Latest results from the KATRIN experiment and insights into the neural network approach

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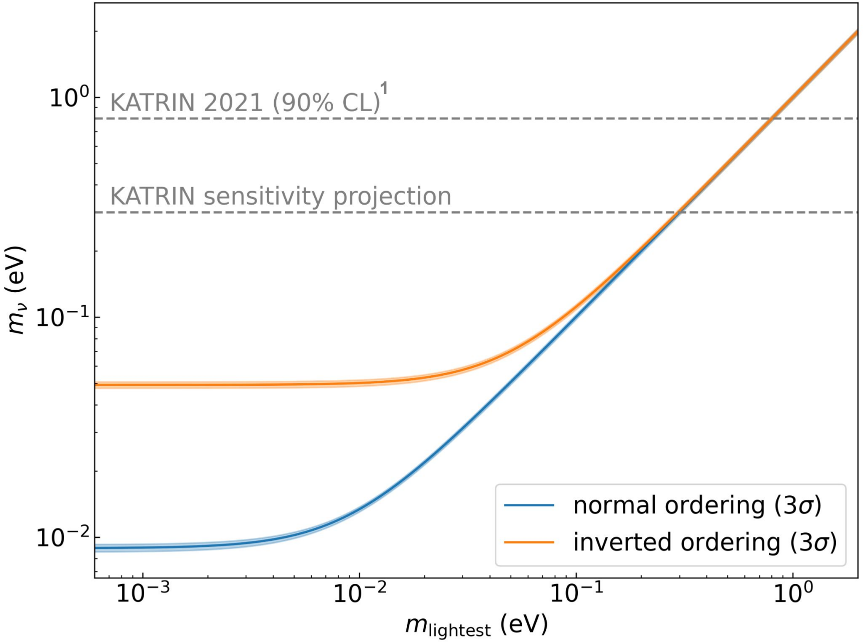
Motivation

- Neutrino oscillations imply that **neutrinos have mass**…
- …but are insensitive to **absolute mass scale**
- Infer information about **mass**
  - via **cosmology** (depends on model, e.g. ΛCDM)
  - via **0νββ-decay** (relies on Majorana nature)
  - via **β-decay** (direct measurement, this talk)

with data from PDG



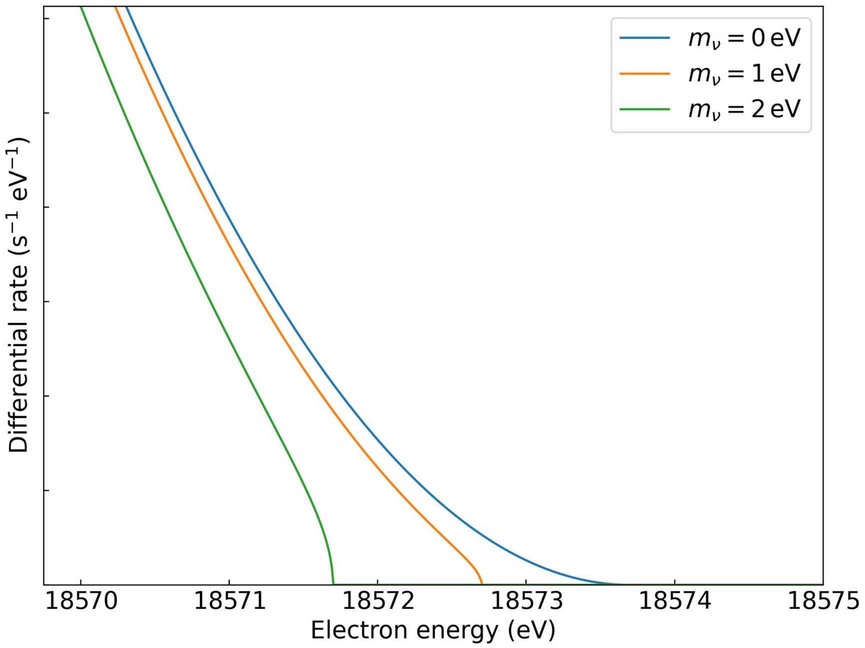
[1]The KATRIN Collaboration. *Nat. Phys.* **18**, 160–166 (2022).

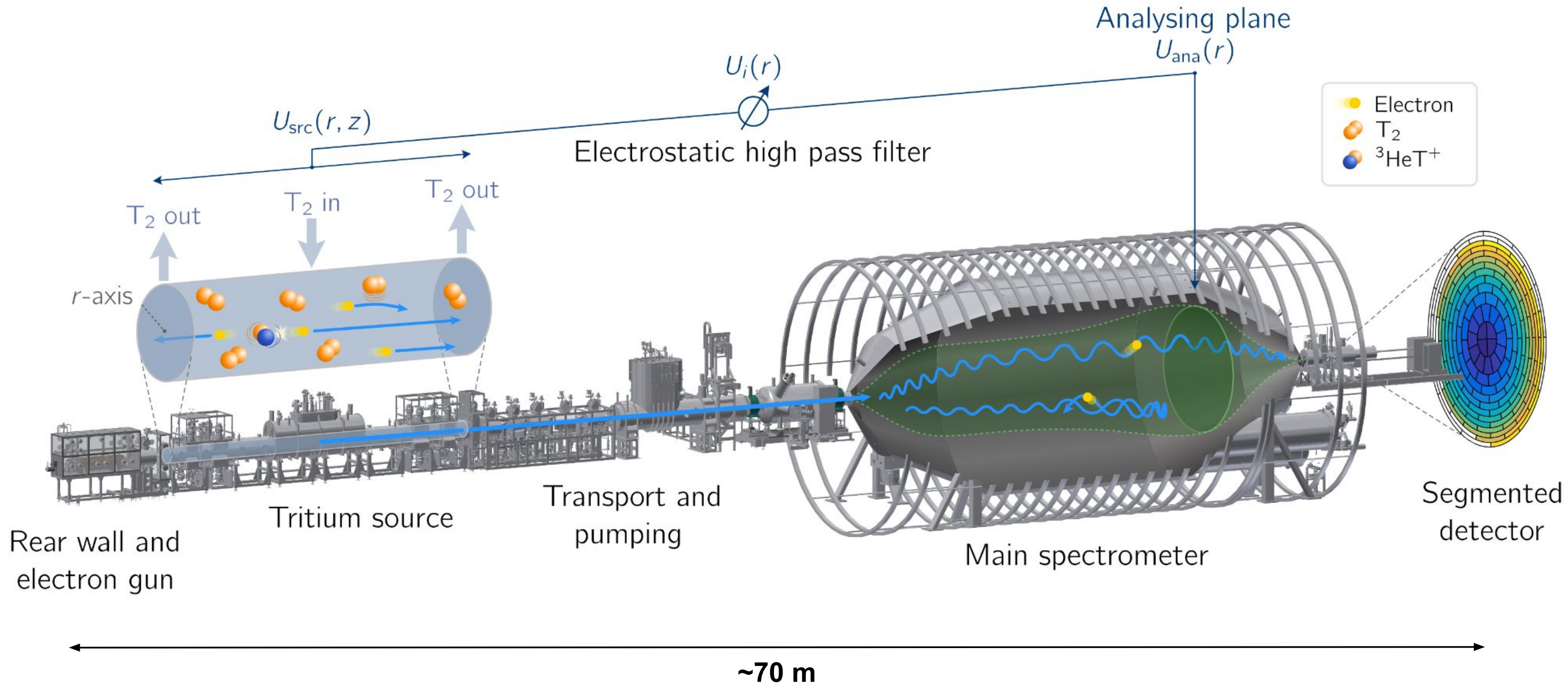
β-decay

- β^--decay: $T_2 \rightarrow {}^3HeT^+ + e^- + \overline{\nu}_e$
- Smoking gun: **spectral distortion** near endpoint E_0
- Challenges:
  - Small effect (eV-scale)
  - Low count rates (close to endpoint)

