Latest results from the KATRIN experiment

Fabian Block for the KATRIN collaboration, Lake Louise Winter Institute 2024

Complementary ways of determining the neutrino mass

- high-precision cosmology

$$\Sigma = \sum_i m_i < 0.06 - 0.14\ eV$$

Stöcker et al., Phys.Rev.D 103 (2021) 12, 123508
Tanseri et al., JHEAp 36 (2022), 1-26

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- neutrino-less double beta decay

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \cdot m_i \right| < 0.04 \; - 0.18 \; eV$$

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model-dependent
(neutrino nature, nuclear matrix elements)

- kinematic neutrino mass measurement

model-independent
(independent of neutrino nature, solely based on kinematic parameters and energy conservation)

Kinematic neutrino mass measurement
(by example of β-decay)

- continuous β-decay spectrum described by Fermi's Golden Rule

$$\frac{d\Gamma}{dE} = C \cdot p \cdot (E + m_e) \cdot (E_0 - E) \cdot \sum_{i=1}^{3} |U_{ei}^2| \sqrt{(E_0 - E)^2 - m_i^2} \cdot F(E,Z) \cdot \theta(E_0 - E \ - \ m_{\nu_i})$$

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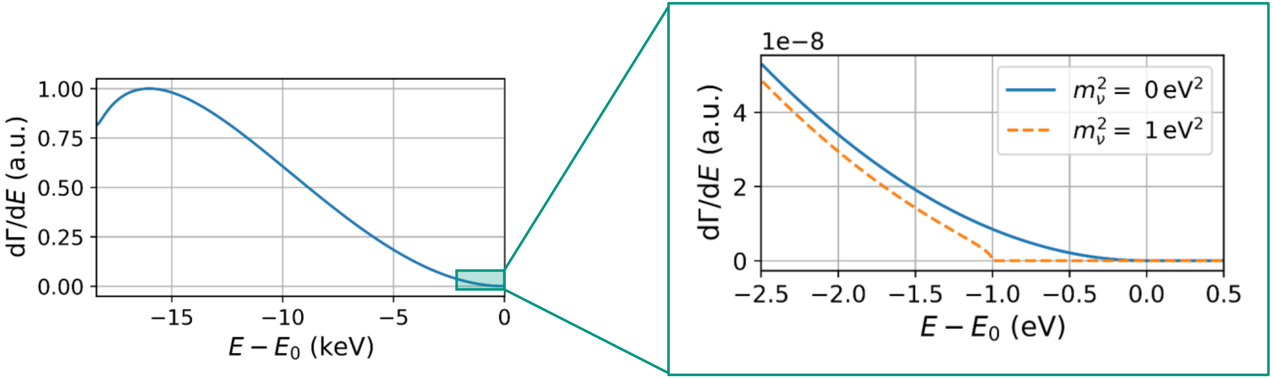
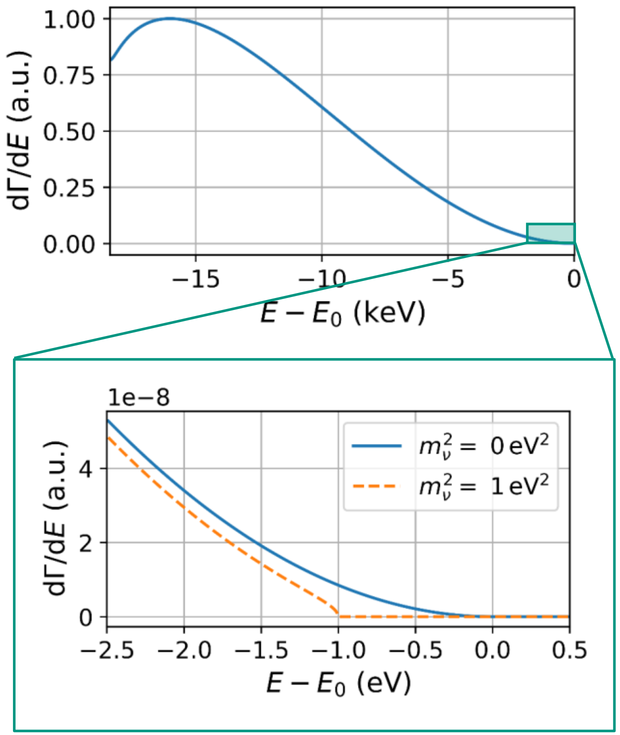
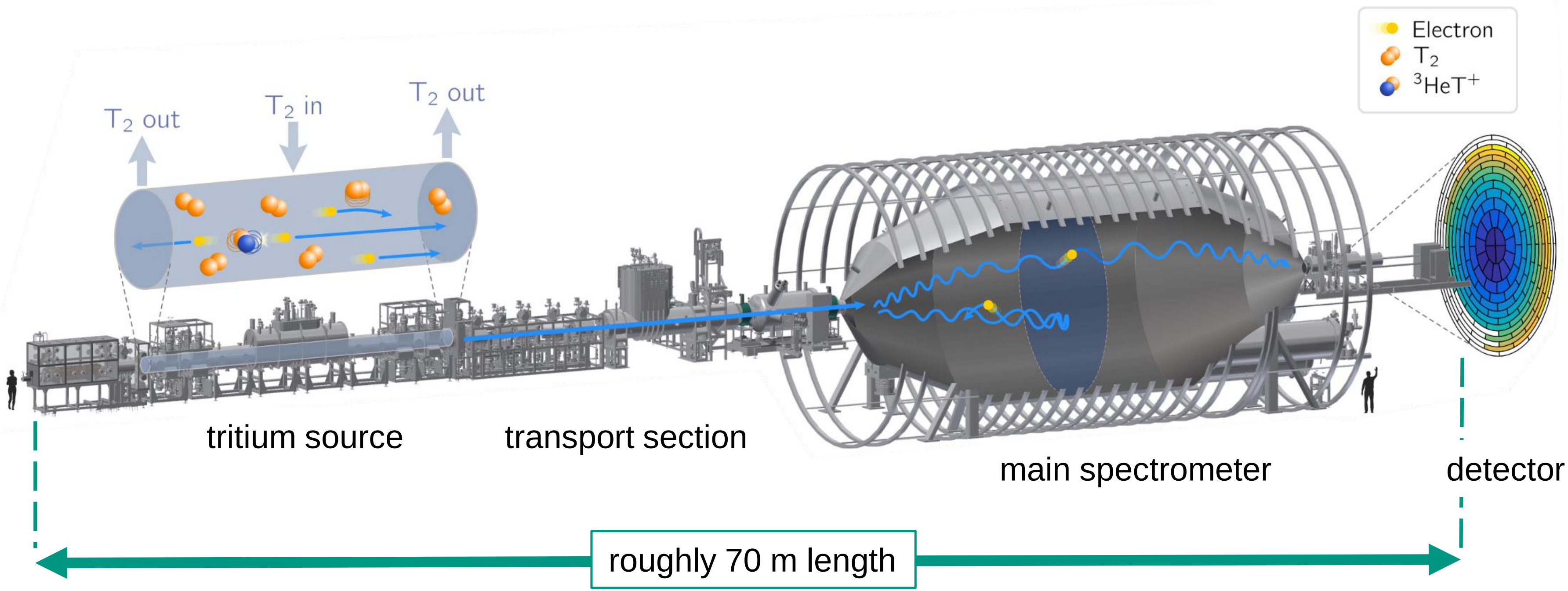


