Search for a light sterile neutrino with the KATRIN experiment

NuMass 2024 Workshop, Genova

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Non-standard or Sterile Neutrino

Karlsruher Institut für Technologie

Sterile neutrino = SM neutral singlet fermion

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DM exists $\Longrightarrow$ uncharged particles under SM gauge group $\Longrightarrow$ singlet fermions

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- Members of dark sector could mix with active neutrinos via neutrino portal coupling
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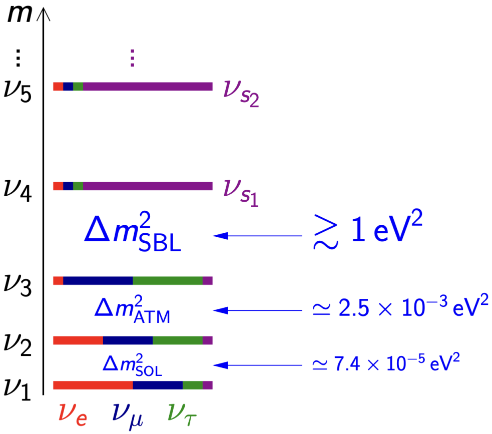
- *Experimental hints for eV scale* :
  - *Appearance* LSND (3σ) and MiniBooNE (4.8σ) excess observations
    Explained by ($\nu_\mu \to \nu_\mathrm{s} \to \nu_\mathrm{e}$)
  - *Disappearance* SAGE and GALLEX: Gallium anomaly (2.9σ deficit)
    Explained by $\nu_e \to \nu_s$
  - The Gallium anomaly reaffirmed by BEST experiment

Interpretation

- SBL anomalies could be explained by an additional neutrino flavor (ν_s)
- There must be at least one additional mass squared difference,
  3ν + 1 framework $\Delta m^2_{SBL} \approx (1-2)\,\mathrm{eV}^2$
- Allowed by solar, atmospheric and long baseline experiments, achieved with $|U_{e4}|^2 \ll 1$



Single β-decay

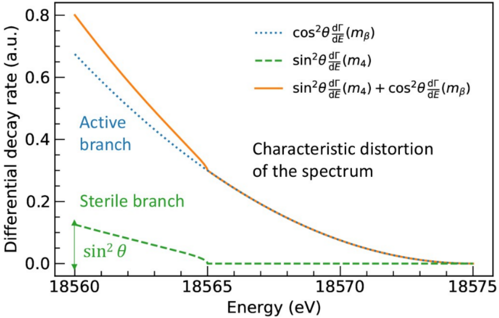
$$m_\nu^2 = \sum_{k=1}^{3} |U_{ek}|^2 m_k^2 \xrightarrow{3+1} \sum_{k=1}^{3} \frac{|U_{ek}|^2}{1 - |U_{e4}|^2} m_k^2$$

- **Differential decay rate**:

$$R_\beta(E, m_\nu^2, m_4^2, |U_{e4}|^2) = \underbrace{(1 - |U_{e4}|^2) \cdot R_\beta(E, m_\nu^2)}_{\text{Active branch}} + \underbrace{|U_{e4}|^2 \cdot R_\beta(E, m_4^2)}_{\text{Sterile branch}}$$

$$= \cos^2\theta \cdot R_\beta(E, m_\nu^2) + \sin^2\theta \cdot R_\beta(E, m_4^2)$$

- A kink at $E_0 - m_4$



KATRIN Experiment

- Kinematics-based neutrino mass experiment
  (expected sensitivity: 0.3 eV (90% CL) after 1000 days of measurement time)
- Current result: m_β< 0.8 eV (90%) CL, *(Nature Phys. 18 (2022) 2, 160-166)*