➔ Source: (Molecular) **Tritium**

  - Low half-life (**12.3 years**)
  - Low endpoint (**18.6 keV**)





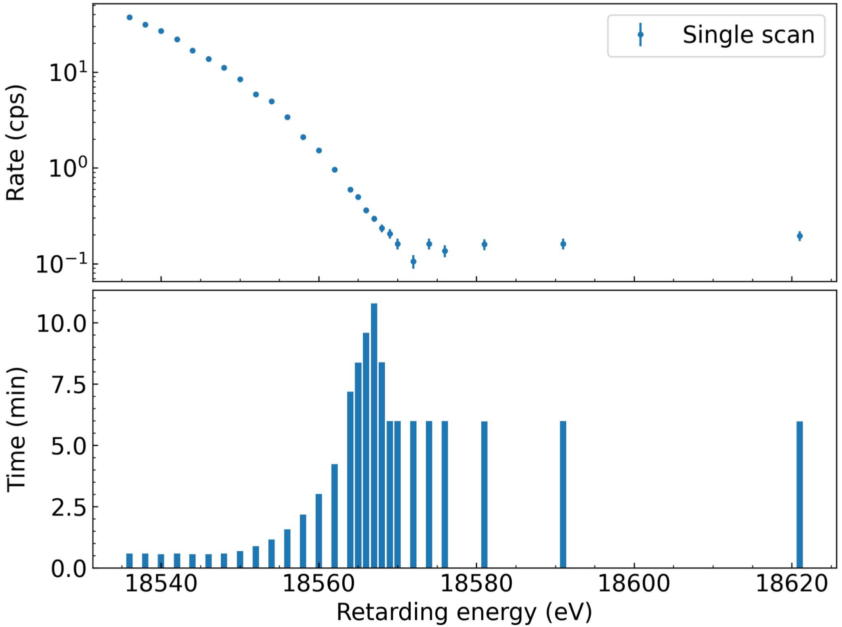
Details in: KATRIN, JINST 16 (2021) T08015

Measurement strategy

- **MAC-E filter**: Only electrons with $E_{||}$ > *retarding energy* reach the detector
  - ➔ Vary retarding energy to scan spectrum
  - ➔ Count events at the detector
  - ➔ **Integral spectrum** (2-3h in total)

➔ **Repeat** scanning procedure O(100) times for one measurement campaign

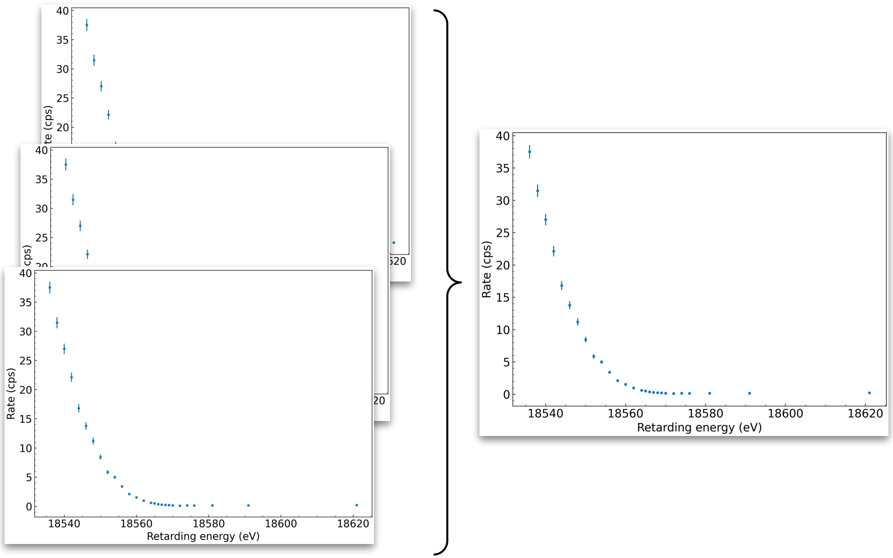
< 1 MB in size after processing



Data combination

Scan combination

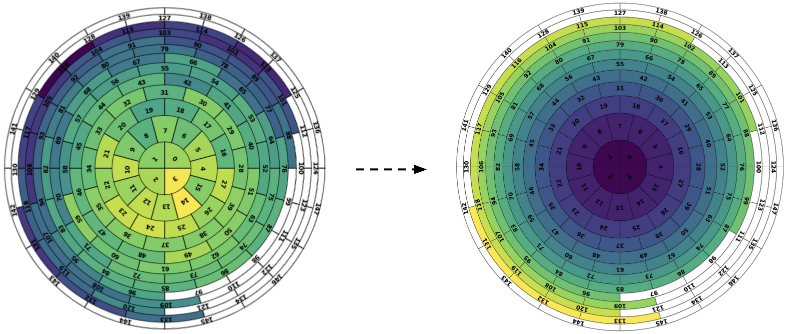
➔ **Sum** counts, use **average retarding energy**



Pixel combination

➔ **Combine** into patches

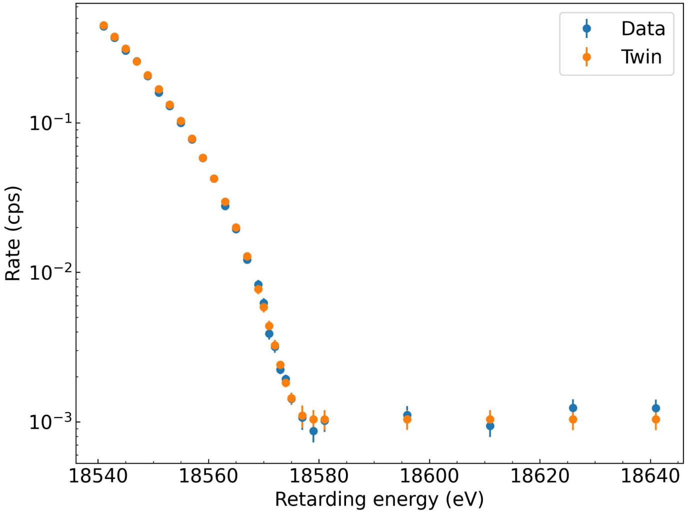
➔ **Sum** counts, use **average response**



Blinding procedure

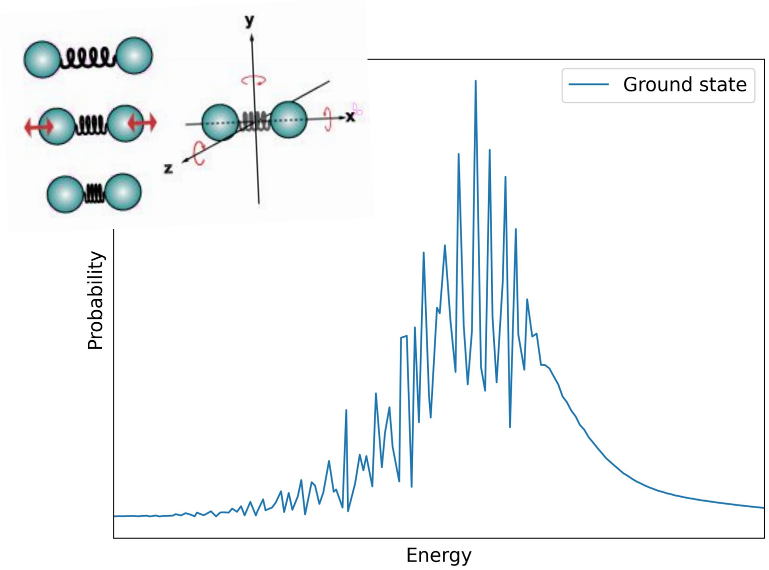
1st: (Asimov) twin data

- "Unfluctuated" copy of each scan ($m_\nu^2 = 0\ eV^2$)



