First sub-electronvolt direct neutrino mass measurement with KATRIN

IMPRS Colloquium

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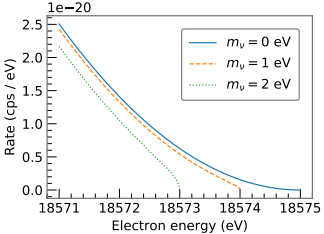
The KATRIN experiment

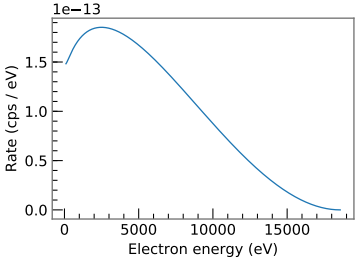
- Direct neutrino mass measurement using the β-decay kinematics
- Designed to measure the effective electron anti-neutrino mass $m_\nu = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$ with a sensitivity of 200 meV (90 % CL)
- Taking neutrino mass data since 2019
- Current world-leading laboratory limit of $m_\nu < 1.1$ eV (90 % CL) from our first neutrino mass campaign[1]

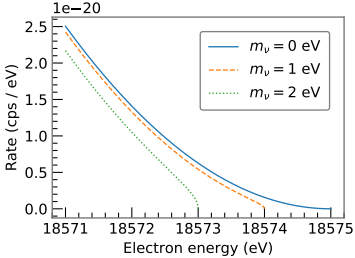


[1] M. Aker et al., Phys. Rev. Lett., Nov 2019

Neutrino mass signal in β-decay

- β-decay: $X \to Y + e + \nu$
- Energy $E_0 = Q - E_{\text{rec}}$ split between e and ν
- ν extremely hard to measure
  $\Rightarrow$ measure energy spectrum of the electrons
- Maximum energy e can get is $E_0 - m_\nu$, but E_0 not known, also due to experimental effects
- Neutrino mass modifies the rate
  $\text{Rate}(E) \propto \sqrt{(E_0 - E)^2 - m_\nu^2}$
- Visible as change of curvature in the spectral shape of the highest energy electrons





Experimental challenge: eV-scale signal

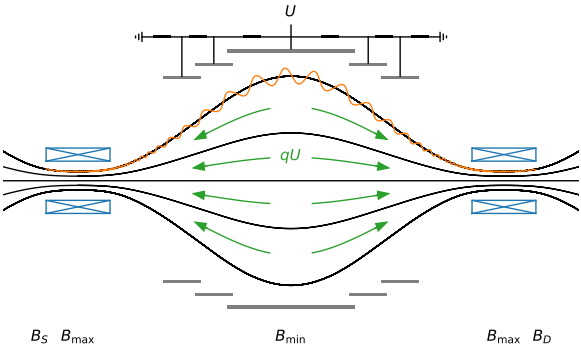
MAC-E filter

- Idea: measure all electrons with kinetic energy $E > qU$

⇒ Apply retarding energy in a spectrometer

- Problem: only parallel component of E "filtered"

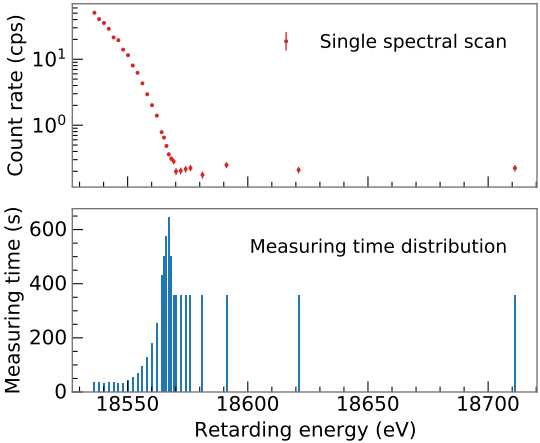
⇒ Gradually decrease the magnetic field to transform the transversal energy into energy parallel to qU



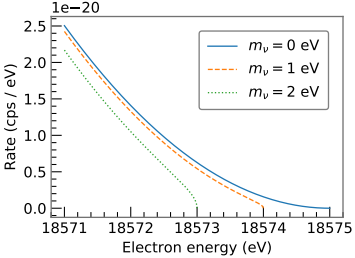
eV-scale resolution, integral measurement as we count all electrons with energy larger than qU

