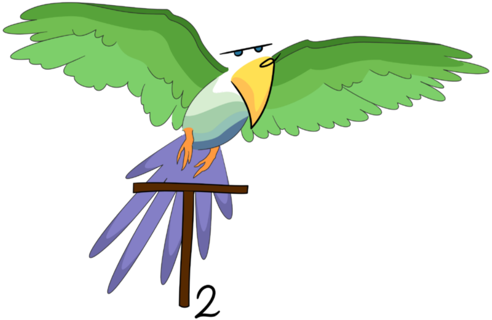
KATRIN neutrino mass analysis

Arbeitstreffen Kernphysik – Schleching 2023

Leonard Köllenberger *for the KATRIN collaboration* | Monday 27th February 2023

Outline

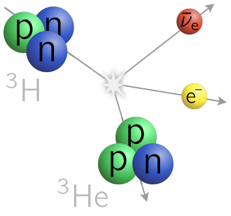


Tritium β-decay

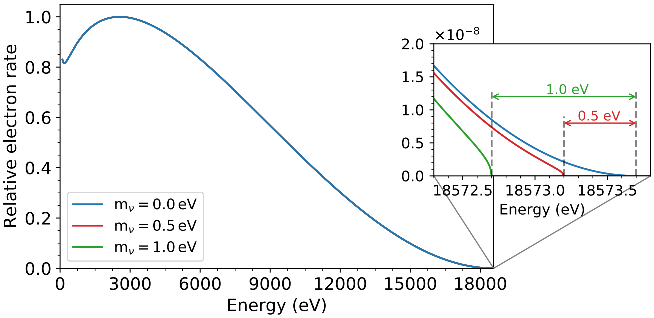
Decay of molecular tritium produces a β-electron spectrum

$$\left(\frac{\mathrm{d}\Gamma}{\mathrm{d}E}\right)_{\text{nucl.}} = C \cdot F\left(Z', E\right) \cdot p\left(E + m_e\right) \cdot \sqrt{(E + m_e)^2 - m_e} \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

$\Longrightarrow$ $m_\nu^2 = \sum_i |U_i|^2 \cdot m_i^2$ can be determined with a precise measurement of the spectral shape near the endpoint



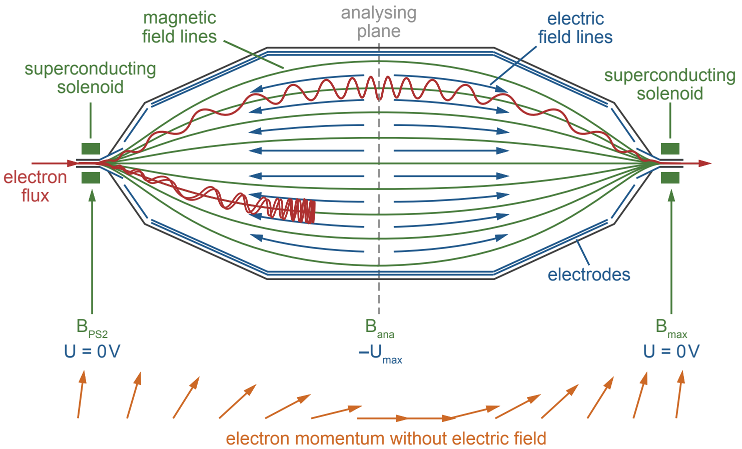
$T_2 \longrightarrow THe^+ + e^- + \bar{\nu}_e$

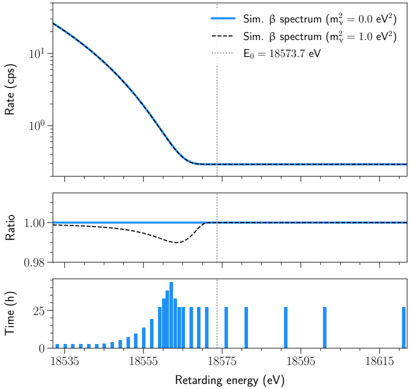


Integrated spectrum measurement

Magnetic **A**diabatic **C**ollimation combined with an **E**lectrostatic filter (MAC-E filter)

Beamson et al. (1980), Lobashev, Spivak (1985), Picard et al. (1992)