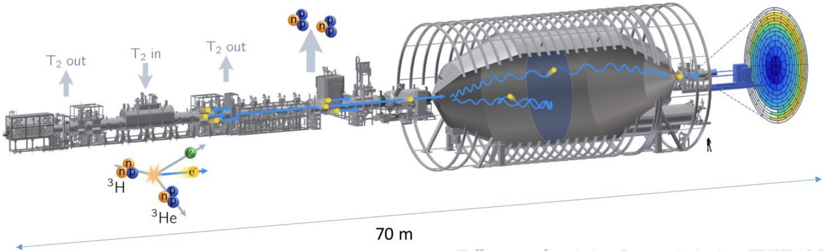
Talk by V. Hannen

Tritium source
- 100 µg of gaseous T_2
- 10^{11} T_2 decays/s

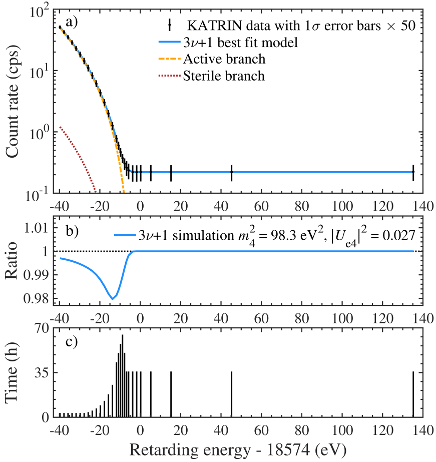
Transport section
- Guidance of electrons
- Removal of tritium

Spectrometer
- Electrostatic filter
- MAC-E filter principle

Detector
- Counts electrons
- Rate vs potential



Sterile Signal in β-decay Spectrum



- Measured integral spectrum $N_{\text{exp}}(qU)$ is fitted to the **model** $N_{\text{model}}(qU, \Theta)$:

$$N_{\text{model}}(qU, \Theta) = A \cdot \int R_{\beta}(E, \Theta) \cdot f(E, qU) + Bg$$

- 6 model parameters:
  - A - Signal amplitude
  - E_0 - effective endpoint energy
  - m^2 - effective mass of electron anti-neutrino
  - Bg - Background rate
  - m_4^2 - sterile neutrino mass
  - $|U_{e4}|^2$ - sterile neutrino mixing

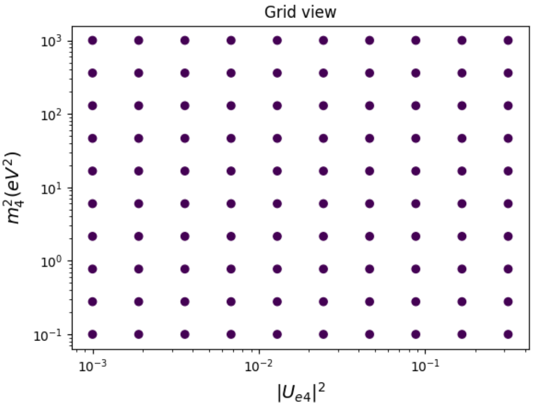
Dataset and Analysis Strategy

- Data selection and combination, active neutrino model configuration are the same as for the active neutrino mass analysis. Talk by W. Xu
- Unblinding procedure[a]
  - Code validation on Monte Carlo twins
  - Tritium spectrum, model, systematics treatment and budget (pull term approach) same as active neutrino mass analysis
  - **Two independent analysis teams with independent codes**:
    - KaFit (exact model evaluation)
    - Netrium (use neural nets for swift model interpolation)

[a] M. Aker et al. "Improved eV-scale sterile-neutrino constraints from the second KATRIN measurement campaign". In: *Phys. Rev. D* 105 (7 2022), p. 072004. DOI: 10.1103/PhysRevD.105.072004.

Analysis method

- Extend Tritium β- spectrum model to 3+1 framework
- **Grid Scan:** 50×50 $\left[\log(|U_{e4}|^2), \log(m_4^2)\right]$ plane
- Contours are drawn at $\Delta\chi^2 = \chi^2 - \chi^2_{BF}$ = 5.99 (95% CL, 2 dof)
- Energy range: $[E_0 - 40, E_0 + 135]$ eV
- Sensitive to $m_4^2 \leq 1600$ eV^2 and $|U_{e4}|^2 \leq 0.5$
- Two complementing analyses
  - **Case-I - Fixed neutrino mass:** m_ν^2 **= 0** $(m_{1,2,3} \ll m_4)$
  - Case-II - Free neutrino mass: m_ν^2 as nuisance parameter