Measurement principle

- Main spectrometer acts as high-pass filter that rejects low-energy electrons
- Set different retarding energies in the main spectrometer
- Count all electrons that pass the filter
- Integral measurement of the tritium β-spectrum
- Repeat the $\approx 2\,\mathrm{h}$ long spectral scan hundreds of times



Model



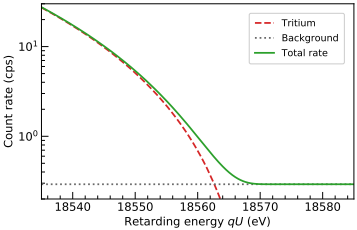
Differential β-spectrum

- Fermi theory of β-decay
- Final states of T_2

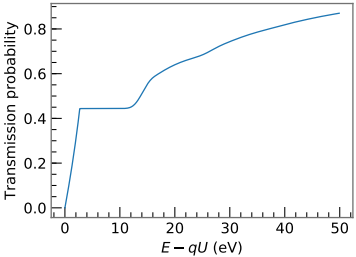
→ Model of measured data ←

$$R(qU) \propto \int_{qU}^{\infty} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E) \cdot R(qU,E)\,\mathrm{d}E + B$$

↓



Integrated β-spectrum + bg

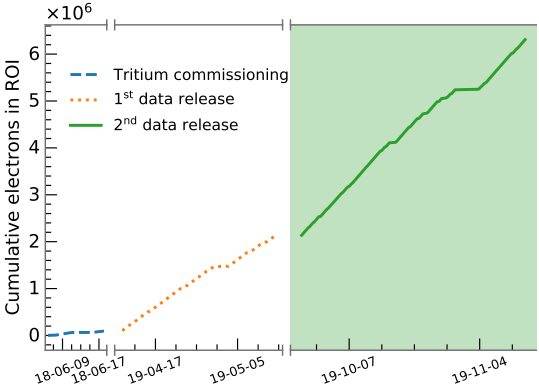


Experimental response

- MAC-E filter transmission
- Energy loss by scattering

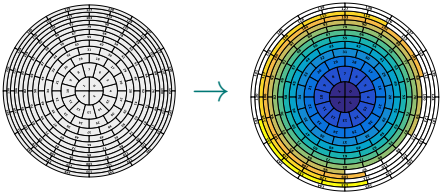
Our second neutrino mass campaign

- Runtime: 2019-09-27 to 2019-11-14
- Scan time: 31 days
  split in 361 scans
- Electrons in ROI: 4.2 million
- Background: 220 mcps
- Source activity: 84 %
- Sensitivity: $m_\nu < 0.7\,\mathrm{eV}$ (90 % CL)
- All plots and analyses still preliminary, to be published soon



Data combination and likelihood

- Scan combination: counts and times added, retarding potentials averaged
- Pixel combination: grouped into rings to account for radial potential effects
- Free parameters
  - 1 Neutrino mass squared m_ν^2
  - 12 ringwise endpoints $E_{0,\text{ring}}$
  - 12 ringwise background rates B_{ring}
  - 12 ringwise signal amplitudes A_{ring}



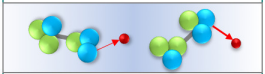
$$R_{\text{ring}}(qU) = A_{\text{ring}} \cdot \int_{qU}^{E_{0,\text{ring}}} \frac{\mathrm{d}\Gamma}{\mathrm{d}E}(E; m_\nu^2, E_{0,\text{ring}}) \cdot R(qU, E)\,\mathrm{d}E + B_{\text{ring}}$$

$$\chi^2_{\text{ring}} = (R_{\text{data}}(qU) - R_{\text{ring}}(qU)) \cdot V^{-1} \cdot (R_{\text{data}}(qU) - R_{\text{ring}}(qU))^T$$

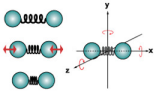
$$\chi^2_{\text{total}} = \sum_{\text{ring}} \chi^2_{\text{ring}}$$