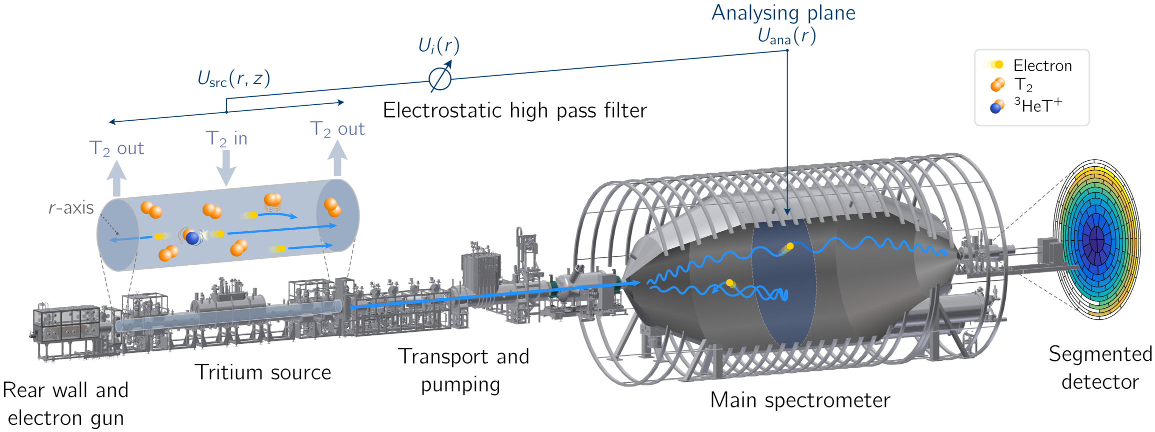


Voltage set points are scanned through to obtain an *integrated spectrum*

The Measurement Time Distribution (MTD) optimised for best sensitivity

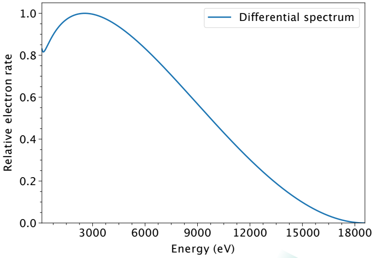
The KATRIN beamline

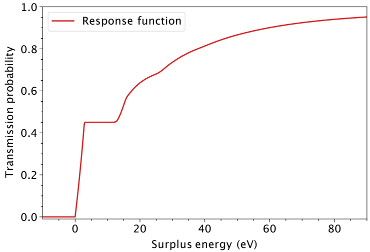
Goal: Measurement of the effective electron anti-neutrino mass with 0.2 eV sensitivity at 90 % C.L.

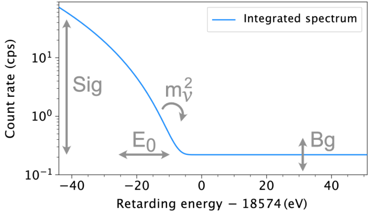


The integrated β-spectrum

$$\dot{N}(qU) = \mathrm{Sig} \cdot N_\mathrm{T} \cdot \frac{\Omega}{4\pi} \cdot \int_{qU}^{E_0} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}\left(E, m_\nu^2, E_0\right) \cdot R(E, qU)\, \mathrm{d}E + N_\mathrm{bg}$$







