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Overview of KATRIN Results on the Neutrino Mass and New Physics Searches

Caroline Fengler[a,*] **for the KATRIN collaboration**

[a] *Institute for Experimental Particle Physics (ETP), Karlsruhe Institute of Technology (KIT) Hermann-von-Helmholtz-Platz 1, 76344 Eggenstein-Leopoldshafen, Germany*

E-mail: caroline.fengler@kit.edu

The KArlsruhe TRItium Neutrino (KATRIN) collaboration aims to measure the neutrino mass by precision spectroscopy of tritium β-decay with 0.2 eV target sensitivity. Recently, KATRIN has improved the upper bound on the effective electron-neutrino mass to 0.8 eV at 90 % confidence level [3].
Probing the neutrino mass is the main purpose of the KATRIN experiment. Beyond this, the ultra-precise measurement of the β-spectrum can be used for new physics searches. We report on the investigations and results on the neutrino mass, as well as on Lorentz Invariance Violations, Light Sterile Neutrinos, and General Neutrino Interactions.

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*Speaker

1. The KATRIN Experiment

Measuring the mass of the neutrino gives access to physics beyond the standard model and has strong implications for astroparticle physics and cosmology. In contrast to cosmological observations or the search for the neutrinoless double beta decay ($0\nu\beta\beta$), the measurement principle at KATRIN follows a purely kinematic and therefore model-independent approach to measure the effective neutrino mass,

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

It relies only on the energy-momentum-conservation of the β-decay of tritium. The differential decay rate of the continuous β-spectrum can be described by Fermi's Golden Rule as follows:

$$\frac{\mathrm{d}\Gamma}{\mathrm{d}E} = C\, p\, (E + m_e)\, (E_0 - E) \sum_i \left|U_{ei}^2\right| \sqrt{(E_0 - E)^2 - m_i^2}\, F(E, Z)\, \Theta(E_0 - E - m_i). \tag{2}$$

Here, $F(E, Z)$ denotes the Fermi function and E_0 is the maximum kinetic energy of the electron given a zero neutrino mass, namely the endpoint energy. Since the shape and endpoint energy of the β-spectrum are dependent on the neutrino mass KATRIN performs high-precision spectroscopy of the β-spectrum's endpoint region to determine the neutrino mass. The experimental setup is shown in figure 1. The decay of gaseous molecular tritium takes place in the source section. The resulting β-electrons are then magnetically guided along the beamline through the transport section. Here, all remaining tritium molecules are extracted and recirculated. The main spectrometer serves the energy discrimination of the electrons, using the Magnetic Adiabatic Collimation combined with an Electrostatic filter (MAC-E filter) principle [8, 23, 26]. Only electrons with sufficient energy to overcome the electrostatic retarding potential can pass the main spectrometer and are counted on the 148 pixel segmented detector. By setting the retarding potential to different values the endpoint region of the integral β-spectrum is scanned [6].

2. The Neutrino Mass Analysis and Results

In order to evaluate the measured count rate as a function of the retarding energy a theoretical prediction of the rate R is needed. For this purpose, the theoretical differential β-spectrum can be convoluted with an experimental response function, accounting for the transmission properties of the experiment including scattering effects:

$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} \underbrace{R_\beta(e, m^2(\nu_e))}_{\text{Beta Spectrum}} \cdot \underbrace{f(E - qU)}_{\text{Response function}}\, \mathrm{d}E + R_{bg} \tag{3}$$

The rate prediction includes the four fundamental parameters describing the spectrum: the spectrum's amplitude A_s, the endpoint E_0, the neutrino mass $m^2(\nu_e)$, and the background rate R_{bg}. The analysis procedure uses the minimisation of negative log-likelihood functions. Systematic uncertainties can be propagated via different methods, such as covariance matrices, Monte Carlo