KATRIN requirements

- goal:
  - resolve spectral distortion close to the β-decay endpoint
- requirements:
  - strong β-decay source
  - excellent energy resolution
  - low background level
  - exact understanding of spectrum shape

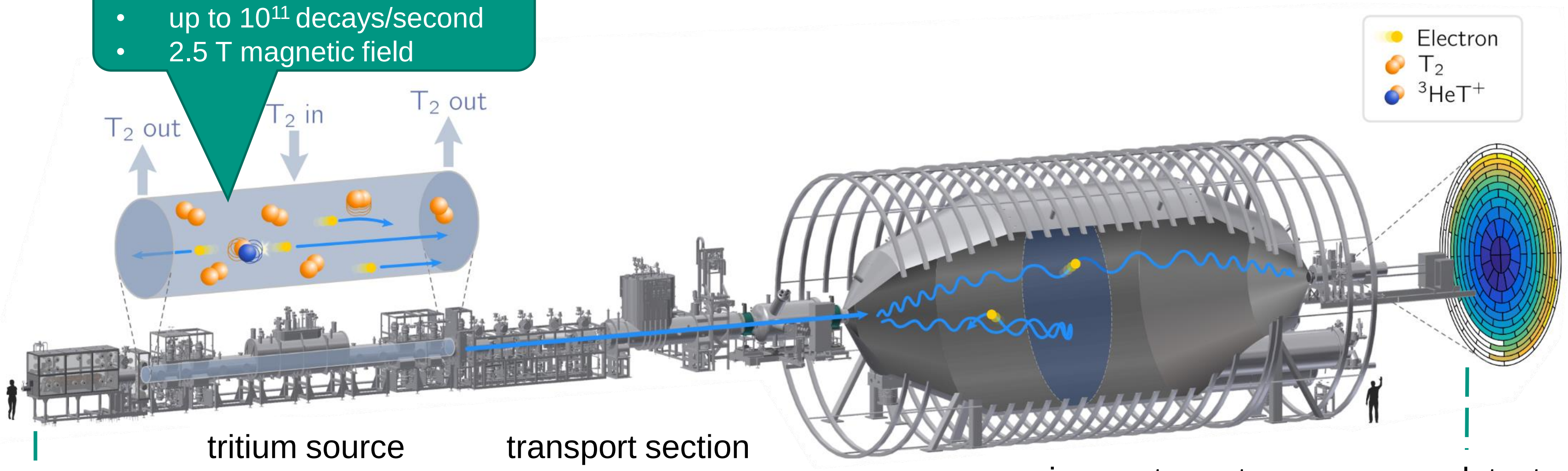


KATRIN experimental setup



KATRIN experimental setup

- molecular, gaseous tritium
- up to 10^{11} decays/second
- 2.5 T magnetic field