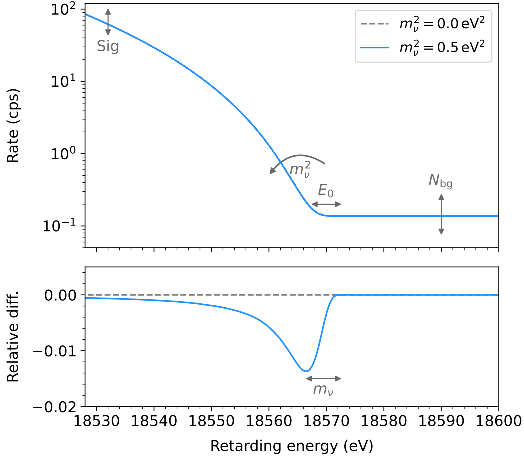
The integrated β-spectrum

- Integrated β-spectrum

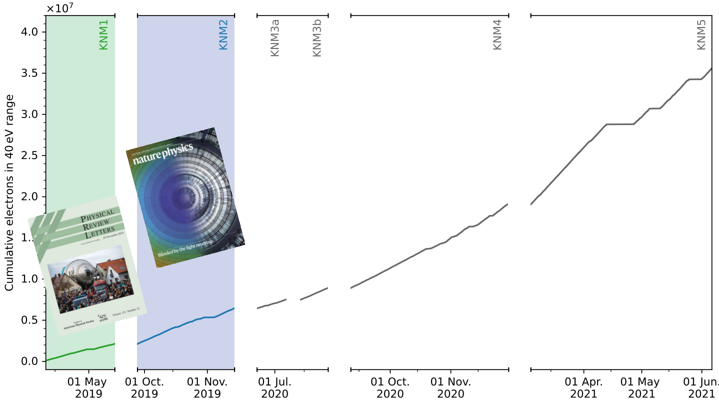
$$\dot{N}(qU) = \mathrm{Sig} \cdot \int_{qU}^{E_0} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}\left(E, m_\nu^2, E_0\right) \cdot R(qU, E)\mathrm{d}E + N_{\mathrm{bg}}$$

- In the most basic form, the spectrum can be characterised by:
  - Spectral amplituder: Sig
  - Endpoint: E_0
  - Squared neutrino mass: m_ν^2
  - Background: N_{bg}

$\Longrightarrow$ In reality this gets a bit more complicated ☺



Measurement campaigns

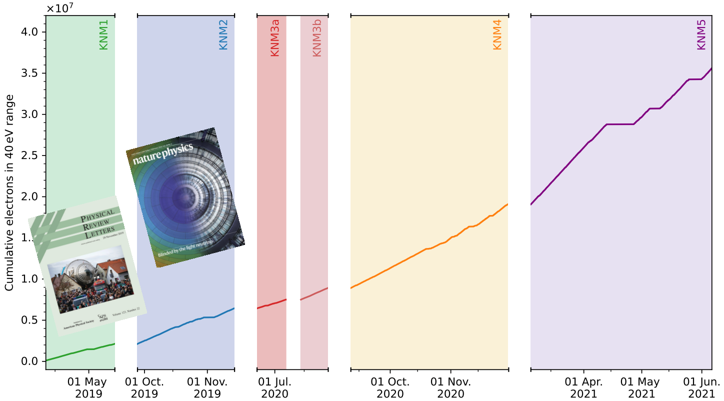


KATRIN **N**eutrino mass **M**easurements

	Time (hrs)	$\boldsymbol{\rho d\sigma}$ **(m^{-2})**	**Bg (mcps)**
KNM1	522	1.09×10^{21}	370
KNM2	294	4.23×10^{21}	278
KNM3a	220	2.07×10^{21}	136
KNM3b	224	3.73×10^{21}	259
KNM4	1267	3.79×10^{21}	150
KNM5	1232	3.79×10^{21}	162

– Published results: KNM1 and KNM2
  Phys. Rev. Lett. 123, 221802
  Nat. Phys. 18, 160–166 (2022)
– Current analysis: KNM1 – KNM5
– Data-taking: KNM6, KNM7, KNM8

Measurement campaigns



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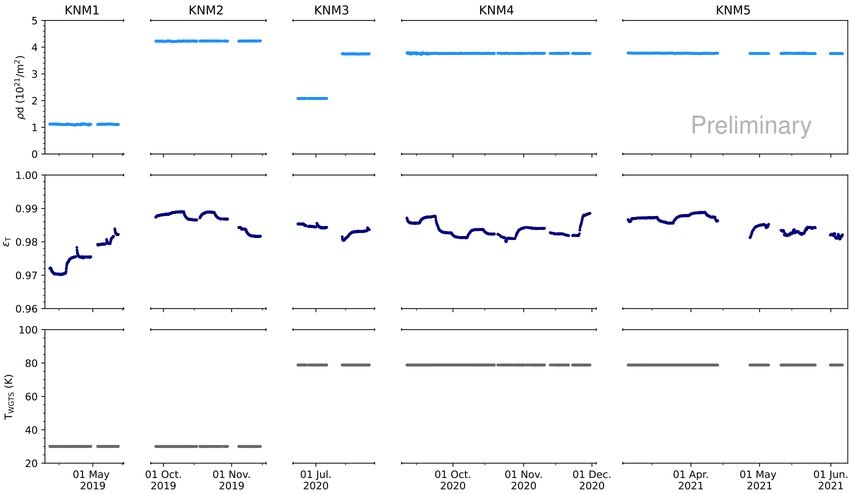
Experimental input parameters