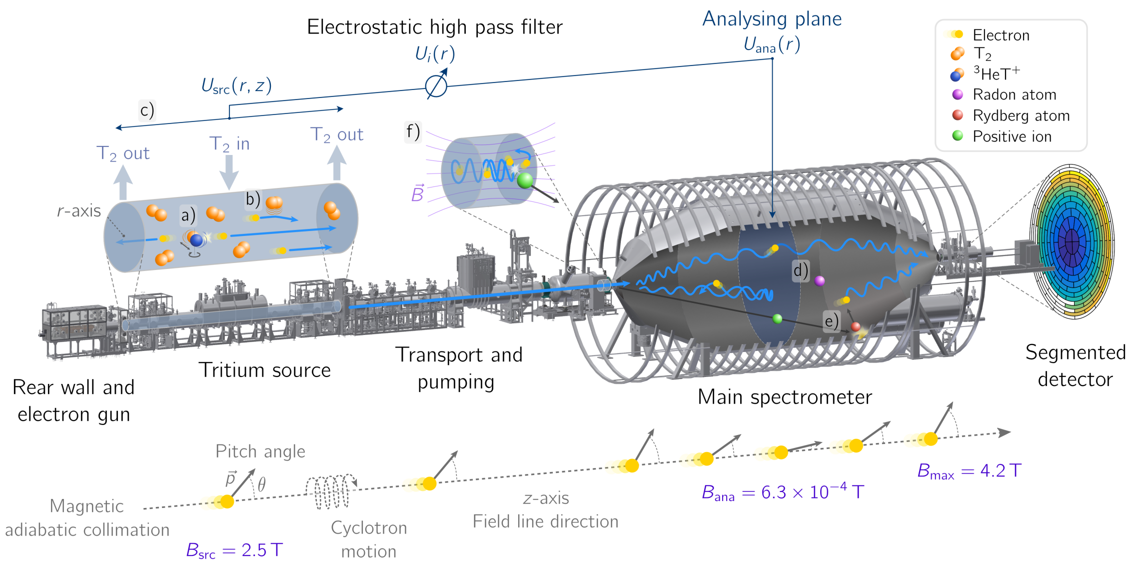


Figure 1: The KATRIN beamline. Tritium decays in the source section. The β-electrons resulting from this decay are magnetically guided through the experiment towards the detector. In the main spectrometer the electrons are discriminated based on their energy using the MAC-E filter principle. Electrons with sufficient energy pass the main spectrometer and are counted at the detector [3].

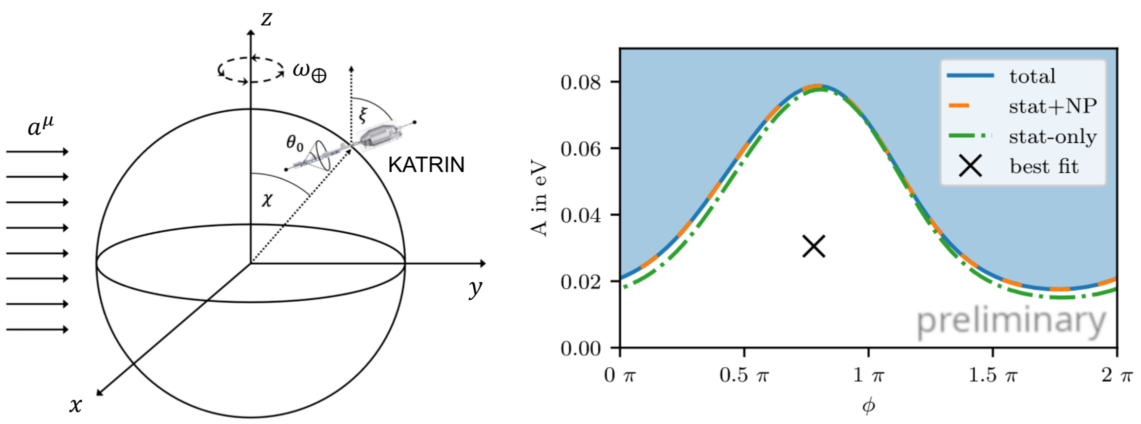
propagation, the pull term, and the Bayesian methods [3, 5]. The pull term method is adding additional fit parameters with constraints from external systematic measurements.