Data collection status

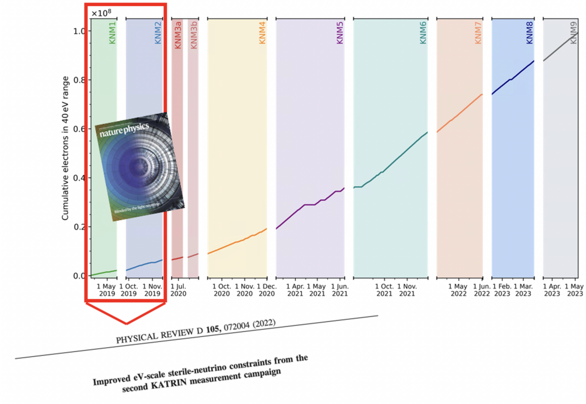


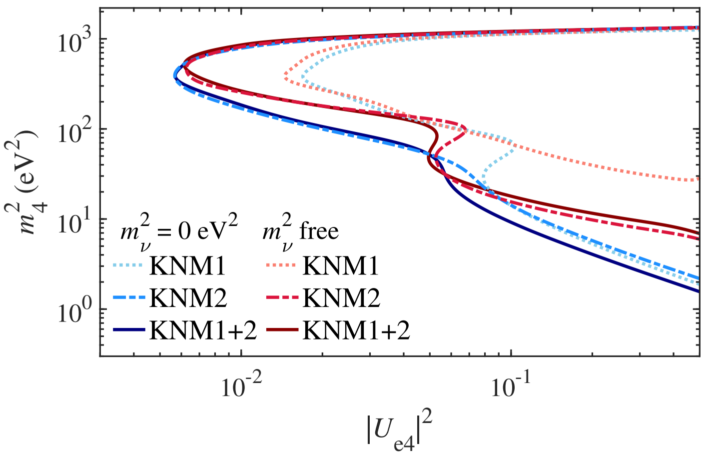
Table: KATRIN Neutrino Mass Measurements (KNM)

Campaign	Time (hrs)	$\rho d\sigma$ (m^{-2})	Bg (mcps)
KNM1	522	1.11×10^{21}	370
KNM2	294	4.23×10^{21}	278
KNM3a	220	2.08×10^{21}	137
KNM3b	224	3.75×10^{21}	258
KNM4	1267	3.77×10^{21}	150
KNM5	1232	3.78×10^{21}	160

- KNM1, KNM2 , KNM3b operated in Nominal Analyzing Plane (NAP) mode

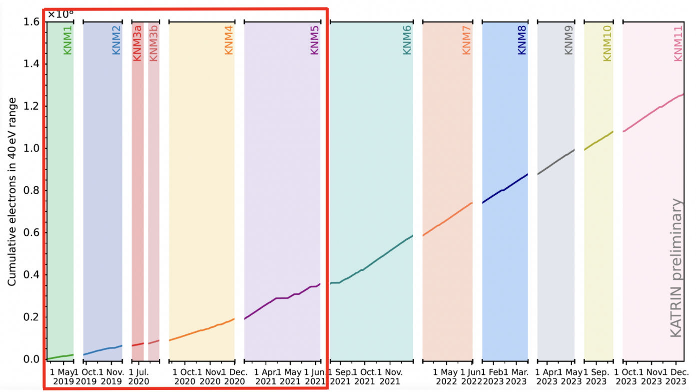
Results from First Two Science Runs

- 5.24×10^6 electrons for 40 eV below E_0, 1265 hours of data
  Best fit:
  - m_4^2 = 59.9 eV^2, $|U_{e4}|^2$ = 0.011, m_ν^2 = 0.0 eV^2
  - $\Delta\chi^2_{null}$ = 0.66
- Active neutrino mass set free
  Best fit:
  - m_4^2 = 87.4 eV^2, $|U_{e4}|^2$ = 0.019, m_ν^2 = 0.57 eV^2
  - $\Delta\chi^2_{null}$ = 1.69
- Signal-to-background ratio of up to 235