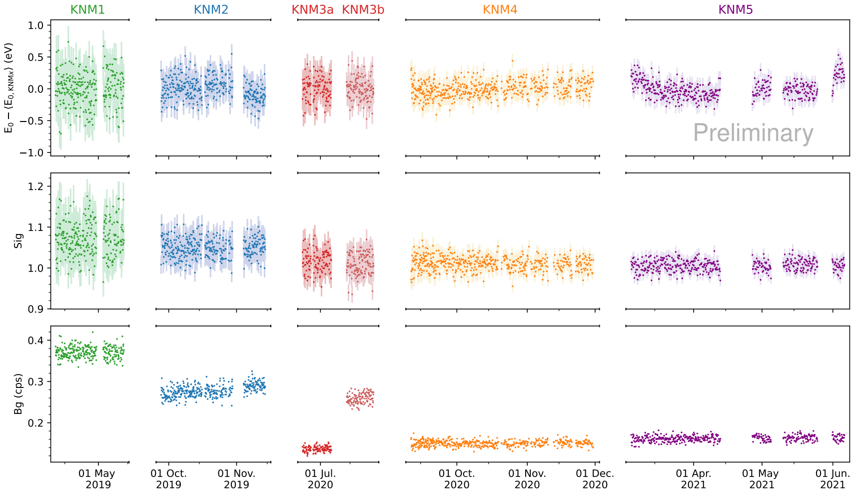
- Column density
  $\Longrightarrow$ Ramped up to stable value of $\sim 3.77 \times 10^{21}\ \mathrm{m}^{-2}$
- Tritium purity
  $\Longrightarrow$ Very stable operation at $>97\,\%$
- Source temperature
  $\Longrightarrow$ $\sim 30\,\mathrm{K} \rightarrow \sim 80\,\mathrm{K}$ with improved gas circulation mode



Run-wise fit parameters

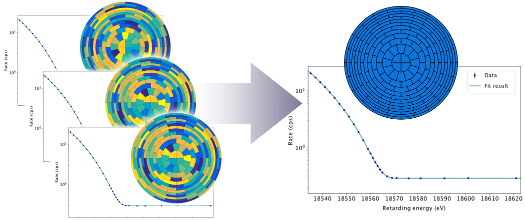
- Experimental settings have been optimised
  - ⟹ Background significantly reduced
- Between KNM1 – KNM5 1987 individual runs were recorded for each pixel
  - ⟹ 244 647 individual spectra taken into account in the analysis

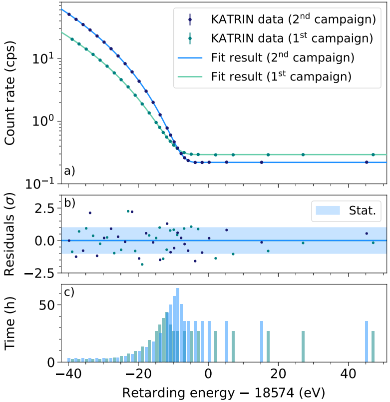
⟹ How do we combine the data?