In a combined analysis of the first two measurement campaigns an upper limit on the neutrino mass of $m_\nu < 0.75$ eV (90 % CL) [3] was reached, which is the first sub-eV neutrino mass limit from a direct kinematic measurement. Currently the combined analysis for measurement campaigns one to five is ongoing with an expected sensitivity of ~ 0.5 eV.

3. Search for Lorentz Invariance Violation in KATRIN Data

The CPT and Lorentz invariance belong to the fundamental symmetries of the Standard Model (SM). Nevertheless, some extensions of the Standard Model, such as String theory [20, 21], loop quantum gravity [15], and non-commutative quantum field theory [11] suggest CPT and Lorentz invariance violations (LIV) at high energies. These deviations from Lorentz invariance are typically described by means of an effective field theory, called the Standard Model Extension (SME) [12, 13, 18], which contains all possible Lorentz-invariance violating operators for neutrino propagation. For many of those operators, strong constrains have been set by oscillation [19] and time-of-flight experiments. However, there are four so called “oscillation-free” modes $\left(a_{\text{of}}^{(d=3)}\right)_{jm}$, which can only be accessed using an interaction process, such as the β-decay in KATRIN [14, 22]. The term of the SME introducing this Lorentz-invariance-violating four-vector a^μ for tritium β-decay can be written as

$$\mathcal{L}^a_{SME} = -\bar{\psi}_w\, a^\mu\, \gamma_\mu\, \psi_w \qquad w \in \{\text{T, He, e}, \nu\}. \tag{4}$$



(a) Sketch of equatorial coordinate system.

(b) 90 % CL exclusion contour for sidereal oscillation.

Figure 2: Search for LIV. (a) Rotation of KATRIN in the Lorentz invariance violating field a^μ. The changing angle between the β-electrons in KATRIN and a^μ causes a change in particle momentum and therefore in a change of the endpoint energy E_0 [2]. **(b)** 90 % CL exclusion contour for sidereal oscillation parameters, amplitude A and phase ϕ, for the first KATRIN measurement campaign. The amplitude translates to the time-dependent component of the Lorentz-invariance-violating vector-field according to equation 5. The parameter space marked in blue is excluded [2].

It gives a Lagrangian contribution for each of the fermions, in particular the tritium, the helium, the electron, and the neutrino. These contributions generate terms at first order $\propto a^\mu p_\mu = a_0 p_0 - a_i p_i$ when calculating the β-decay spectrum. This leads to a change of the external particles' momenta with a time-dependent and a time-independent component, which directly translates to a time-dependent and time-independent shift of the endpoint energy E_0.

The layout of the KATRIN experiment allows for an investigation of the influence of the Lorentz-invariance-violating vector-field a^μ on the particle momentum and endpoint energy, as visualised in figure 2a. The Earth and therefore the KATRIN experiment rotates with $\omega_\oplus$ in a^μ, while the electrons move with up to a maximum acceptance angle θ_0 along the KATRIN beamline. The changing angle between a^μ and the electron momentum translates into a sidereal oscillation of the endpoint energy E_0. This gives access to the Lorentz-invariance-violating parameter $\left|\left(a_{\text{of}}^{(3)}\right)_{11}\right|$, the periodically time-dependent component of the spherical decomposition of a^μ [14, 22]. The time-independent components $\left|\left(a_{\text{of}}^{(3)}\right)_{00}\right|$ and $\left|\left(a_{\text{of}}^{(3)}\right)_{10}\right|$ can be probed by looking for a global shift of the endpoint energy E_0.