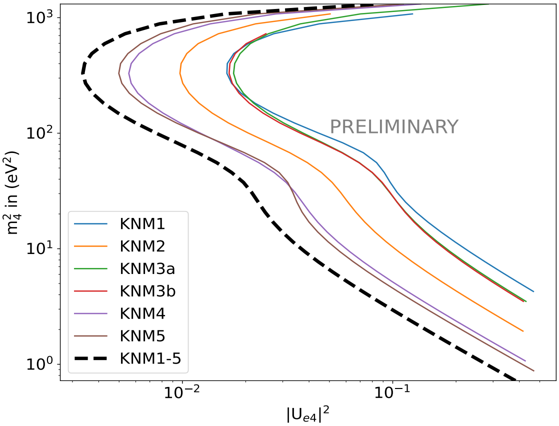
Data collection status

- Significant experimental development: Shifted Analyzing Plane (SAP) background reduction method
  Lokhov et al., EPJ C 82 (2022) 3, 258
- KNM1 to KNM5: 20 % of expected KATRIN data



Sensitivity Results From Five Science Runs

- **Case-I**: $m_\nu^2 = 0$ eV^2
- 40 eV fit range, $|U_{e4}|^2 \in [0, 0.5]$
- Stat. only + all systematics 95% CL
- Gain in overall sensitivity with increased statistics
  S. Mohanty, PoS EPS- HEP2023 (2024)



Campaign	KNM1	KNM2	KNM3a	KNM3b	KNM4	KNM5	KNM1-5
No. of signal electrons ($\times 10^6$)	2.0	4.3	1.1	1.4	10.2	16.8	35.8

Impact of Systematics

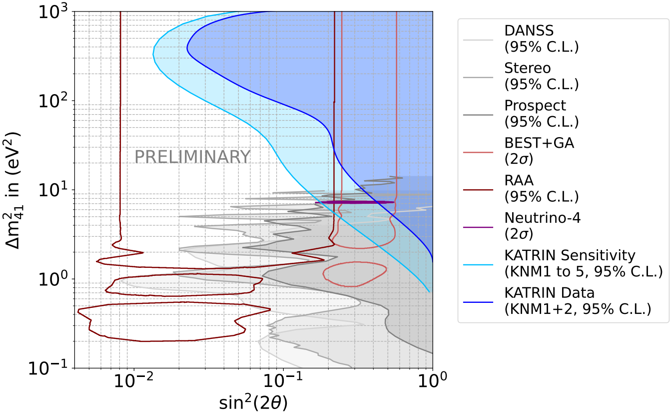
- Calculating 68% CL uncertainty on $|U_{e4}|^2$: $\sigma_{syst} = \sqrt{\sigma^2_{Stat+Syst} - \sigma^2_{Stat}}$
- Statistically dominated uncertainties
- Largest systematic contribution: Penning Bg (low m_4^2), Column Density (high m_4^2)

Sensitivity comparison to other experimental results

- Translation of parameters:

$$\sin^2(2\theta) = 4|U_{e4}|^2(1 - |U_{e4}|^2)$$

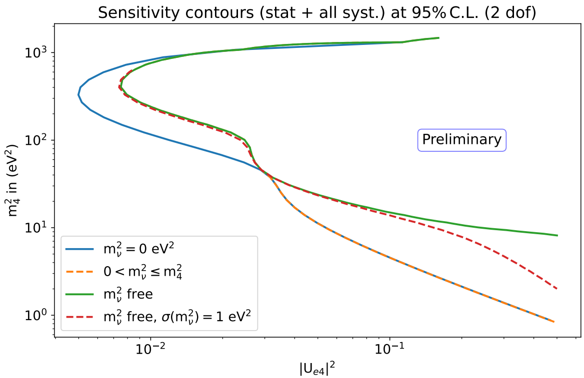
- Large Δm^2_{41} solutions of RAA and BEST+GA anomalies excluded
- Current KATRIN data extends exclusion bounds from SBL oscillation experiments for $\Delta m^2_{41} \geq 10$ eV^2
- Probing large parameter space for light sterile neutrino anomalies
- Expected KNM1-5 sensitivity yields improved constraints in the sterile parameter space