tritium source

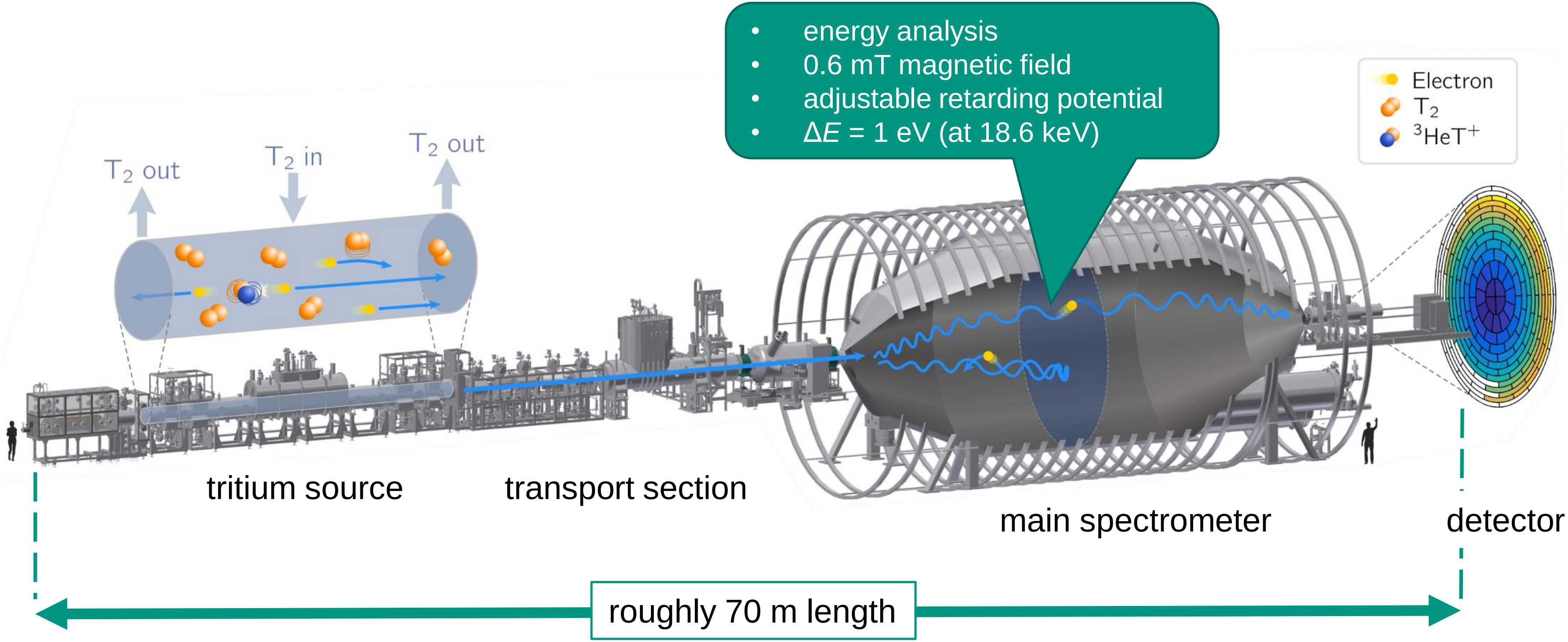
transport section

main spectrometer

detector

roughly 70 m length

KATRIN experimental setup



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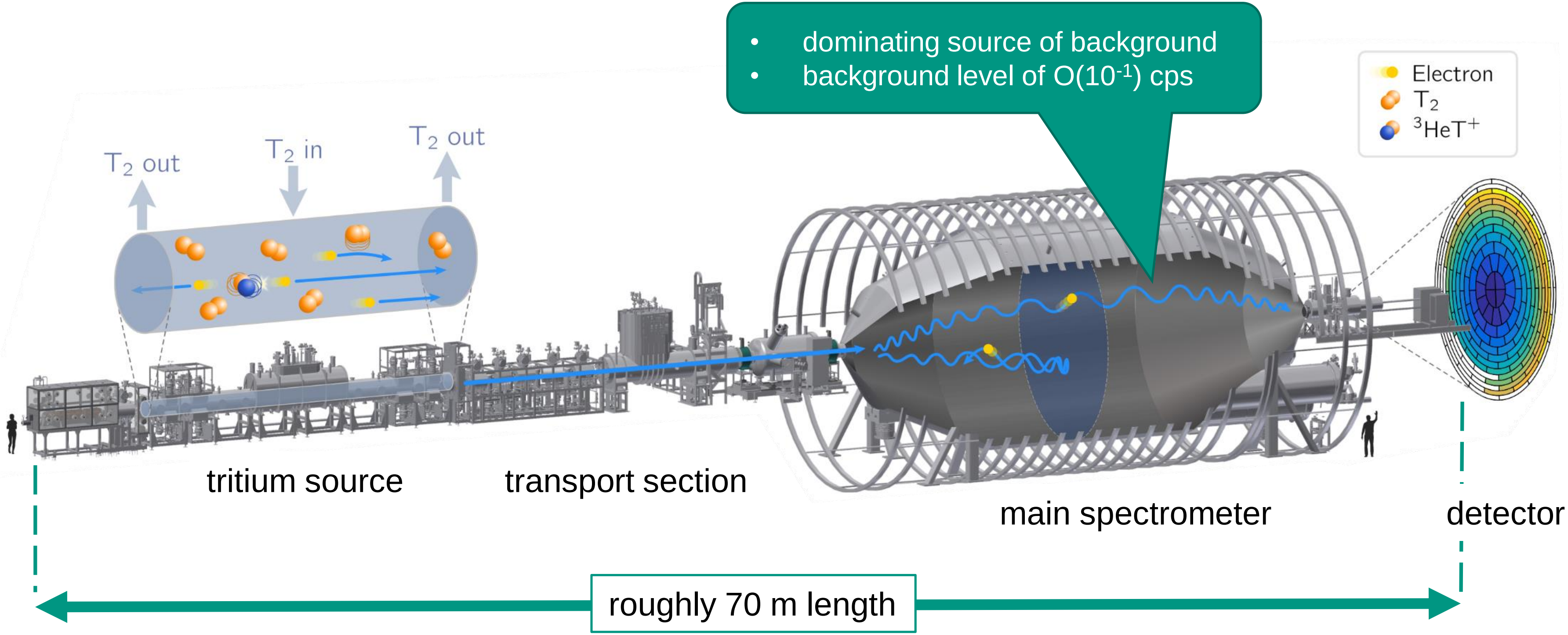

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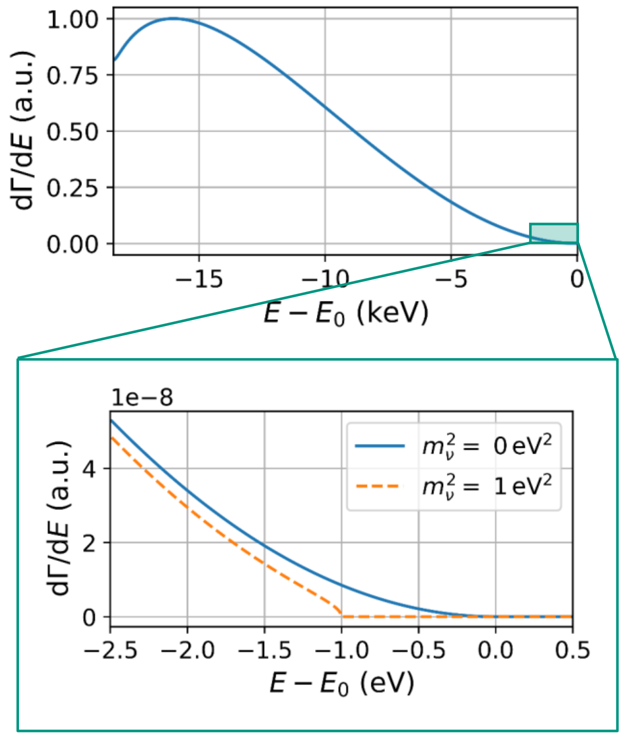
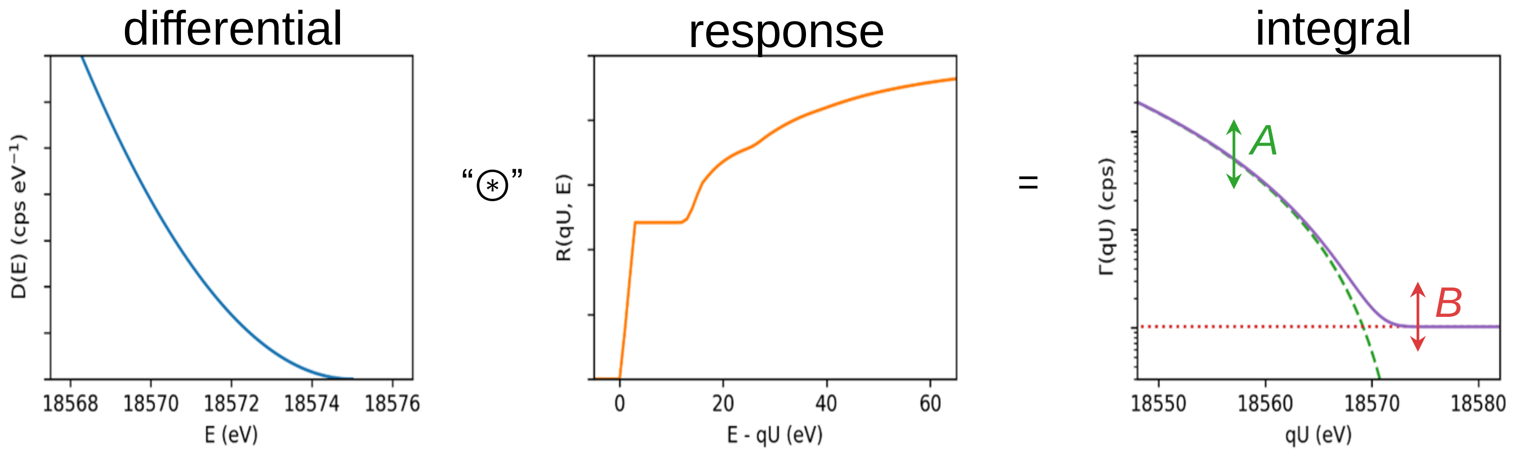