For the analysis each scan of the β-spectrum is fit separately, resulting in a 2 h binning of the data. The values for the endpoint energy of each scan are then investigated for their temporal evolution. The estimated amplitude A of the E_0 oscillation is connected to $\left|\left(a_{\text{of}}^{(3)}\right)_{11}\right|$ via

$$A = \sqrt{\frac{3}{2\pi}} \left|\left(a_{\text{of}}^{(3)}\right)_{11}\right| \sqrt{B^2 \cos^2\chi \cos^2\xi + (\beta_{rot} - B\sin\xi)^2}. \tag{5}$$

The obtained sensitivity contour of the amplitude A and phase ϕ for the first KATRIN measurement campaign is shown in figure 2b. No significant oscillation or global shift of E_0 was observed. However, the first upper limit of the time-dependent component is $\left|\left(a_{\text{of}}^{(3)}\right)_{11}\right| < 3.7\times10^{-6}$ GeV (90 %

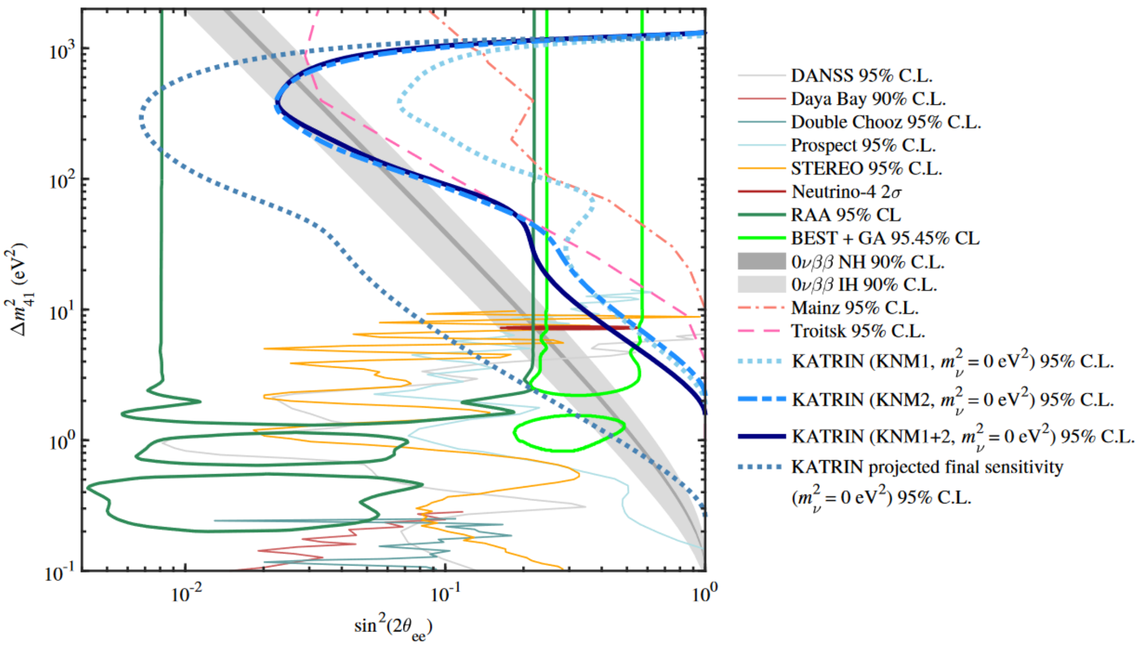


Figure 3: 95 % CL exclusion contours for light sterile neutrinos from the first two KATRIN measurement campaigns. The projected final sensitivity assumes 1000 days measurement time and background reduction to 130 mcps. Large Δm^2_{41} solutions of the RAA and GA were largely excluded [4].

CL). It was furthermore possible to improve the existing upper limits on the time-independent components to $\left|\left(a^{(3)}_{\text{of}}\right)_{00}\right| < 3.0 \times 10^{-8}$ GeV (90 % CL) and $\left|\left(a^{(3)}_{\text{of}}\right)_{10}\right| < 6.4 \times 10^{-4}$ GeV (90 % CL) [2].