Run combination

– Runs taken under similar conditions can be stacked into one spectrum
– Counts are summed, input parameters are averaged





Fit is performed with *i* contributing spectra of each campaign

⟹ One minimisation

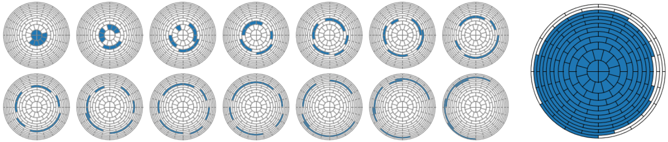
⟹ One combined likelihood, $\mathcal{L}$

$$-\log \mathcal{L} = \sum_i -\log \mathcal{L}_i \left(m_\nu^2, E_{0i}, \mathrm{Sig}_i, \mathrm{Bg}_i \right)$$

– One common neutrino mass, m_ν^2
– Multiple campaignwise E_0, Sig, and Bg

⟹ Principle was used in combined KNM1 – KNM2 analysis (multi-period analysis)

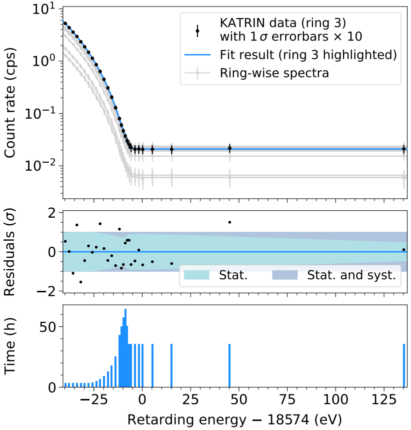
Pixel combination



Detector segments with similar transmission conditions are grouped

⟹ Uniform (NAP setting)

⟹ Multi-patch (SAP setting)



Fit is performed with *i* contributing spectra of each segment

⟹ One minimisation

⟹ One combined likelihood, $\mathcal{L}$

$$-\log \mathcal{L} = \sum_i -\log \mathcal{L}_i \left(m_\nu^2, E_{0\,i}, \mathrm{Sig}_i, \mathrm{Bg}_i \right)$$

– One common neutrino mass, m_ν^2

– Multiple detector segmentwise E_0, Sig, and Bg

⟹ Principle was used in KNM2 analysis (multi-ring analysis)

Unbiased analysis

Analysis is performed in paralell by different fitting teams, using independent code

Model blinding:

- Additional broadening is applied to the model (FSD) $\rightarrow \Delta m_\nu^2 = -2\sigma^2$
- Neutrino mass is shifted into an unknown direction
- Other fit parameters are uneffected