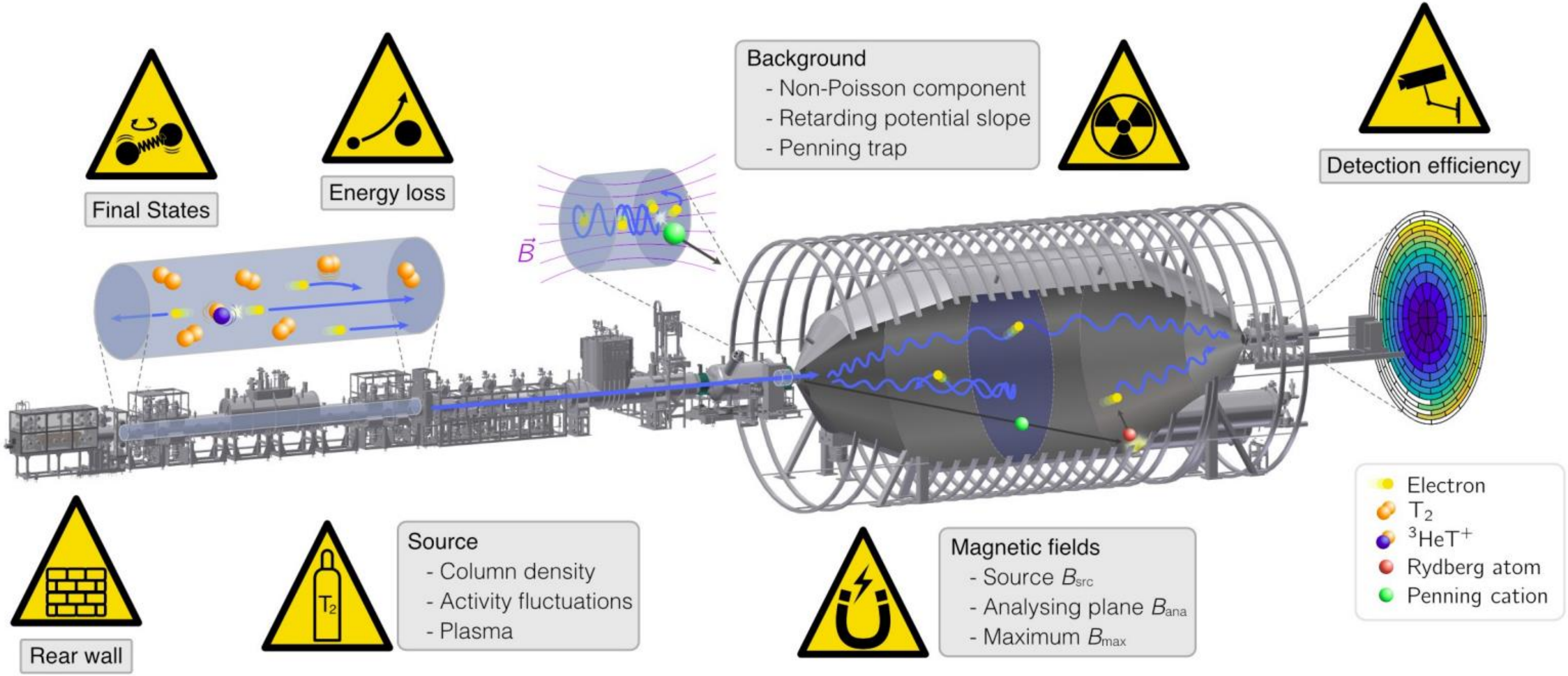
Exact understanding of spectrum shape

- KATRIN measures the integral β-decay spectrum

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



Exact understanding of spectrum shape



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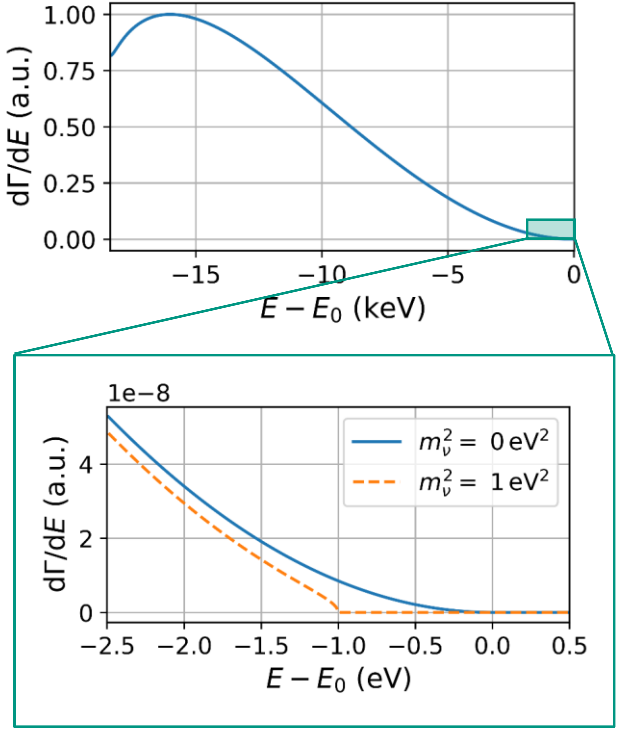