2nd: Model blinding on real data

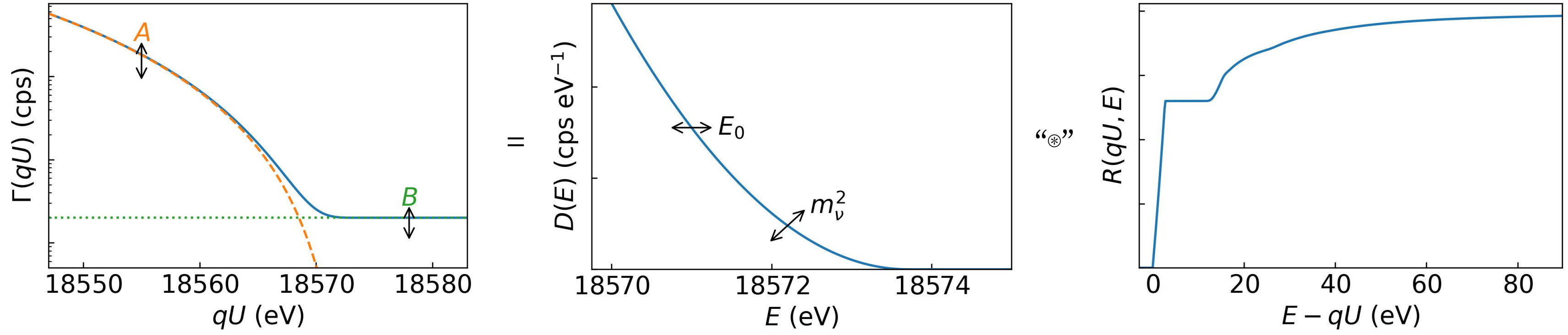
- Modified molecular final state distribution



Analysis strategy

- Maximum likelihood fit of **model:**

$$\Gamma(qU) \propto A \int_{qU}^{E_0} D(E; m_\beta^2, E_0)\, R(qU, E)\, \mathrm{d}E + B$$



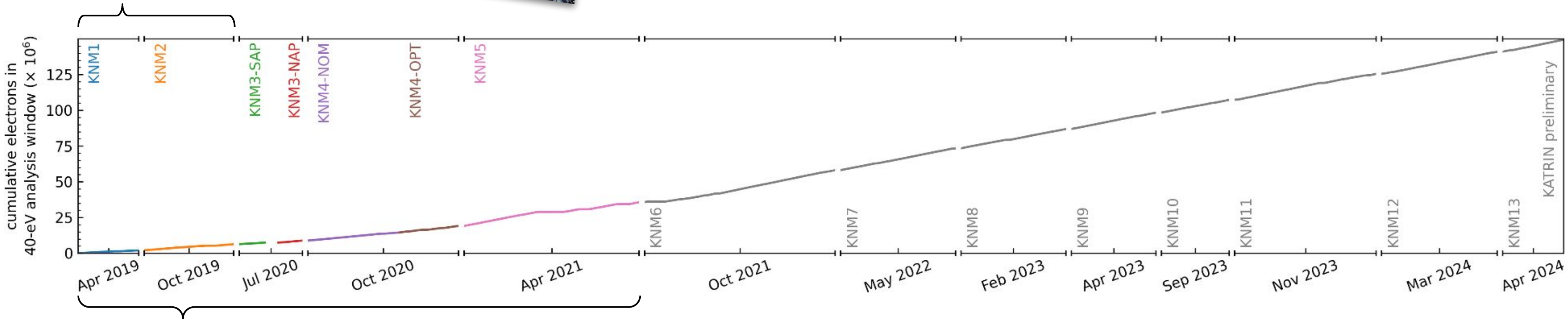
with free **amplitude** A, **squared neutrino mass** m_ν^2, **endpoint** E_0 and **background** B

- **Theoretical** (Fermi theory, molecular excitations) and **experimental** inputs (calibration measurements)

Current status

m_ν < 0.8 eV (90% CL)

[M. Aker et al., Nature Phys. 18 (2022) 2, 160-166]



- **259** measurement days
- **~36 Mio** electrons
- Sensitivity below **0.5 eV** (90% CL)

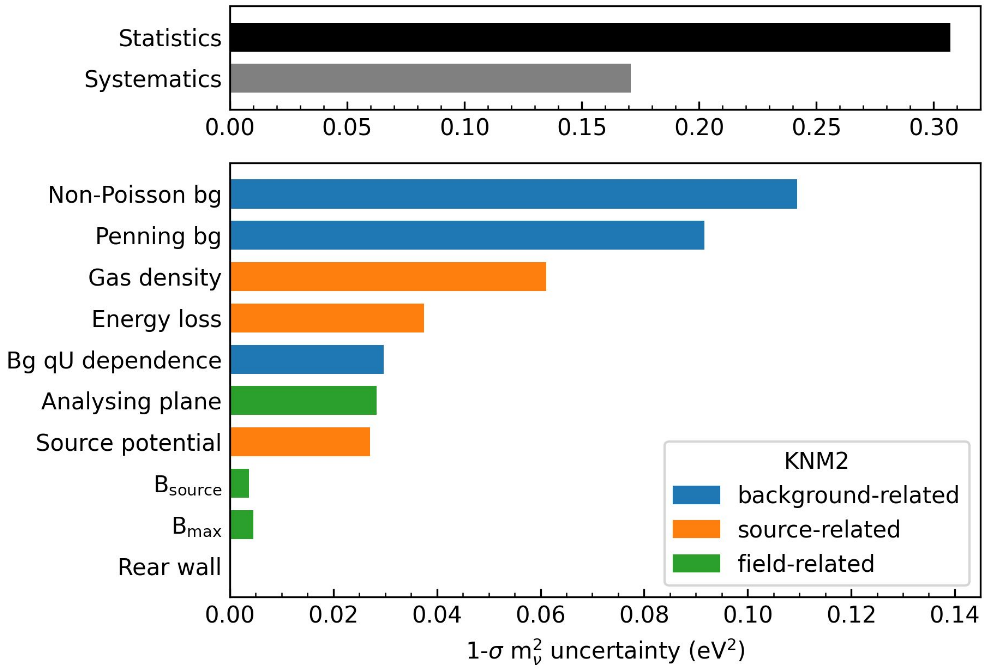
➔ **Result** presented at **Neutrino 2024** (last week)