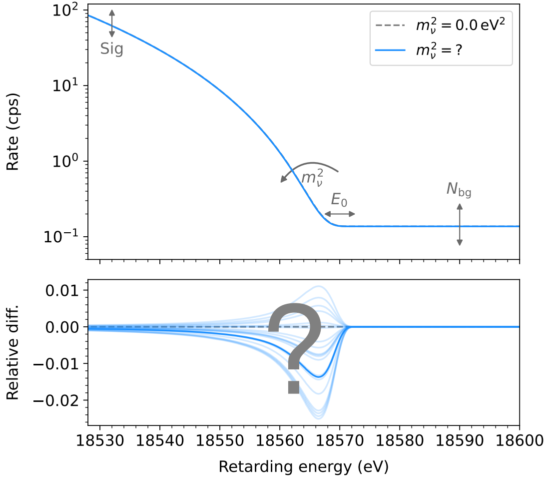
Three stage unblinding procedure

1.) Code validation on Asimov spectra

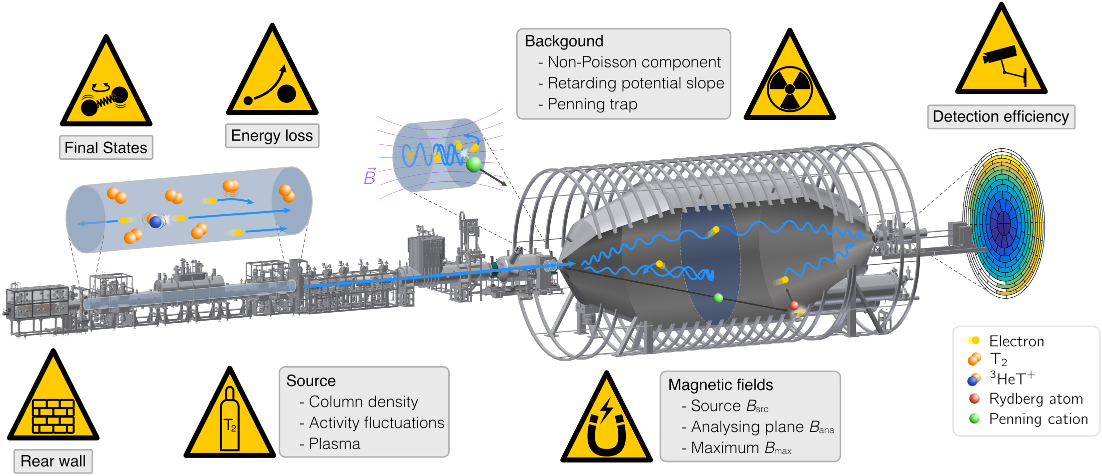
2.) Blinded analysis of data

3.) Final unblinded analysis of data

$\Longrightarrow$ Unbiased neutrino mass result



Sources of systematic uncertainties



Treatment of systematics

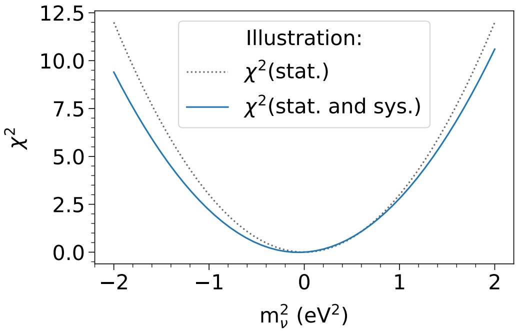
In the KNM1 and KNM2 analyses, systematics have been propagated via:

$\Longrightarrow$ Pull term

$\Longrightarrow$ Covariance matrix

$\Longrightarrow$ Monte Carlo propagation

$\Longrightarrow$ Markov Chain Monte Carlo (MCMC)



Future approach – pull term:

- Adding additional free parameters (θ_i)
- Constraining parameters with a penalty term

$\Longrightarrow$ Adding pull terms widenes the χ^2 distribution:

$$\chi^2\left(m_\nu^2, E_0, \mathrm{Sig}, \mathrm{Bg}, \theta_1, \dots\right) + \frac{\left(\theta_1 - \hat{\theta}_1\right)^2}{\sigma_{\theta_1}^2} + \dots$$

In the combined KNM1-5 analysis:

- Pull term as multivariate normal distribution
- Treatment of correlations between campaigns and segments

$\Longrightarrow$ ~280 fit parameter and ~100 correlations

Latest KATRIN neutrino mass results – KNM1

First measurement campaign

Fit strategy: Stacked uniform fit

$\Longrightarrow$ One spectrum with 27 data points

$\Longrightarrow$ Four free fit parameters (m^2_ν, E_0, Sig, Bg)

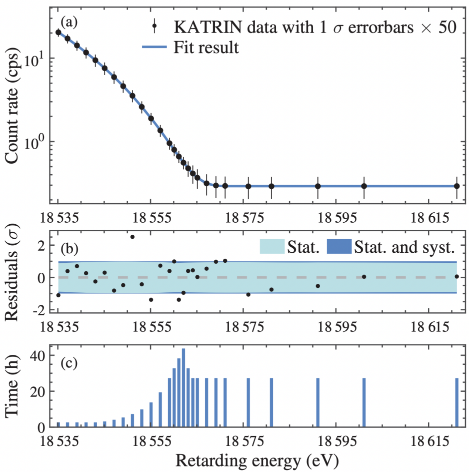
Statistics dominated fit result

$$m^2_\nu = -1.0 \pm 1.0\,\mathrm{eV}^2$$

Factor of $\sim$ 2 improvement on previous m_ν limit

$$m_\nu < 1.1\,\mathrm{eV}\ (90\,\%\ \mathrm{CL})$$

Phys. Rev. Lett. **123** (2019) 221802



Latest KATRIN neutrino mass results – KNM2

Second measurement campaign

Fit strategy: Stacked multi-ring fit

$\Longrightarrow$ 12 spectra with $12 \times 28 = 336$ data points

$\Longrightarrow$ 37 free fit parameters (m_ν^2, $12 \cdot E_0$, $12 \cdot$Sig, $12 \cdot$Bg)