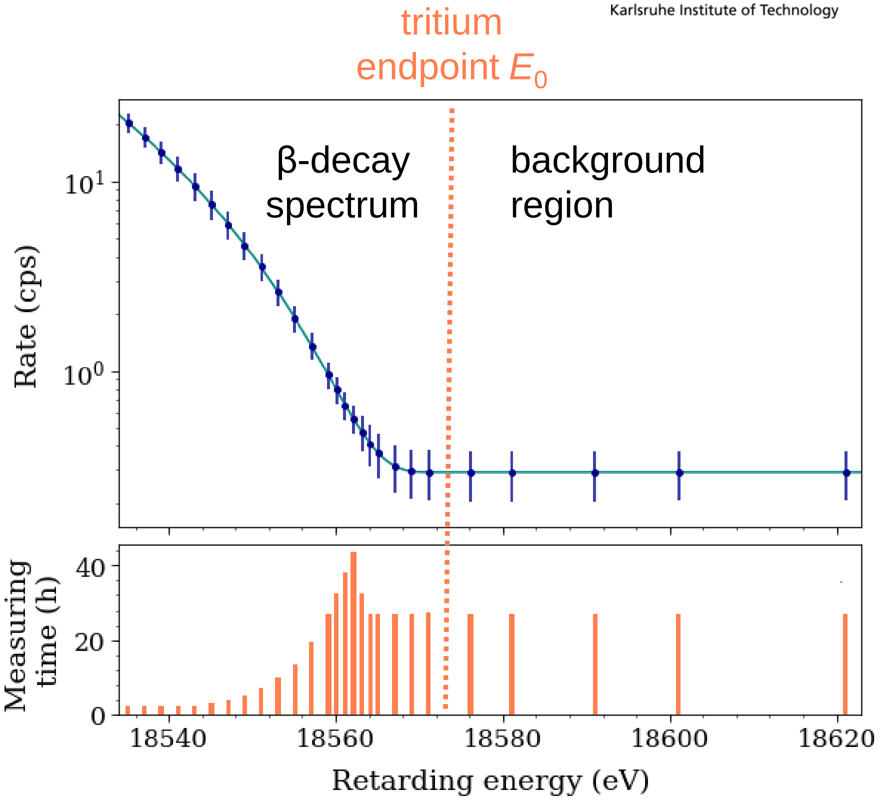
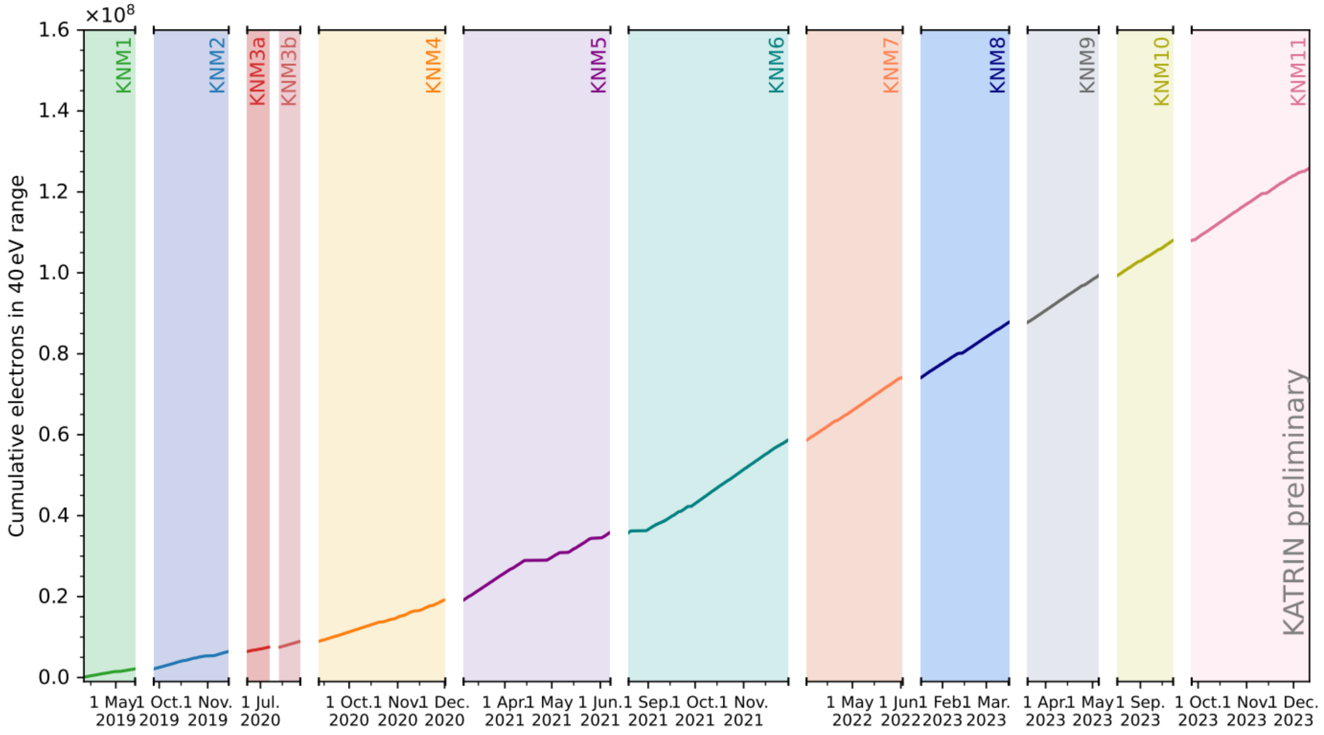


KATRIN tritium scan

- ~30 set points of the retarding potential with varying duration
- scan interval ranges from $E_0 - 40$ eV up to $E_0 + 130$ eV
- ~ 3 hours measurement time per scan
- O(500) scans per year