Experimental improvements

- **Statistics dominated**, systematics non-negligible

- **Background**-related systematics dominate

- Significant contribution from **analysing plane fields**



Experimental improvements

- **Statistics dominated**, systematics non-negligible

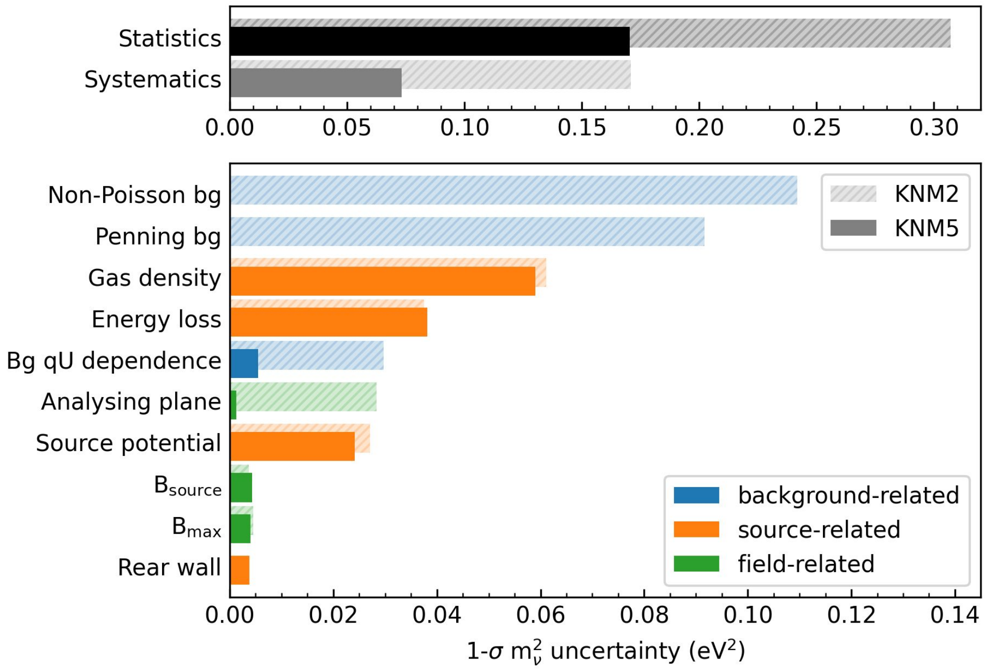
➔ Still statistics dominated, **significant improvements** of systematics

- **Background**-related systematics dominate

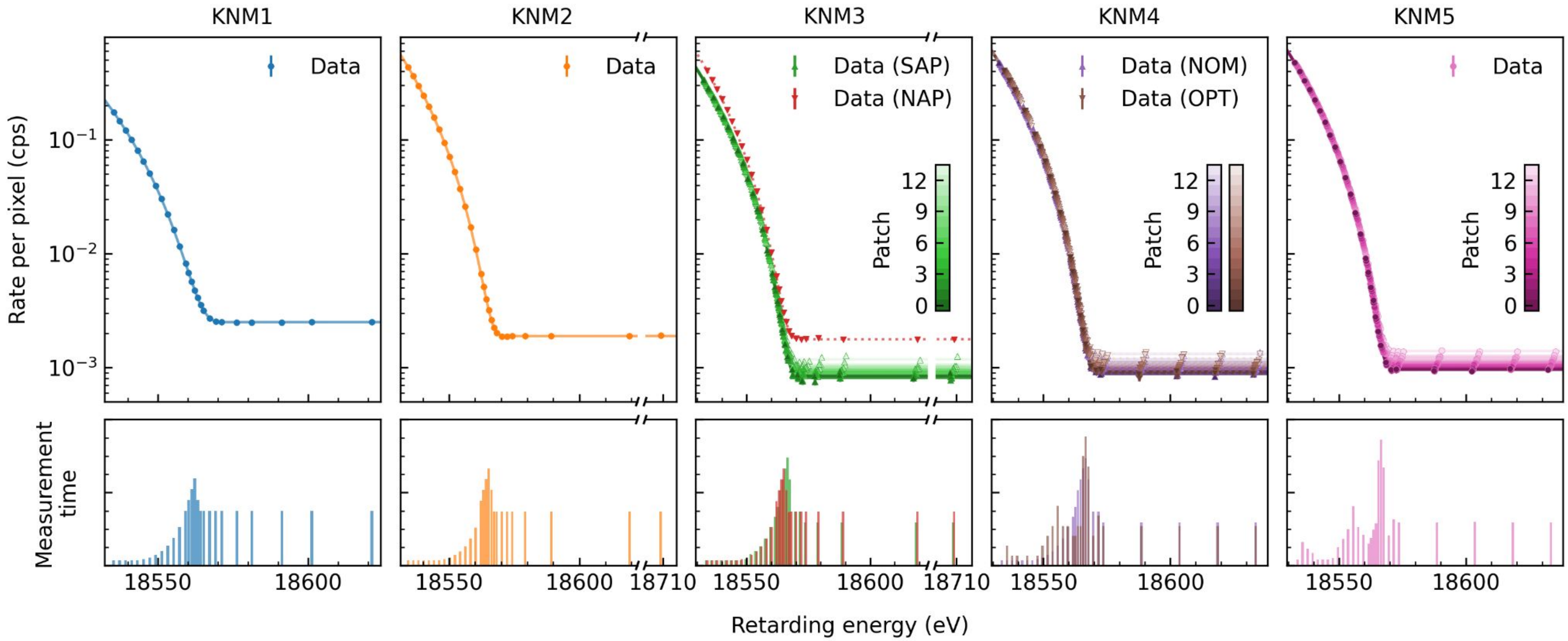
➔ Successful **mitigation**: New measurement mode (SAP), removal of Penning trap
Lokhov et al., [Eur. Phys. J. C 82, 258](#) (2022)

- Significant contribution from **analysing plane fields**

➔ **High-statistic ^{83m}Kr** calibration campaign
K. Altenmüller et al., [J.Phys.G 47 6, 065002](#) (2020)



Data



➔ Simultaneous fit of **59** integrated **spectra** (1609 data points) with **computationally challenging** model

Neural net

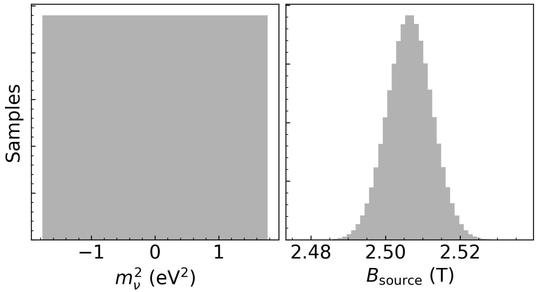
- Idea: **Approximate** KATRIN model with a **neural net**

  C. Karl et al., [EPJ C 82 5, 439](#) (2022)

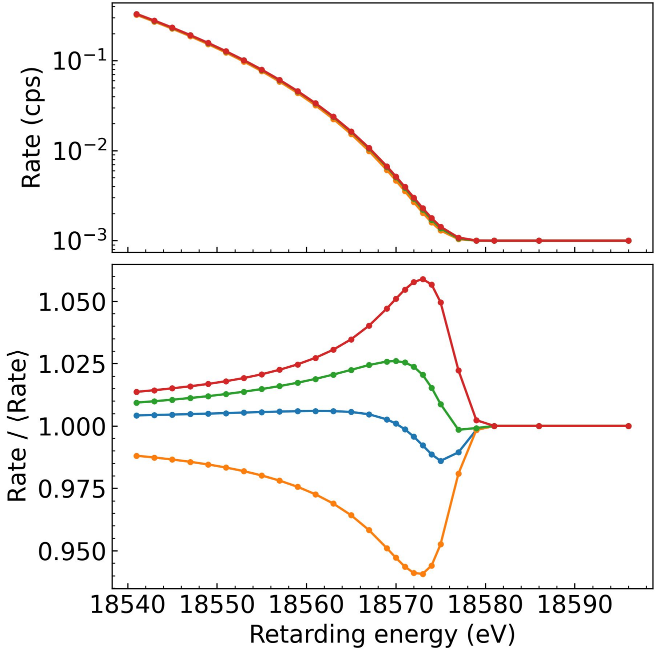
➔ Sample **input parameter space** in “region of interest”

➔ Generate **sample spectra** (~2.4 x 10^6 per net)