Systematics overview

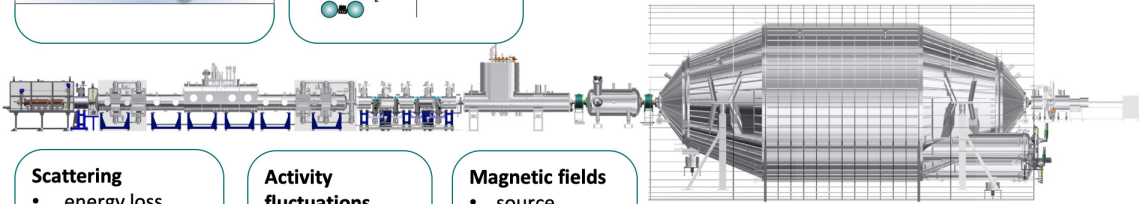
Source electric potential



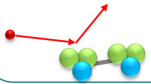
Molecular Final States



Background:
- time correlation (radon, penning trap)
- retarding potential dependence



Scattering
- energy loss
- column density



Activity fluctuations

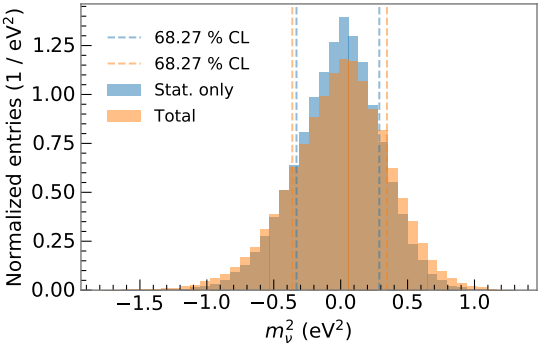
Magnetic fields
- source
- spectrometer
- detector

Detection efficiency

Systematics treatment

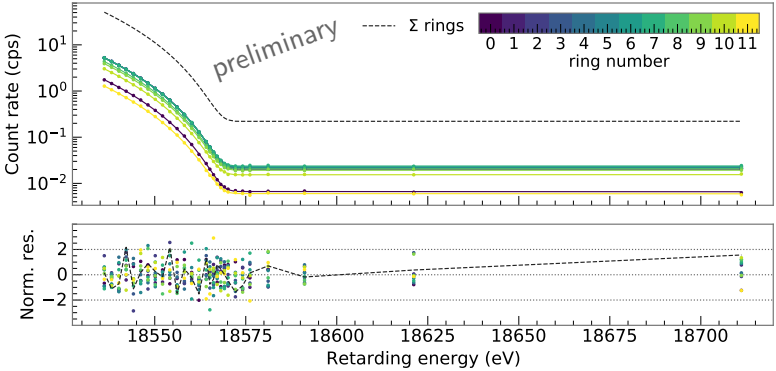
- Approach: Monte Carlo propagation of uncertainty
- Idea: fit multiple times
  - Stat.: randomize spectrum according to statistical uncertainty of data points
  - Syst.: randomize model parameters according to their knowledge
- Retrieve best-fit and uncertainties from the resulting fit-parameter distributions

⇒ Propagation of distributions



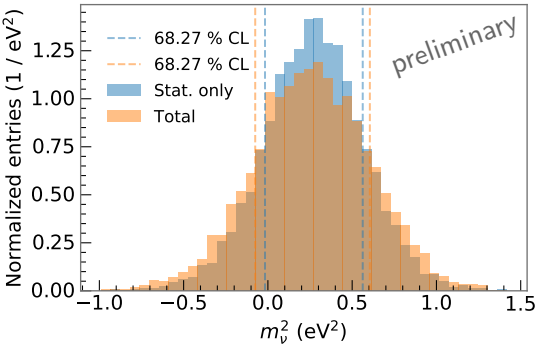
Data fit

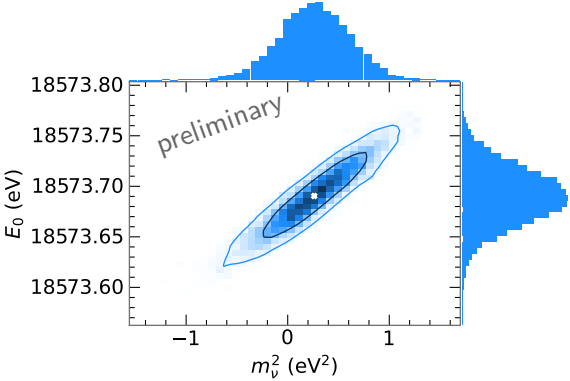
- Multi-ring fit spectrum from Monte Carlo propagation with total uncertainty
- 3 ringwise parameters, 1 shared neutrino mass squared, 37 free parameters
- $\chi^2 = 277$ at 299 dof $\Rightarrow$ p-value 81 %