Overview of data taking



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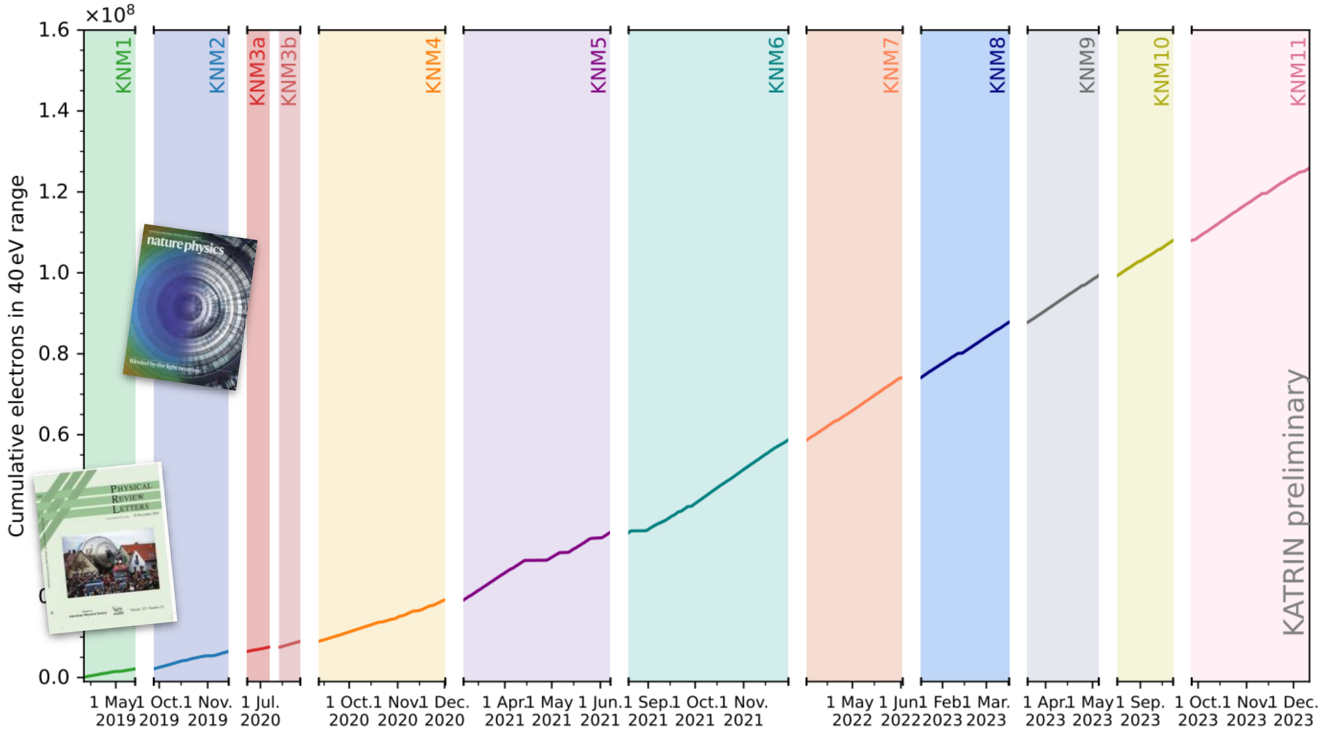
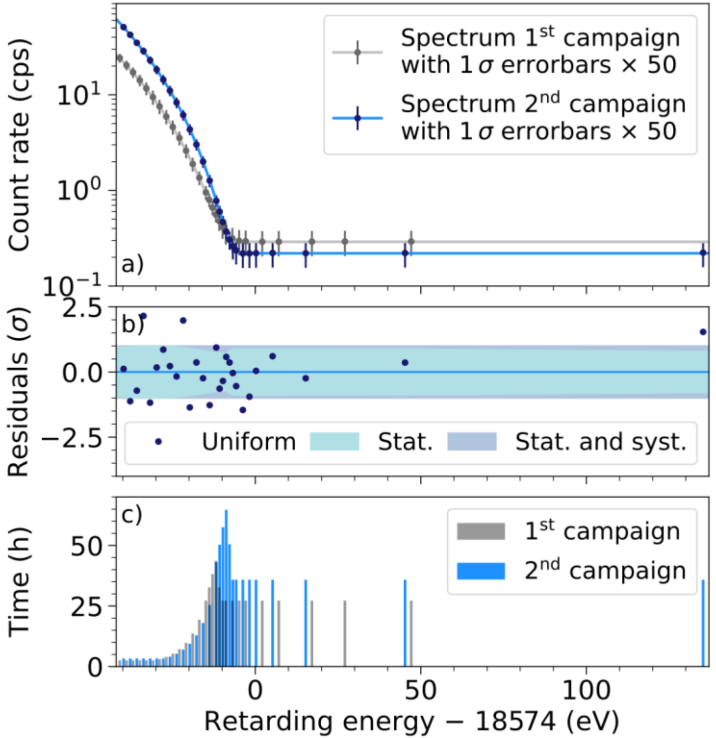


Latest neutrino mass result

- first measurement campaign
  - best fit: $m_\beta^2 = (-1.0^{+0.9}_{-1.1})$ eV²
  - limit: $m_\beta < 1.1$ eV (90% CL)

M. Aker et al., Phys. Rev. Lett. **123**, 221802

- second measurement campaign
  - best fit: $m_\beta^2 = (0.26^{+0.34}_{-0.34})$ eV²
  - limit: $m_\beta < 0.9$ eV (90% CL)



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M. Aker et al., Phys. Rev ... 02

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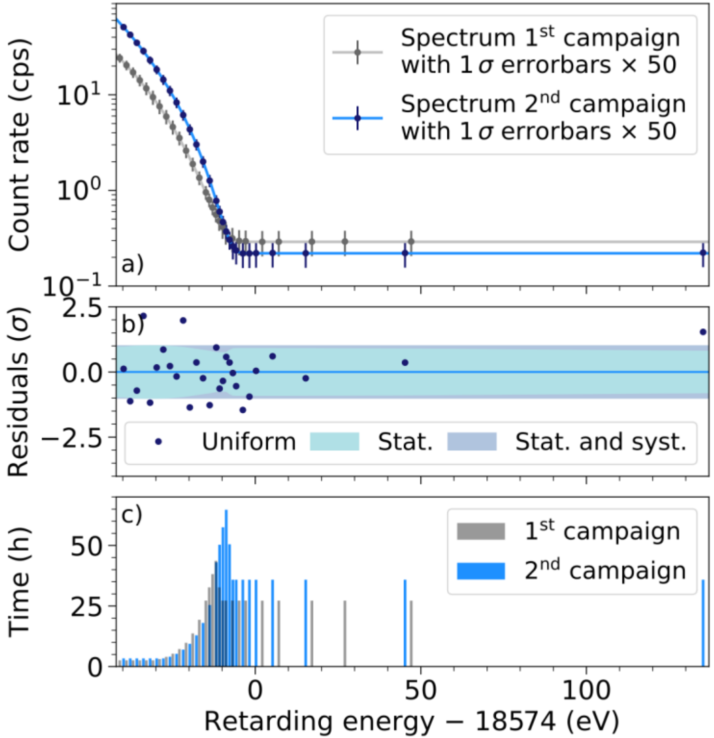
  - be ... $= (0.26^{+0.34}_{-0.34})$ eV²
  - ... $m_\beta < 0.9$ eV (90% CL)