➔ Train neural net to predict **spectrum shape**



➔ Key: **Heavily parallelizable**



Neural net

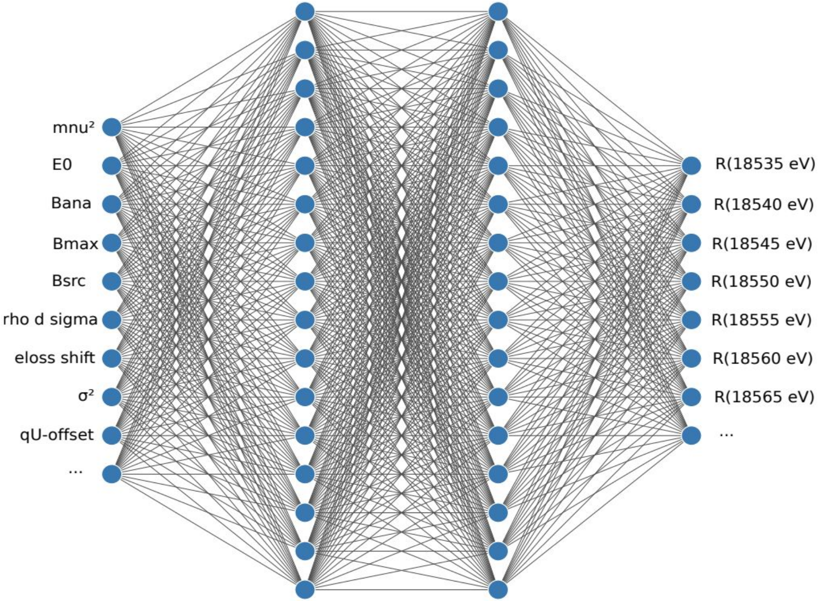
- **High accuracy** achieved, **x1000** speed-up

  C. Karl et al., [EPJ C 82 5, 439](EPJ C 82 5, 439) (2022)

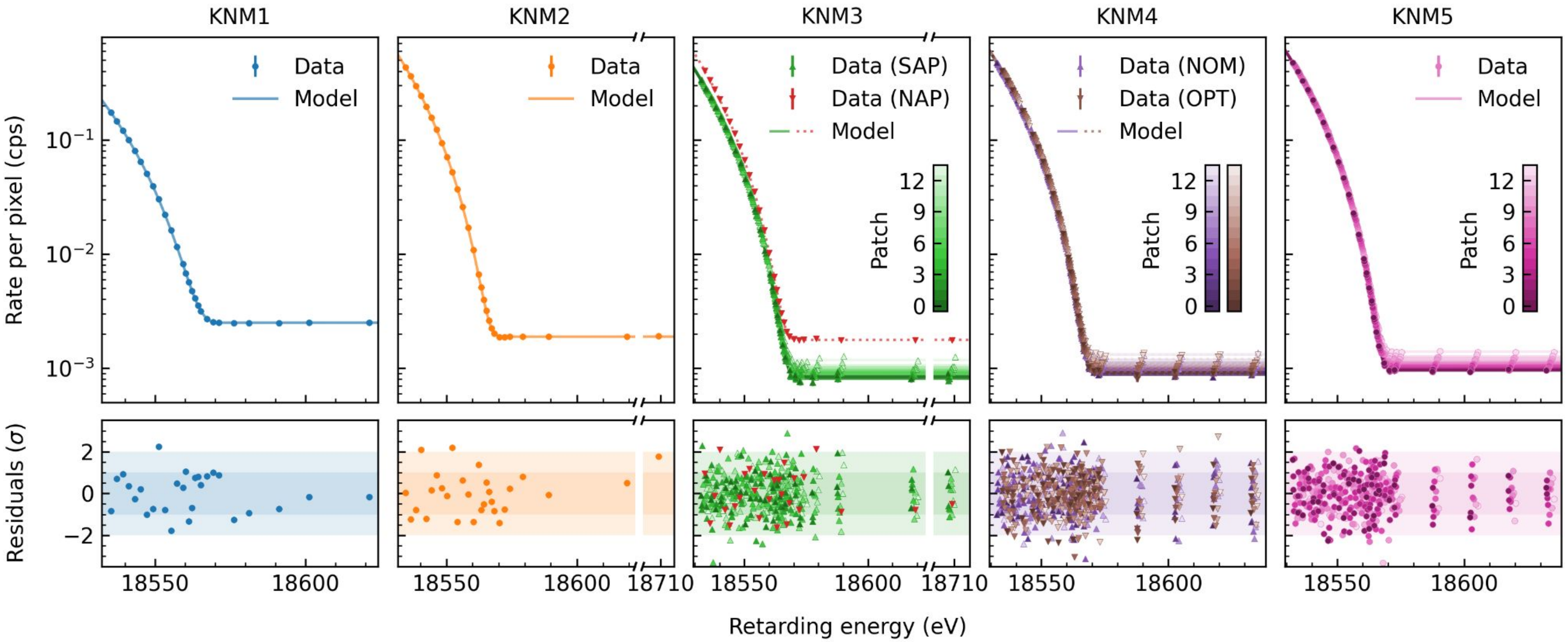
- **Simple** neural net:

  - **Dense feed-forward** architecture
  - **Two hidden layers** (128 nodes each, mish activation function)

➔ **Simultaneous fit** with common m_ν^2 in **O(min)**

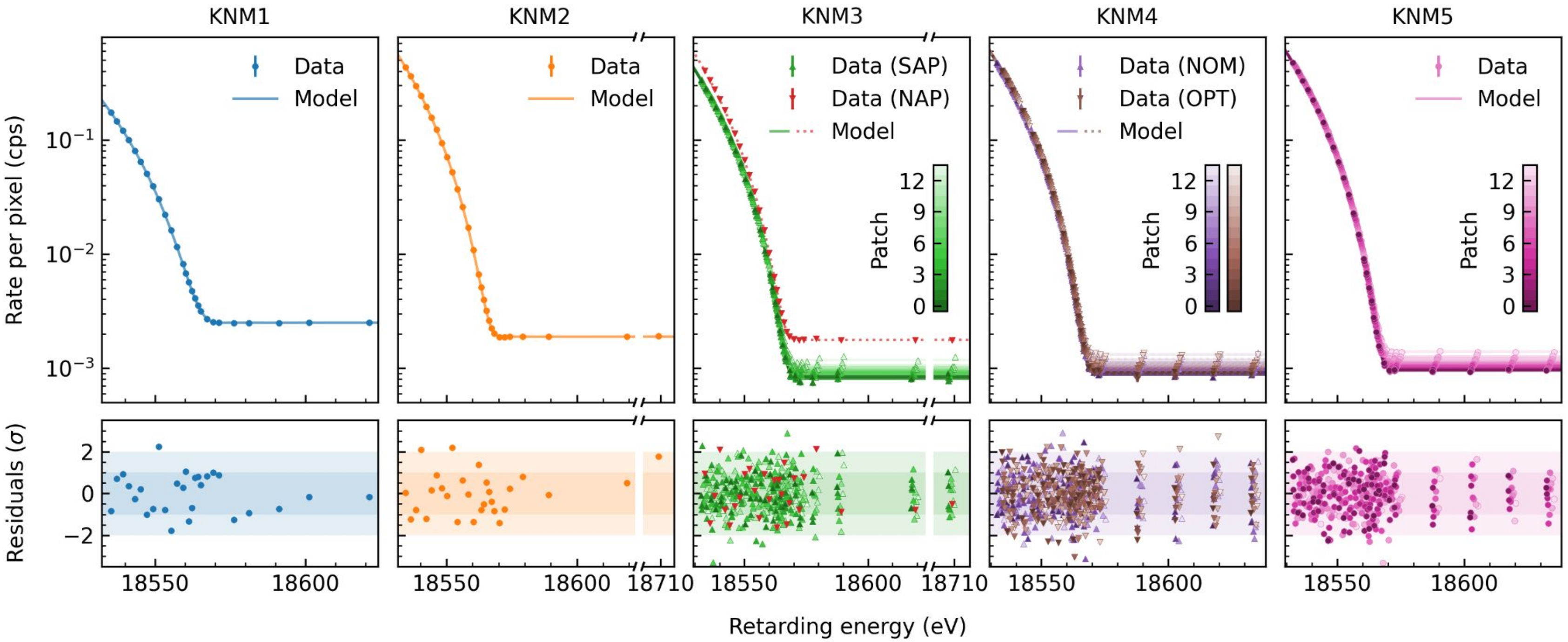


Results



KNM1
KNM2
KNM3
KNM4
KNM5
Data
Model
Data (SAP)
Data (NAP)
Data (NOM)
Data (OPT)
Patch
12
9
6
3
0
Rate per pixel (cps)
10^{-1}
10^{-2}
10^{-3}
Residuals (σ)
2
0
−2
18550
18600
18710
Retarding energy (eV)