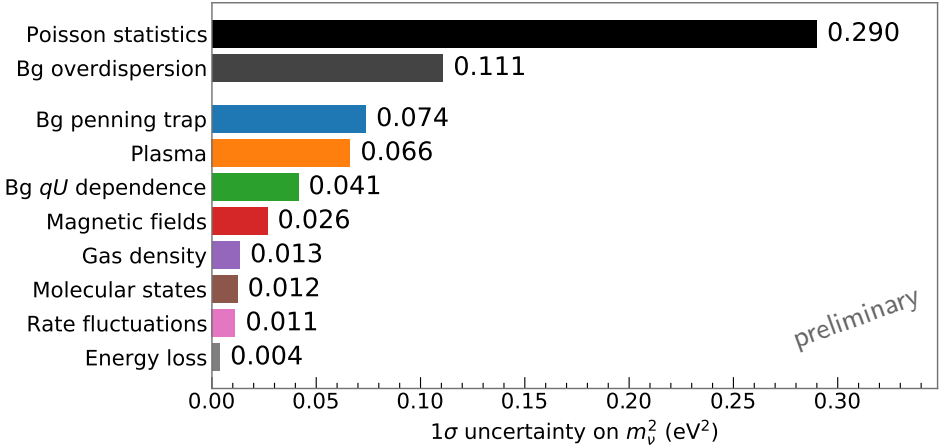
Neutrino mass squared distribution

Stat. only	$m_\nu^2 = 0.27 \pm 0.29\,\mathrm{eV}^2$	$E_0 = 18\,573.69 \pm 0.02\,\mathrm{eV}$
Total	$m_\nu^2 = 0.26 \pm 0.34\,\mathrm{eV}^2$	$E_0 = 18\,573.69 \pm 0.03\,\mathrm{eV}$





Uncertainty breakdown

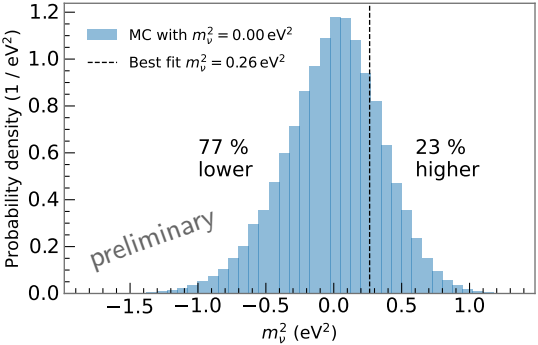


Design requirement for KATRIN final: $\sigma_{\text{total}} = 0.024\,\text{eV}^2$, $\sigma_{\text{stat}} = \sigma_{\text{syst}} = 0.017\,\text{eV}^2$,

Comparison with expectation for $m_\nu^2 = 0\,\mathrm{eV}^2$

- Generate randomized datasets including statistical and systematical uncertainty with $m_\nu^2 = 0\,\mathrm{eV}^2$
- Compare our best-fit of $0.26\,\mathrm{eV}^2$ with the resulting distribution
- $23\,\%$ probability to have a value "as high" as ours

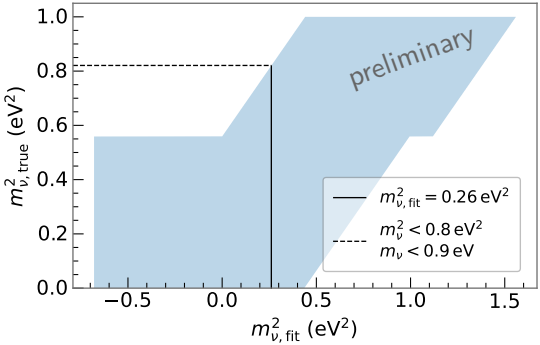
$\Rightarrow$ Fully compatible with expectation for $m_\nu^2 = 0\,\mathrm{eV}^2$