4. Search for Light Sterile Neutrinos in KATRIN Data

Motivated by multiple anomalies in the neutrino oscillation data such as the reactor antineutrino anomaly (RAA) [24] and the gallium anomaly (GA) [1, 7, 17], the KATRIN data is analysed for an eV-scale sterile neutrino. For this search a model with three active and one sterile neutrino species is considered. A sterile neutrino appears as a kink-like structure in the electron energy spectrum. The obtained exclusion contour on the sterile parameter space for the first two KATRIN measurement campaigns is shown in figure 3. No significant sterile neutrino signal was observed. However, solutions for large sterile masses Δm^2_{41} of the reactor antineutrino and gallium anomaly [4] were excluded. Further details concerning the analysis procedure are provided in the proceedings by Leonard Köllenberger.

5. Search for General Neutrino Interactions in KATRIN Data

The theory of General Neutrino Interactions (GNI) [9] is a generalised approach to search for novel interactions which contribute to the weak interaction of neutrinos. It is an extension of the neutrino Non-Standard Interactions (NSI), covering scalar (S), pseudoscalar (P), vector (V), axial vector (A) and tensor (T) interactions. In the theory of GNI all possible higher order interaction terms of neutrinos with fermions are added to the Standard Model, embedded into an Effective Field Theory (EFT). This approach requires close to no presumptions,

$$\mathcal{L}_{\mathrm{SMEFT}}(\phi_{\mathrm{SM}}) = \mathcal{L}_{\mathrm{SM}}(\phi_{\mathrm{SM}}) + \sum_{n\geq 5}\sum_{i} \frac{1}{\Lambda^{n-4}} C_i^{(n)} O_i^{(n)}(\phi_{\mathrm{SM}}). \tag{6}$$

Several contributions of the GNI can be investigated through a search for shape variations of the β-spectrum. Such modifications can then be identified in the KATRIN β-spectrum by means of energy-dependent contributions to the rate. The GNI Lagrangian for the 4-fermion-interaction of the β-decay can be written as

$$\mathcal{L}_{\mathrm{GNI}}^{\mathrm{CC}} = -\frac{G_{\mathrm{F}} V_{\gamma\delta}}{\sqrt{2}} \sum_{j=1}^{10} \left(\overset{(\sim)}{\epsilon}_{j,\mathrm{ud}} \right)^{\alpha\beta\gamma\delta} \left(\bar{e}_\alpha O_j \nu_\beta\right) \left(\bar{u}_\gamma O_j' d_\delta\right) + h.c. \tag{7}$$

Here, G_{F} is the Fermi constant and $V_{\gamma\delta}$ is the CKM matrix. $\overset{(\sim)}{\epsilon}_{j,\mathrm{ud}}$ are the flavour space tensors describing the strength of interaction type $j \in \{\mathrm{L/R, S, P, T}\}$ with respect to Standard Model Fermi interaction, with L/R being left-/right-handed vector interactions. ϵ_j and $\tilde{\epsilon}_j$ act on left-handed and right-handed particles, respectively. From the Lagrangian, the total differential decay rate for the KATRIN experiment including the GNI contributions for three active (β) and a sterile (N) neutrino is derived as [10]

$$\begin{aligned}\frac{\mathrm{d}\Gamma}{\mathrm{d}E} &= \frac{G_{\mathrm{F}}^2 V_{\mathrm{ud}}^2}{2\pi^3} \sqrt{(E+m_e)^2 - m_e^2}\,(E+m_e)(E_0 - E) \Bigg\{ \boxed{\sum_{k=\beta,\mathrm{N}}} \sqrt{(E_0-E)^2 - m_k^2} \\ &\times \boxed{\xi_k} \left[1 + \boxed{b_k \frac{m_e}{E+m_e} - b_k' \frac{m_k}{E_0 - E} - c_k \frac{m_e m_k}{(E+m_e)(E_0-E)}} \right] \Theta(E_0 - m_k - E) \Bigg\}. \end{aligned} \tag{8}$$

The additional GNI contributions are marked with boxes. The dimensional coefficients ξ_k, b_k, b_k', and c_k are defined in terms of the flavour space tensors $\overset{(\sim)}{\epsilon}_{j,\mathrm{ud}}$ and the sterile mixing angle U_{e4}. The Standard Model total differential decay rate is recovered by setting $\xi_{\mathrm{N}} = b_k = b_k' = c_k = 0$. Since a strong energy dependency of the GNI contribution is needed to be observable in the β-spectrum, the analysis focuses on the parameters ξ_k and b_k'. The sensitivity of the following parameter combinations have been investigated on Monte Carlo of the second KATRIN measurement campaign:

- **ξ_β & b_β'**: This parameter combination only effects the shape of the β-spectrum for the active neutrinos. Figure 4 shows the 95 % CL sensitivity for the effective neutrino mass m_β^2 over b_β'. The sensitivity on the neutrino mass is slightly influenced by the GNI parameter. Thus, new physics contributions might be relevant for the neutrino mass search. Since the term $\xi_\beta b_\beta'$ depends on $\tilde{\epsilon}_{\mathrm{S}}$ and $\tilde{\epsilon}_{\mathrm{T}}$, it will be possible to derive exclusion limits on these contributions.

- **ξ_β & ξ_{N}**: Considering the GNI parameter ξ_{N} implies adding a sterile neutrino to the β-spectrum. The same can be done using the usual $3+1\nu$ model, as in section 4. A comparison

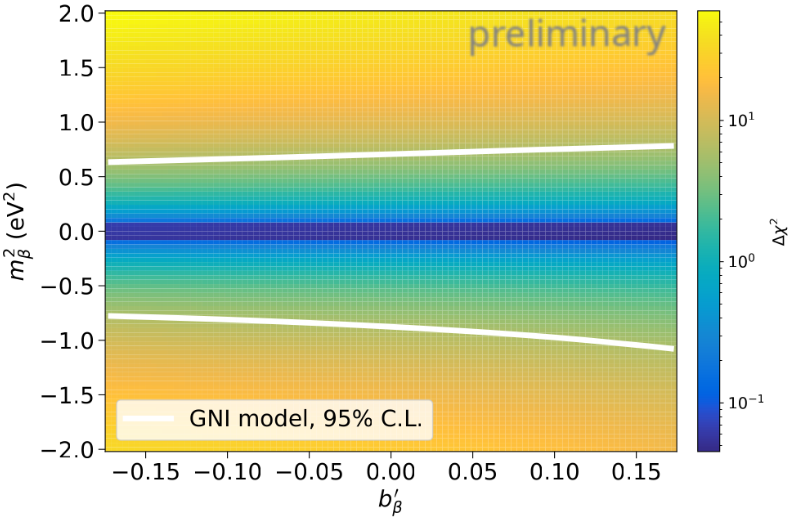


Figure 4: 95 % sensitivity for the GNI parameter b'_β on the KATRIN β-spectrum using the second measurement campaign Monte Carlo. The sensitivity on the neutrino mass m^2_β is slightly dependent on b'_β.

of the sensitivity at 95 % CL for the GNI and $3+1\nu$ model is depicted in figure 5. For comparison, the GNI parameter ξ_N was transformed into the sterile parameter space by $\xi_N = \tan^2\theta \cdot (g_A^2 + 3g_V^2)$. The crosscheck shows a good agreement between the models. Furthermore, the sensitivity on ξ_N can be propagated to the sensitivities on the ϵ factors that depend on ξ_N. The resulting sensitivity at 95 % CL for tensor, left-/right-handed vector and scalar interactions are shown in figure 6. The highest sensitivity is reached for $|\epsilon_T|$ at $O(10^{-2})$. Other experiments, such as the LHC [25] and neutron decay [16] investigations, constrain similar parameters at $O(10^{-3})$. It is expected that the sensitivity on the tensor interactions from KATRIN will be able to compete for a larger data set.

- **ξ_β, ξ_N & b'_N**: Adding the b'_N parameter causes an additional shape distortion of the sterile spectrum. This again enables setting exclusion limits on various GNI contributions. The corresponding studies are currently ongoing.