Results

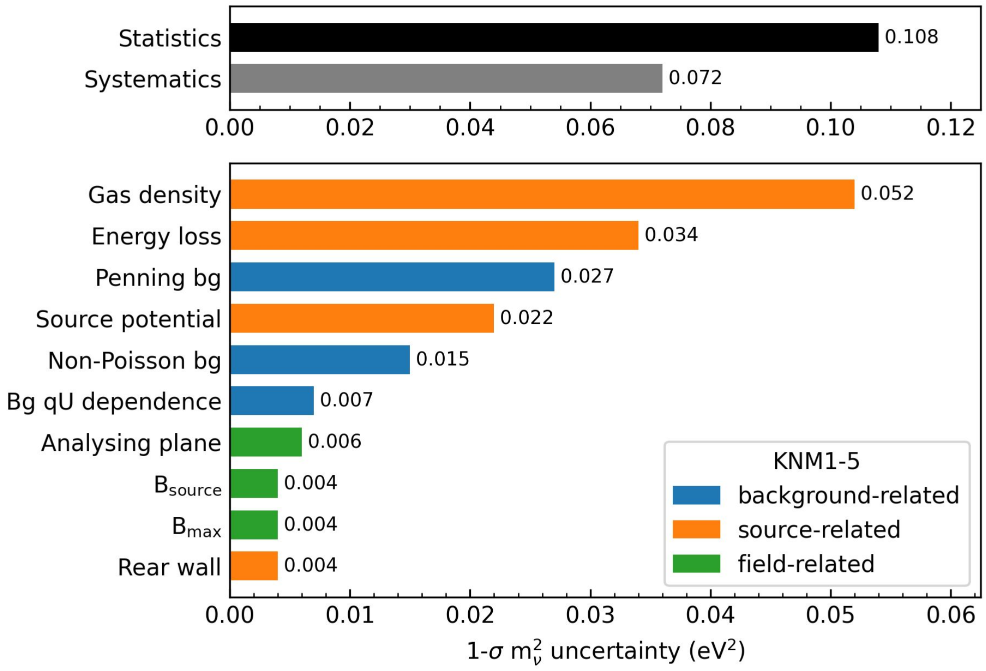


➔ Fit result: $\mathbf{m_\nu^2 = -0.14^{+0.13}_{-0.15}\ eV^2}$ (p-value: 0.84)

Preprint: http://arxiv.org/abs/2406.13516

Systematic uncertainties

- **Statistics dominated**, systematics non-negligible
- **Background**-related systematics **subdominant** fur future campaigns due to mitigation techniques
- Increased **conservative uncertainties** in source scattering in this release



New upper limit

- **KATRIN's new upper limit:**

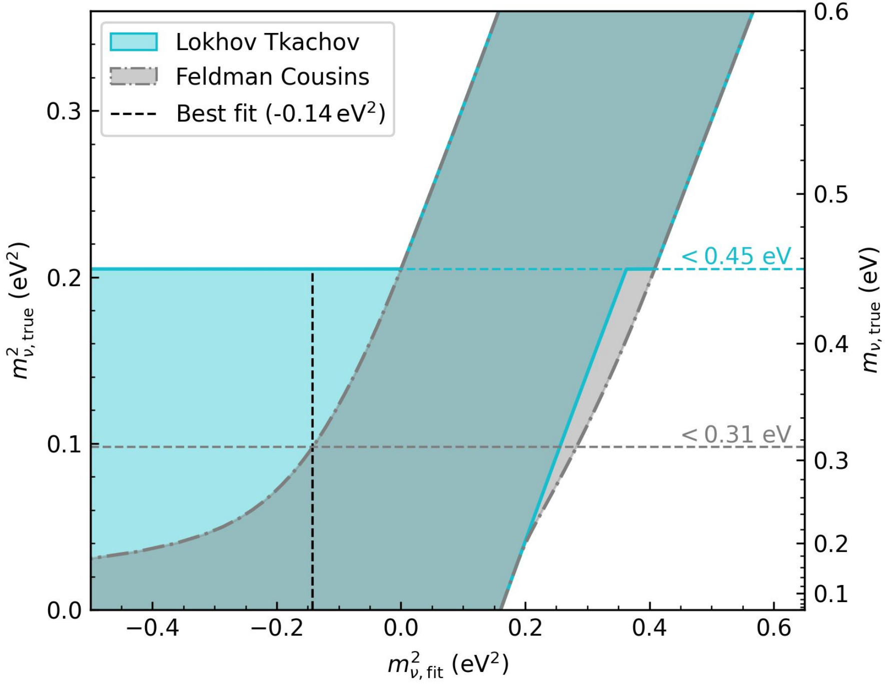
  m_ν < 0.45 eV (90% CL)

  using **Lokhov-Tkachov** construction

- Feldman-Cousins limit:

  m_ν < 0.31 eV (90% CL)

- **Bayesian analysis** in preparation



Beyond the neutrino mass

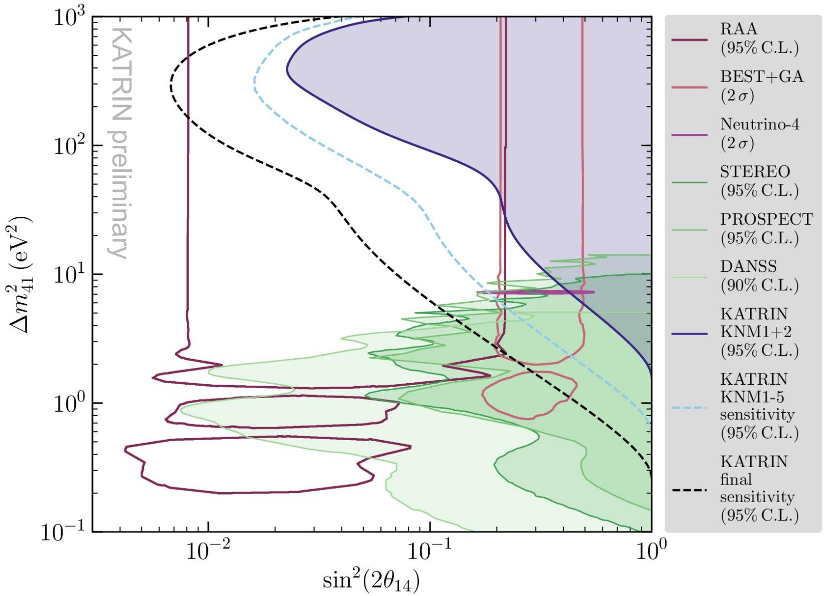
- KATRIN data allows to **probe** various “**beyond”-the-standard-model** theories, e.g.