Limit using method of Lokhov and Tkachov

- Insert best-fit into belt using method of Lokhov and Tkachov[2] (90 % CL)
- Coincides with method of Feldman and Cousins for upper limits with $m^2_{\nu,\text{fit}} \geq 0$
- Sensitivity: $m_\nu < 0.7\,\text{eV}$ (90 % CL)
- Limit: $m_\nu < 0.9\,\text{eV}$ (90 % CL)

⇒ **First sub-electronvolt direct neutrino mass measurement and sensitivity**

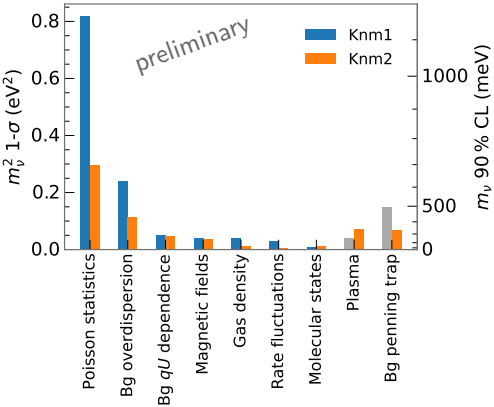


[2] A. V. Lokhov and F. V. Tkachov, Phys. Part. Nucl., May 2015

Comparison with first neutrino mass campaign

quantity (eV^2 | eV)	Knm1	Knm2	improvement
best fit	-0.96	0.26	–
Poisson uncertainty	0.97	0.29	factor 3.3
other uncertainties	0.31	0.16	factor 1.9
total uncertainty	1.04	0.34	factor 3.2
90 % CL sensitivity	1.1	0.7	factor 1.5
90 % CL limit	1.1	0.9	factor 1.2

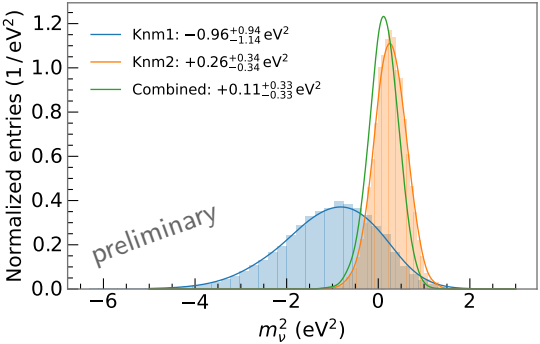
- Significantly more statistics collected
- Improvement of all "known" systematics
- New systematic effects identified, counter-measurements in progress



Comparison of sensitivity

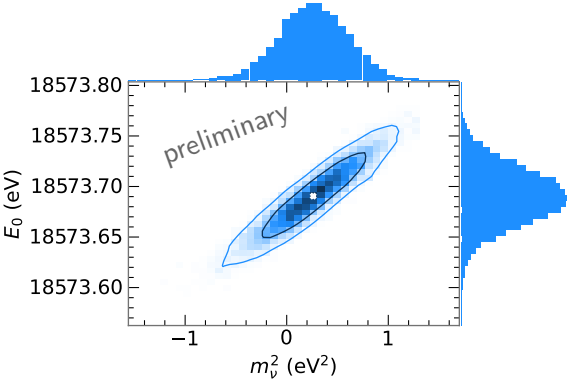
Combination with first neutrino mass campaign

- Multiply distributions retrieved by MC propagation
- Equivalent to adding χ^2 profile
- Does not include correlations of systematics, but...
  - ... dominated by stat. uncertainty
  - ... followed by non-Poissonian background
  - ... and other uncorrelated effects
- Combined:
  $m_\nu^2 = 0.11 \pm 0.33\,\mathrm{eV}^2$
  $m_\nu < 0.8\,\mathrm{eV}$ (90 % CL)



Wrapping up

- Second KATRIN neutrino mass campaign successfully analysed
- Sensitivity: $m_\nu < 0.7\,\text{eV}$ (90 % CL)
- Best fit: $m_\nu^2 = 0.26 \pm 0.34\,\text{eV}^2$
- Limit: $m_\nu < 0.9\,\text{eV}$ (90 % CL)
- Limit combined with first campaign: $m_\nu < 0.8\,\text{eV}$ (90 % CL)



- Publication upcoming
- Still only about $\frac{1}{50}^{\text{th}}$ of the final statistics, stay tuned! :)

Thanks to everyone involved! Thank you for your attention!