Impact of active neutrino on sterile neutrino search

Possible treatments for m_ν^2: Extension of Case-II

- Free m_ν^2
  Correlation between m_4^2 and m_ν^2.
- Pull term using $\mathbf{0}\pm\mathbf{1}$ eV^2
  Intermediate sensitivity between two extremes (fixed and free)
- $m_4^2 > m_\nu^2 \geq 0$: Limit m_ν^2 by mass of right-handed neutrino
  Reasonable option of optimizing sensitivity in addition to free m_ν^2 case



Summary

- New physics beyond the SM can include sterile neutrinos at all mass scales
- KATRIN uniquely addresses SBL anomalies via spectral shape analysis
- Results from first two science runs (KNM1 + KNM2):
  - No significant sterile-neutrino signal observed
  - Improved exclusion limits w.r.t. complementary experiments

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Outlook:

- Analysis on data for first five science runs ongoing
- Stay tuned for upcoming release!


John Wilkerson, UNC/TUNL (he/him)
R. G. Hamish Robertson
Joseph Formaggio
KATRIN
Diana Parno
Anton Huber (IAP)
Andrew Gavin
Korbinian Urban
Heiko Bouquet
Kevin Gauda
Enrico Ellinger
marco roellig
Joachim Wolf

Thank You

Backups

Experimental hints

- *Appearance* LSND (3σ) and MiniBooNE (4.8σ) excess observations. Explained by ($\nu_\mu \rightarrow \nu_\mathrm{s} \rightarrow \nu_\mathrm{e}$)
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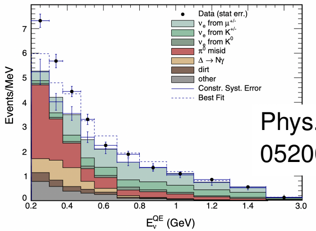
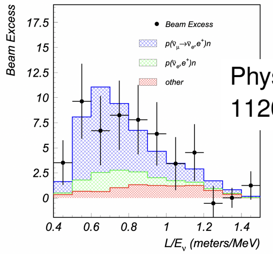
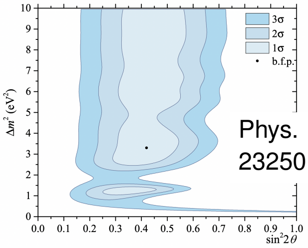


Phys. Rev. D 103, 052002 (2021)

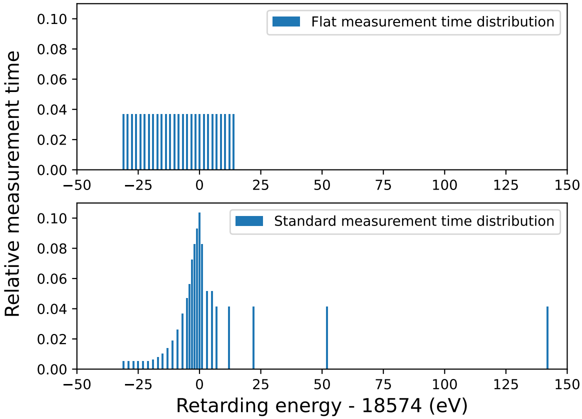


Phys. Rev. D, Vol. 64, 112007 (2001)

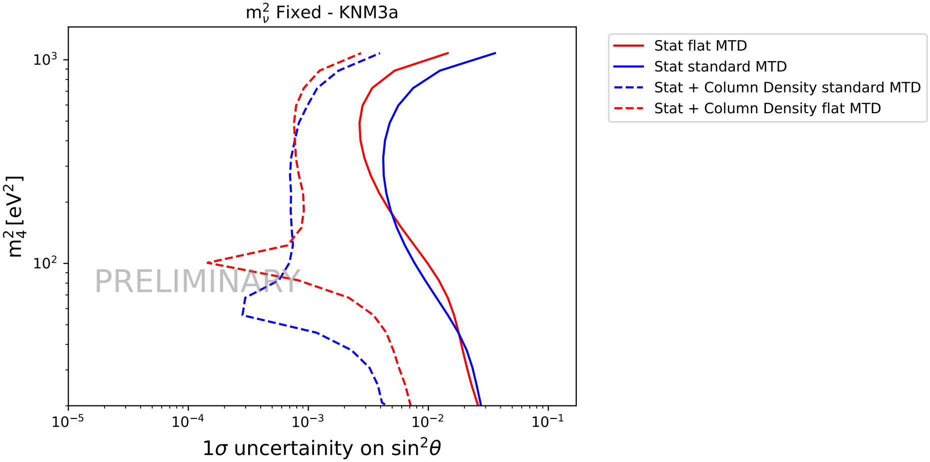


Phys. Rev. Lett. 128, 232501 (2022)