➔ Search for cosmic relic neutrinos
M. Aker *et al.*, Phys. Rev. Lett. **129**, 01180 (2022)

➔ Search for eV-scale sterile-neutrinos
M. Aker *et al.*, Phys. Rev. D **105**, 072004 (2022)

➔ Search for Lorentz-invariance violation
M. Aker *et al.*, Phys. Rev. D **107**, 082005 (2023)

➔ Many more studies **work in progress**

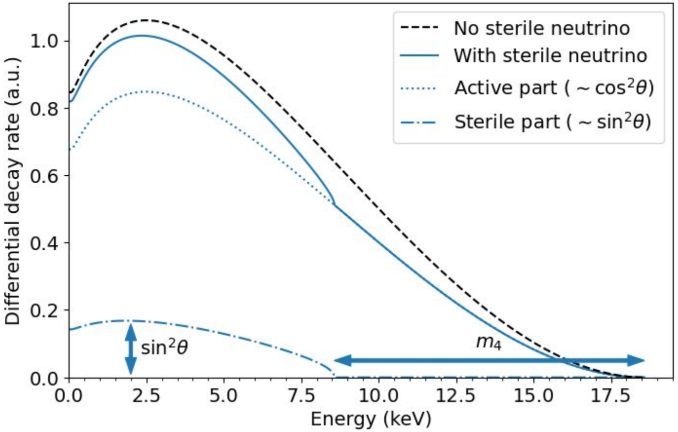


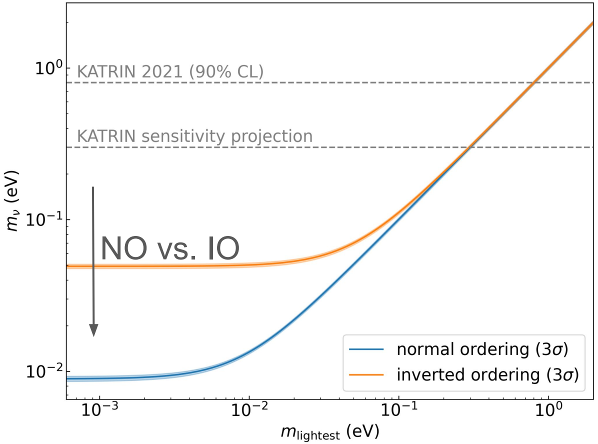
Poster from X. Stribl, Neutrino 2024

Beyond KATRIN

- **Data taking** will **continue** until end of 2025
- 2026: Installation of a new detector (**TRISTAN**) to search for **keV sterile neutrinos**

  D. Siegmann et al , J. Phys. G: Nucl. Part. Phys. 51 085202 (2024)
- 2027 onwards (KATRIN++): **Research and Development** for next neutrino mass experiments
  - Differential methods
  - Atomic tritium





Conclusion

- **Successful analysis** of first five measurement campaigns using a **neural net**

  New upper limit: m_ν < 0.45 eV at 90% CL

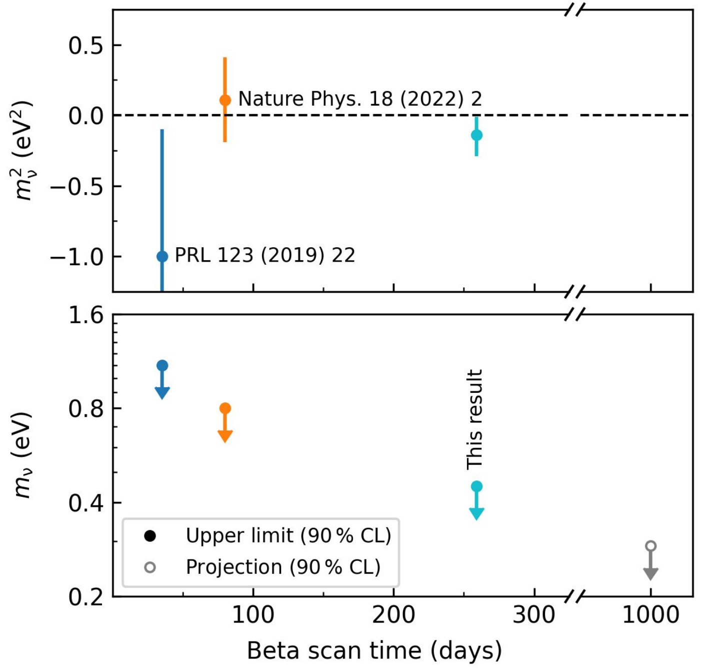
➔ **Paper submitted** to journal, preprint available at http://arxiv.org/abs/2406.13516

➔ Upcoming **release of data and model inputs** planned

➔ Beyond standard model studies ongoing, **stay tuned!**

- Data taking **ongoing**, **14th** measurement campaign about to start

➔ Target **sensitivity** below **0.3 eV** end of 2025



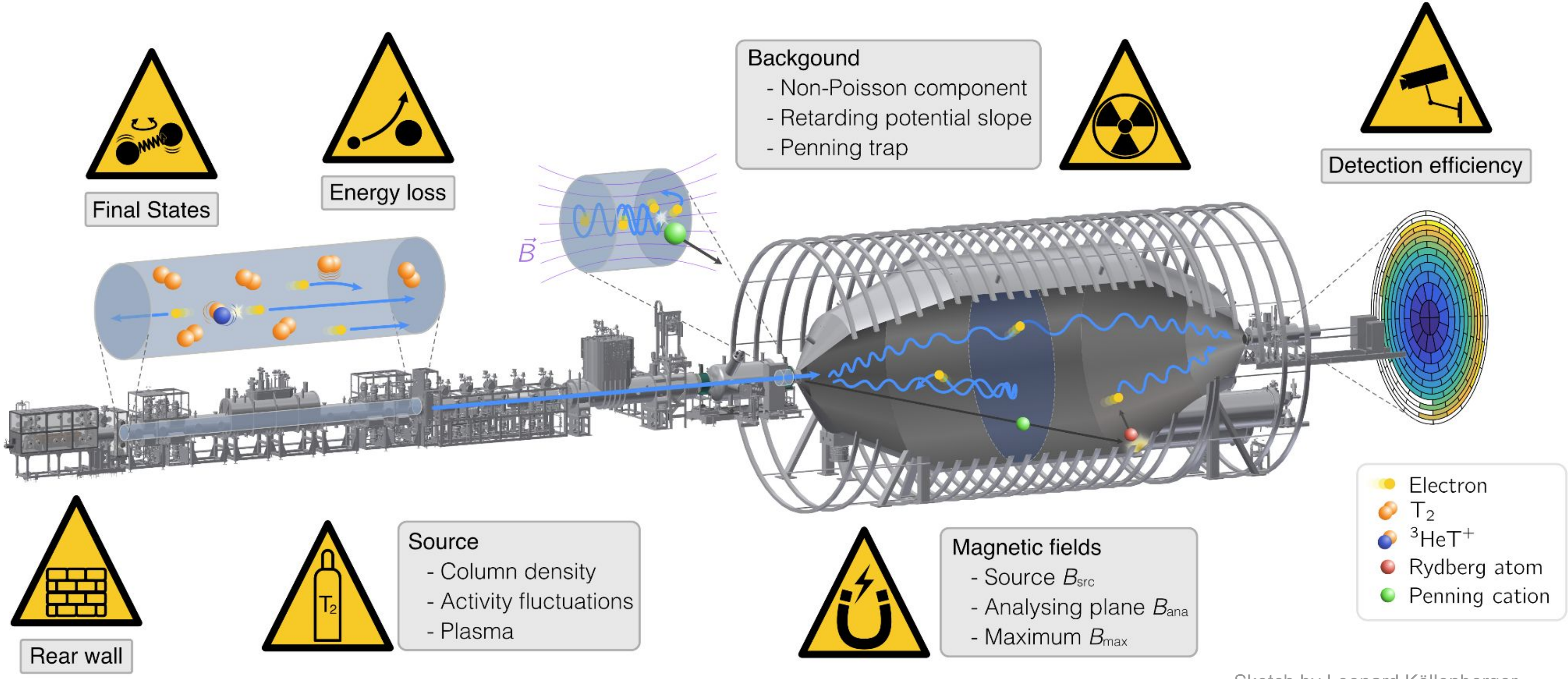
Thank you for your attention!