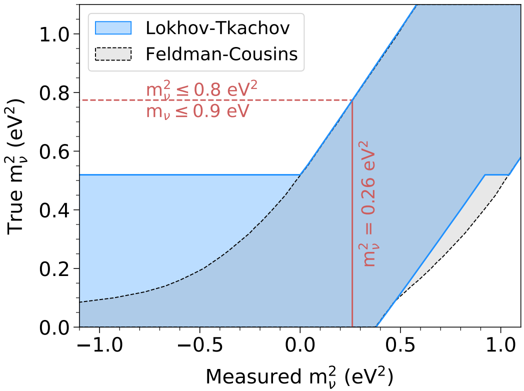
Statistics dominated fit result

$$m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$$

New sub-eV neutrino mass limit

$$m_\nu < 0.9\,\text{eV}\ (90\,\%\ \text{CL})$$

Nat. Phys. **18**, 160–166 (2022)



Latest KATRIN neutrino mass results – combined results

Fit strategy: Multi-period uniform fit

$\Longrightarrow$ Data is stacked *within* the measurement phases

$\Longrightarrow$ Two spectra with $27+28=55$ data points

$\Longrightarrow$ 7 free fit parameters (m_ν^2, 2·E_0, 2·Sig, 2·Bg)

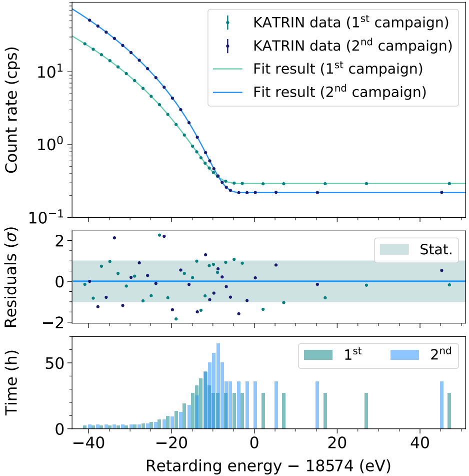
Statistics dominated fit result

$$m_\nu^2 = 0.08 \pm 0.32\,\mathrm{eV}^2$$

Sub-eV upper limit on the neutrino mass

$$m_\nu < 0.8\,\mathrm{eV}\ (90\,\%\ \mathrm{CL})$$

Nat. Phys. **18**, 160–166 (2022)



Summary

Leading upper limit on the neutrino mass from direct single β-decay measurements

$\Longrightarrow$ KATRIN combined analysis of KNM1 and KNM2 measurement campaigns

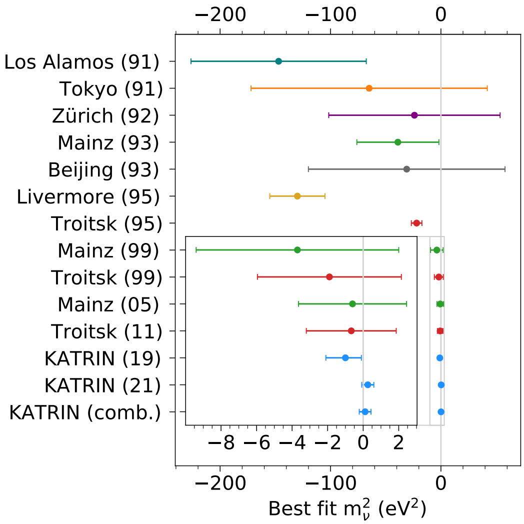
$$m_\nu < 0.8\,\text{eV (90 \% CL)}$$

Nat. Phys. **18**, 160–166 (2022)

Towards improved sensitivity

$\Longrightarrow$ KATRIN combined analysis of KNM1 to KNM5 measurement campaigns is ongoing

$\Longrightarrow$ Expected sensitivity $<0.5\,\text{eV}$



Future challenges and outlook

- KATRIN combined analysis of KNM1 – KNM5 in progress
- Mixed multi-period, multi-patch analysis
  $\Longrightarrow$ Combined fit of 45 spectra with one shared m_ν^2
- Treatment of systematics via pull terms
  $\Longrightarrow$ Fit with $\sim$ 280 fit parameters
- Combined fit is computationally challanging
- Currently two complementing approaches are persued to improve computation time:
  - Model calculation through neural nets (arXiv:2201.04523)
  - Improved computation performance