6. Summary

The KATRIN collaboration has determined a neutrino mass limit in the sub-eV range. This is the current world-best limit from direct single β-decay measurements at $m_\nu < 0.75$ eV (90 % CL). Further New Physics studies illustrate that the scientific potential of KATRIN extends well beyond the neutrino-mass search. New limits on the components of the Lorentz-invariance-violating vector a^μ, as well as on the sterile neutrino mass Δm^2_{41} have been set using data of the first two measurement campaigns. Improved limits are expected for an extended data set. Additionally, a new project, namely the search for General Neutrino Interactions, has been introduced. The corresponding studies could give insight into novel interactions contributing to the weak interaction.

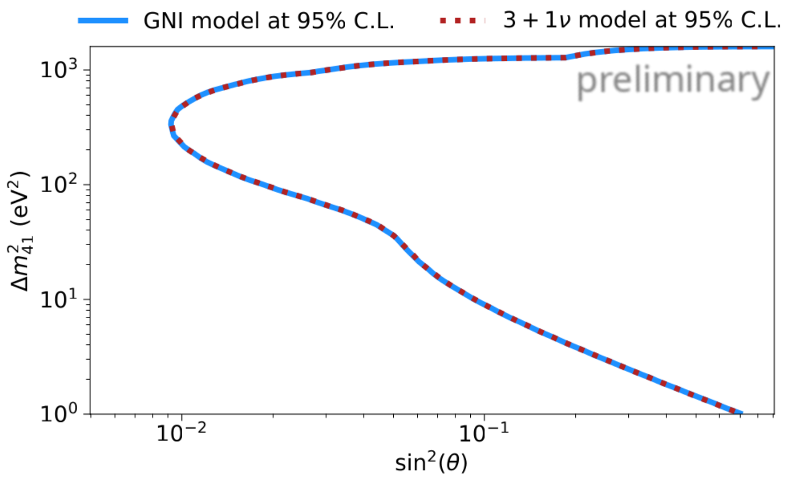


Figure 5: Crosscheck between GNI and $3 + 1\nu$ model sensitivities at 95 % CL on second measurement campaign Monte Carlo. The GNI parameter is transformed into the sterile parameter space by $\xi_\mathrm{N} = \tan^2\theta \cdot (g_\mathrm{A}^2 + 3g_\mathrm{V}^2)$. The models are in a good agreement.

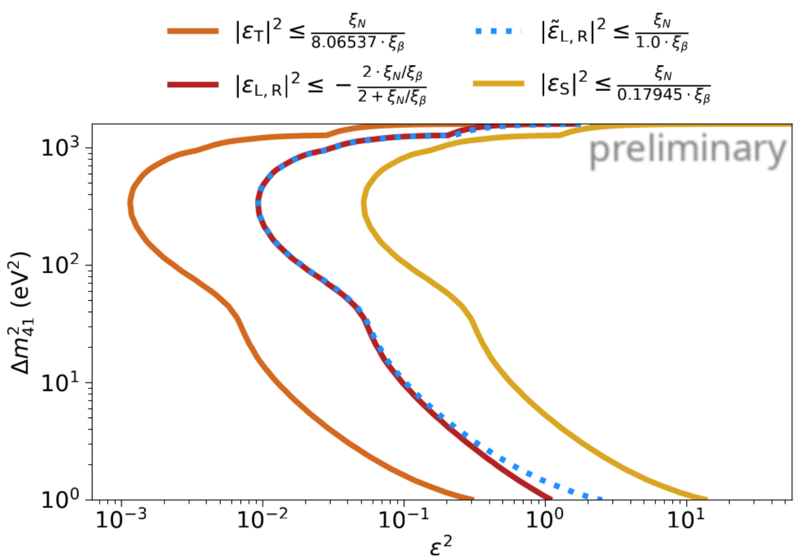


Figure 6: 95 % sensitivity for various ϵ contributions, on second measurement campaign Monte Carlo. The contours are derived from the sensitivity of GNI parameter ξ_N using the given transformations. The transformation factors are composed of nuclear form factors and follow from [10]. The indices refer to the type of interaction: tensor (T), left-/right-handed vector (L/R), and scalar (S).

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