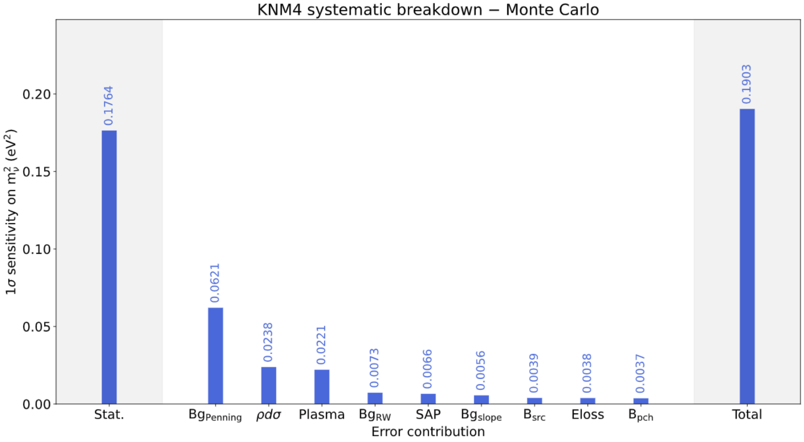
Measurement time distribution - Standard vs Flat



Raster scan on different measured time distributions



Monte Carlo breakdown



Active neutrino correlation with sterile neutrino

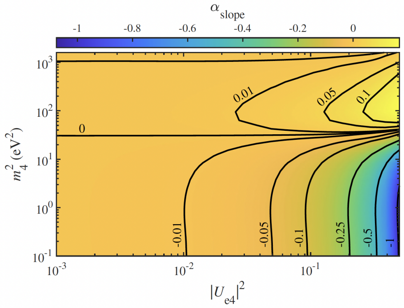
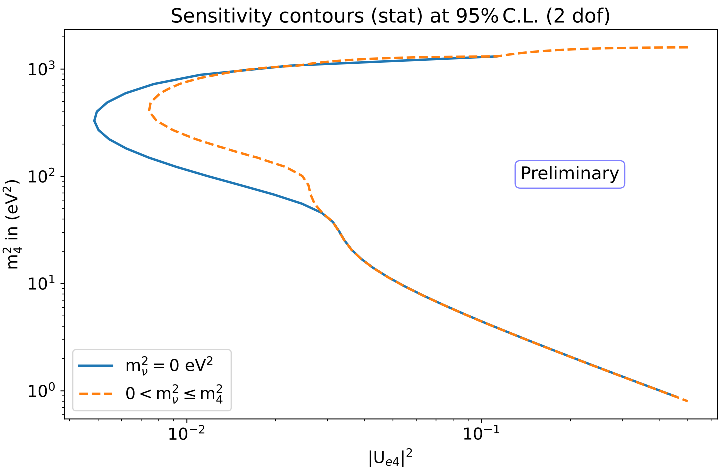


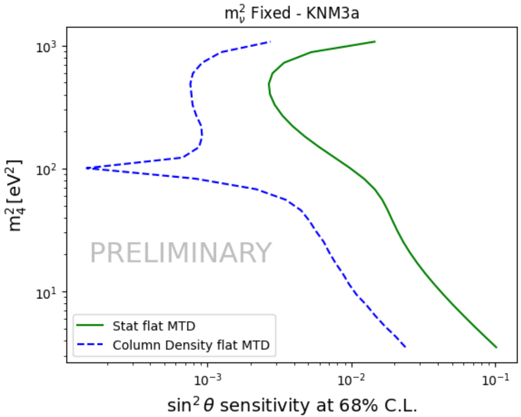
FIG. 4. The correlation between active and sterile neutrino mass is approximately a linear slope $m_\nu^2 = \alpha_{\text{slope}} \cdot m_4^2 + \text{const}$ for various values of m_4^2 and $|U_{e4}|^2$ by analyzing simulated spectra. The gradient indicates the magnitude of α_{slope}. For small mixing $|U_{e4}|^2 < 0.01$, we observe small slope values $|\alpha_{\text{slope}}| < 0.01$. For larger mixing, we find a strong negative correlation for small $m_4^2 \lesssim 30$ eV^2 and a weaker positive correlation for larger m_4^2.