46th KATRIN Collaboration Meeting, March 2024 @ TUM

We acknowledge the support of Helmholtz Association (HGF), Ministry for Education and Research BMBF, the doctoral school KSETA at KIT, Helmholtz Initiative and Networking Fund, Max Planck Research Group, and DFG in Germany; Ministry of Education, Youth and Sport in the Czech Republic; INFN in Italy; the National Science, Research and Innovation Fund via the Program Management Unit for Human Resources & Institutional Development, Research and Innovation in Thailand; and the DOE Office of Science, Nuclear Physics in the United States. This project has received funding from the ERC under the European Union Horizon 2020 research and innovation programme. We thank the computing cluster support at the Institute for Astroparticle Physics at KIT, Max Planck Computing and Data Facility (MPCDF), and the National Energy Research Scientific Computing Center (NERSC) at LBNL.

Backup

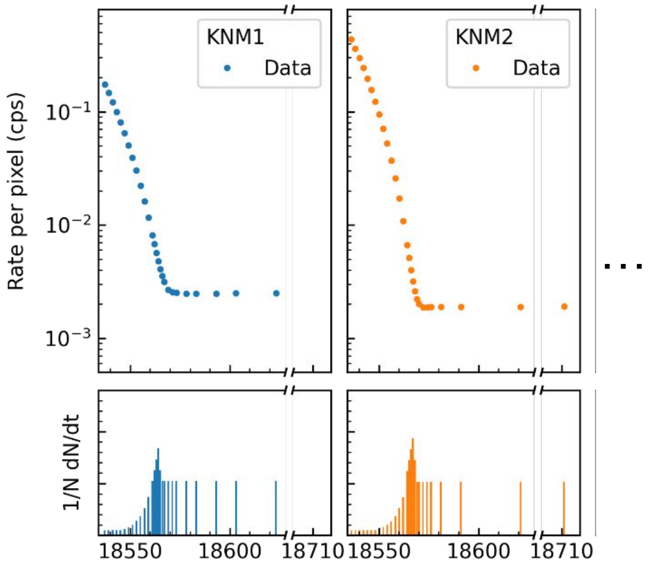
Systematic uncertainties



Sketch by Leonard Köllenberger

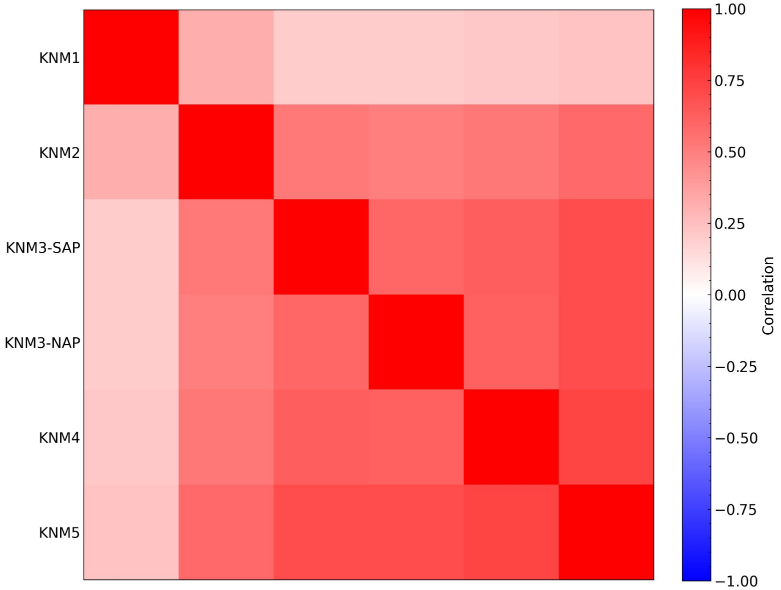
Upcoming data release: Spectra

- Will be released as a **JSON** file containing the processed **measured spectra** for KNM1-5
- Includes for each set point:
    - **Retarding voltage** applied to the main spectrometer
    - **Total measurement time** at the given set point
    - **Total number of counts** that hit the detector
- Detailed description in **supplement of publication**
- Less than **100kB** in size, upload details tbd



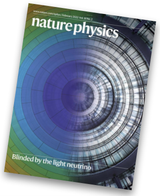
Upcoming data release: Model inputs

- Will be released as a **JSON** file containing all **systematic inputs** to calculate the model (e.g. magnetic fields)
- Includes **uncertainties** and **correlations** needed to evaluate likelihood
- No publication of **code framework**, detailed description in various publications
- Less than **100kB** in size, upload details tbd



e.g. gas density correlation matrix

KATRIN Neutrino Mass 2 (*KNM2*)



- Best fit compatible with zero (**p-value: 0.8**):

  $m_v^2 = (0.26 \pm 0.34)\ \mathrm{eV}^2$

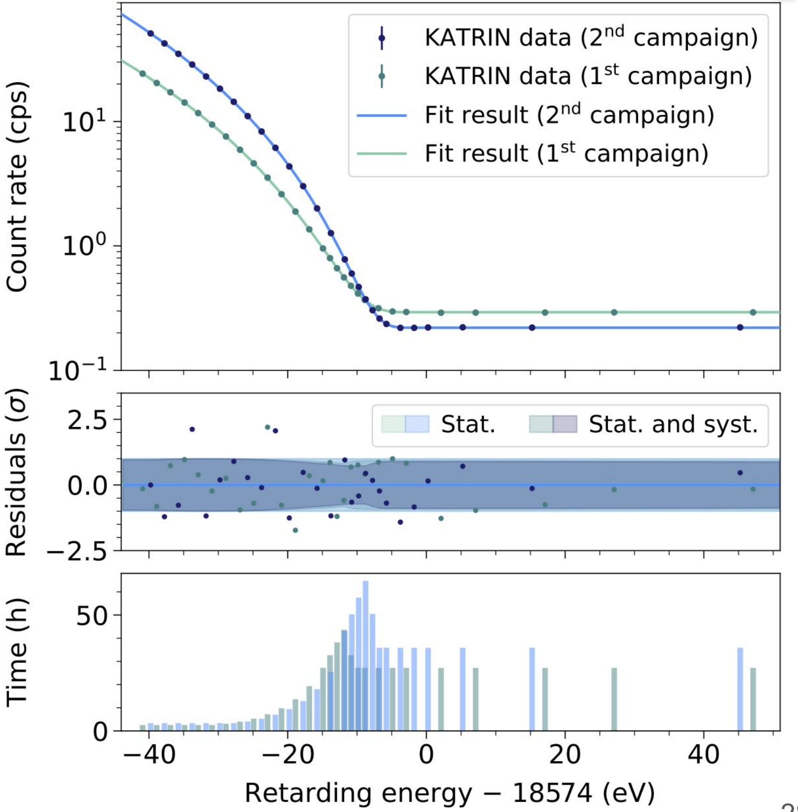
  Aker et al., [Nat. Phys. 18, 160–166]() (2022)

- Derived upper-limit using Lokhov-Tkachov confidence belt:

  $m_v < 0.9$ eV at 90% CL

- Combined with KNM1:

  $m_v < 0.8$ eV at 90% CL



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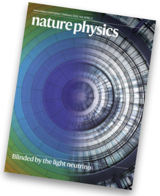

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