first direct neutrino-mass measurement
with sub-eV sensitivity

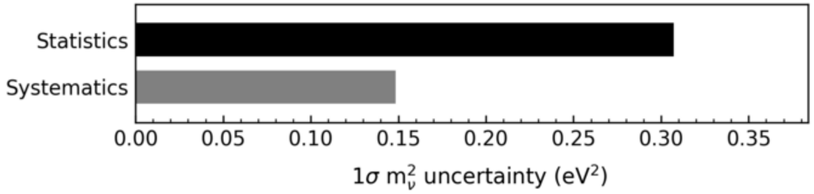
- combined result: $m_\beta < 0.8$ eV (90% CL)

M. Aker et al., *Nat. Phys.* **18**, 160–166 (2022)



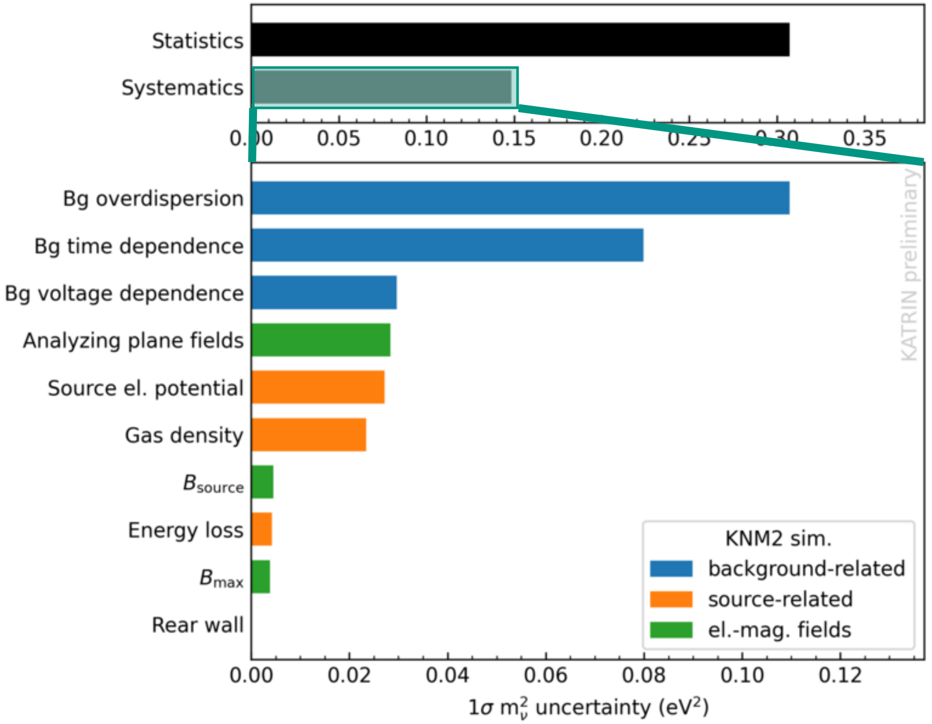
Uncertainty breakdown of KNM2

- statistical uncertainty dominates
  - systematics non-negligible



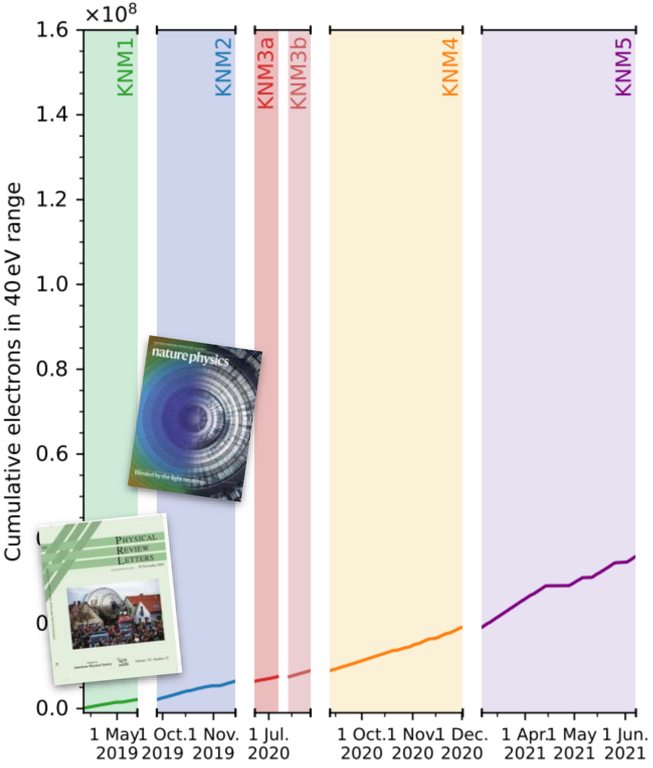
Uncertainty breakdown of KNM2

- statistical uncertainty dominates
  - systematics non-negligible
- background-related uncertainties dominate systematics budget



Next analysis release

- combined analysis of first five campaigns
  - currently in unblinding process
  - next data release in summer

