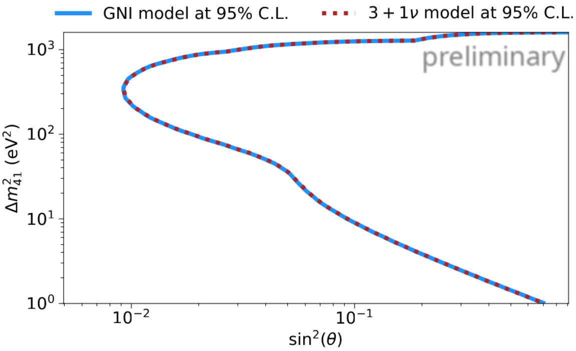
10.1016/j.ppnp.2018.08.002, 10.1002/andp.201300072

Preliminary Study on first year MC at 95 % CL



Sensitivity of GNI for right-handed neutrino

Preliminary Study on first year MC

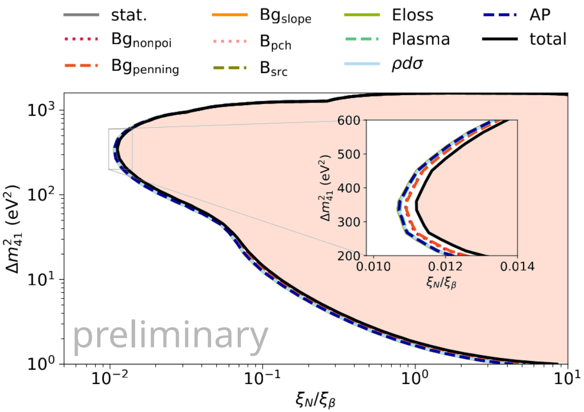


- Able to probe sterile parameter space with GNI model using $\xi_N = \tan^2\theta \cdot (g_A^2 + 3g_V^2)$.
- Cross-check between GNI and $3+1$ ν model $\longrightarrow$ shows good agreement

Sensitivity of GNI for right-handed neutrino

- Ordering of systematic effects agrees with sterile neutrino analysis.
- Sensitivity is dominated by statistics.
  $\longrightarrow$ Further improvement by adding more data.

Preliminary Study on first year MC



Effect of GNI parameters on β-spectrum

- Effect of GNI on sterile neutrino spectrum
- b'_N enhances/diminishes kink-like structure of right-handed neutrino spectrum.