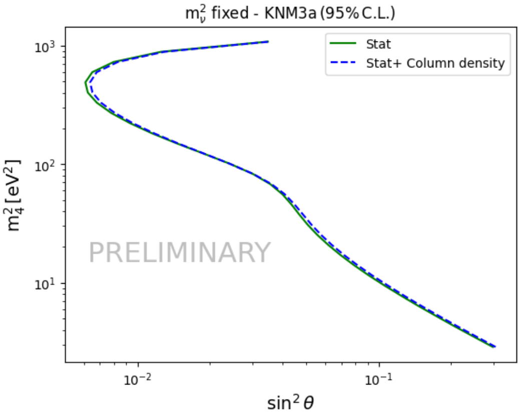
$m_\nu^2 = 0$ vs $m_4^2 > m_\nu^2 \geq 0$



Impact of Measured Time Distribution

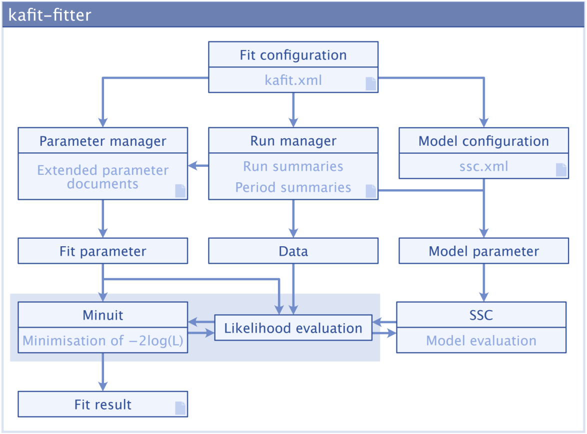
- Objective: To investigate spikes in the raster contours.





Schematic overview of KaFit

- C++ based fitting framework used to analyse measured KATRIN data and simulated data
- Applicable for Frequentist (based on MINUIT class of ROOT) and Bayesian analysis
- Minimisation is performed with MINUIT by minimising the -2log(L)



Testing applicability of Wilks' Theorem

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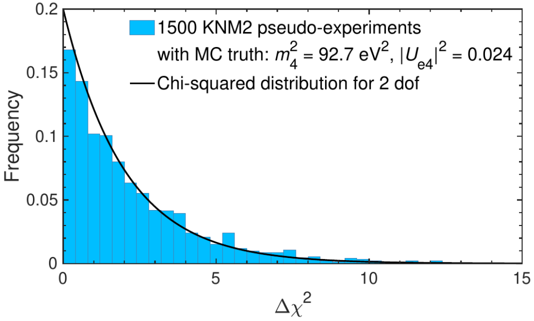
Previously done

- Generate $\mathcal{O}(10^3)$ twins with statistical fluctuations for particular choice of MC truth
- Perform fitting for sterile parameter values on a grid and for MC truth for each sample ($m_\nu^2 = 0$)
- Evaluate $\Delta\chi^2 = \chi^2_{\text{MC truth}} - \chi^2_{\text{best fit}}$ for each sample
- Compare distribution of $\Delta\chi^2$ values to χ^2-distribution with 2 dof



(c) KNM2, MC truth: $m_4^2 = 92.7\,\text{eV}^2$ and $|U_{e4}|^2 = 0.024$

Taken from H.9 of Schlüter, L. (2022). Neutrino-Mass Analysis with sub-eV Sensitivity and Search for Light Sterile Neutrinos with the KATRIN Experiment. PhD Thesis, TU München, Garching bei München.