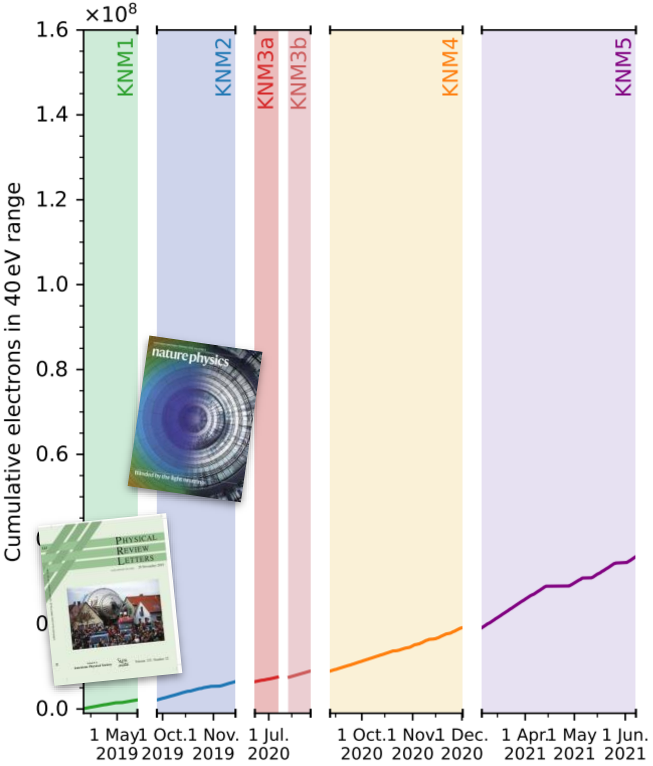


Next analysis release

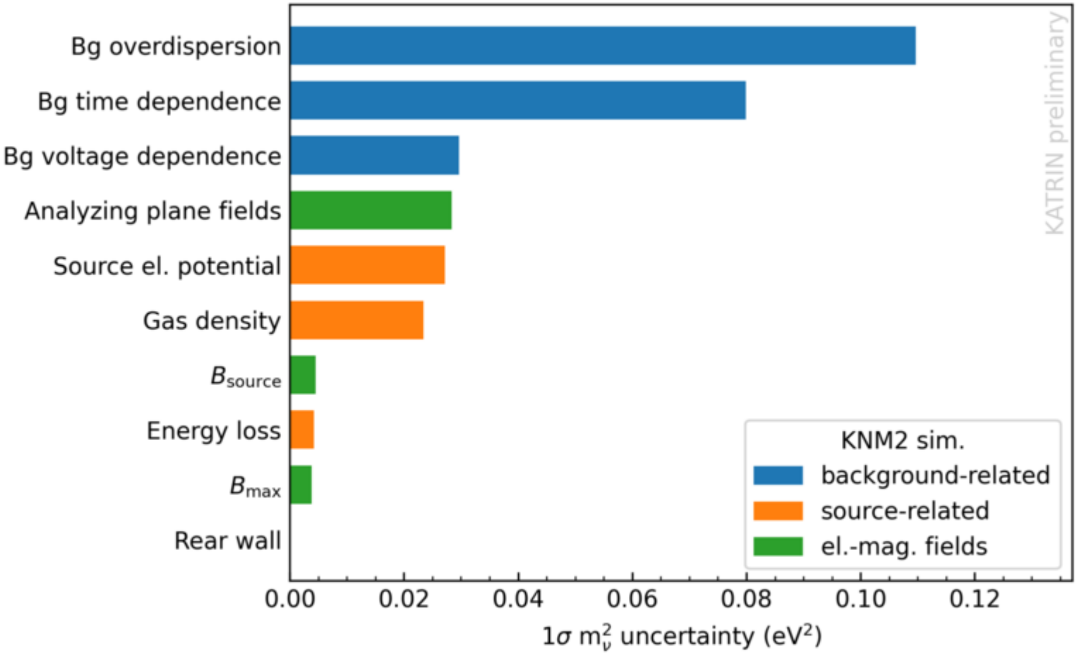
- combined analysis of first five campaigns
  - currently in unblinding process
  - next data release in summer
- sensitivity projection:

$$m_\beta < 0.5 \text{ eV (90\% CL)}$$

- improvements
  - factor six in statistics
  - background reduction
  - more accurate knowledge of systematics

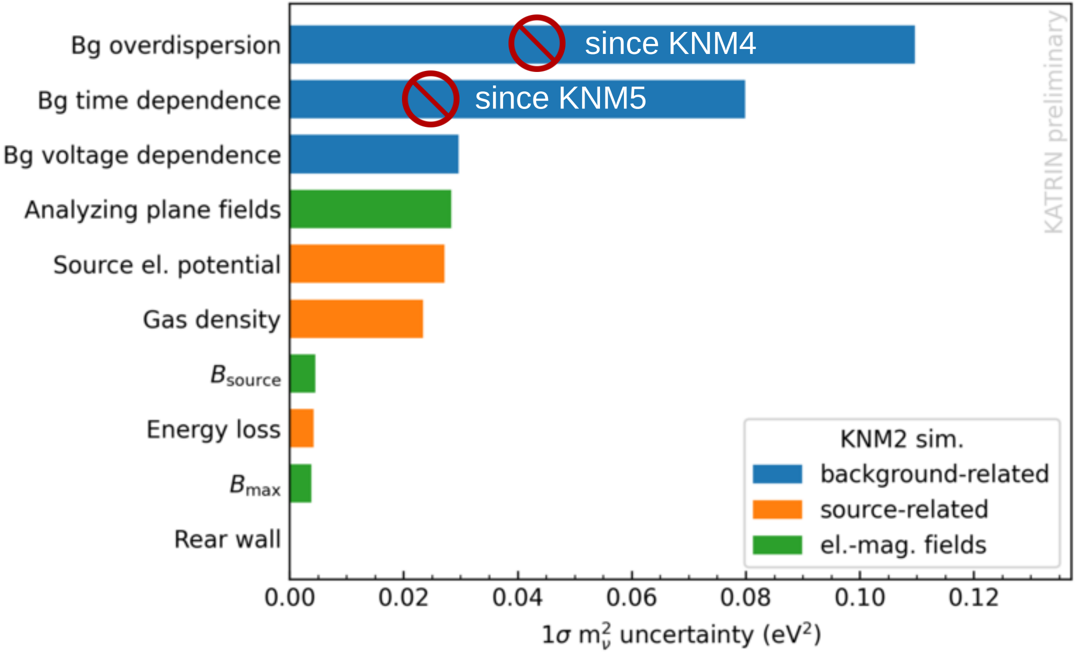


Next analysis release - uncertainty breakdown



Next analysis release - uncertainty breakdown

Karlsruhe Institute of Technology



counter measures implemented for data taking

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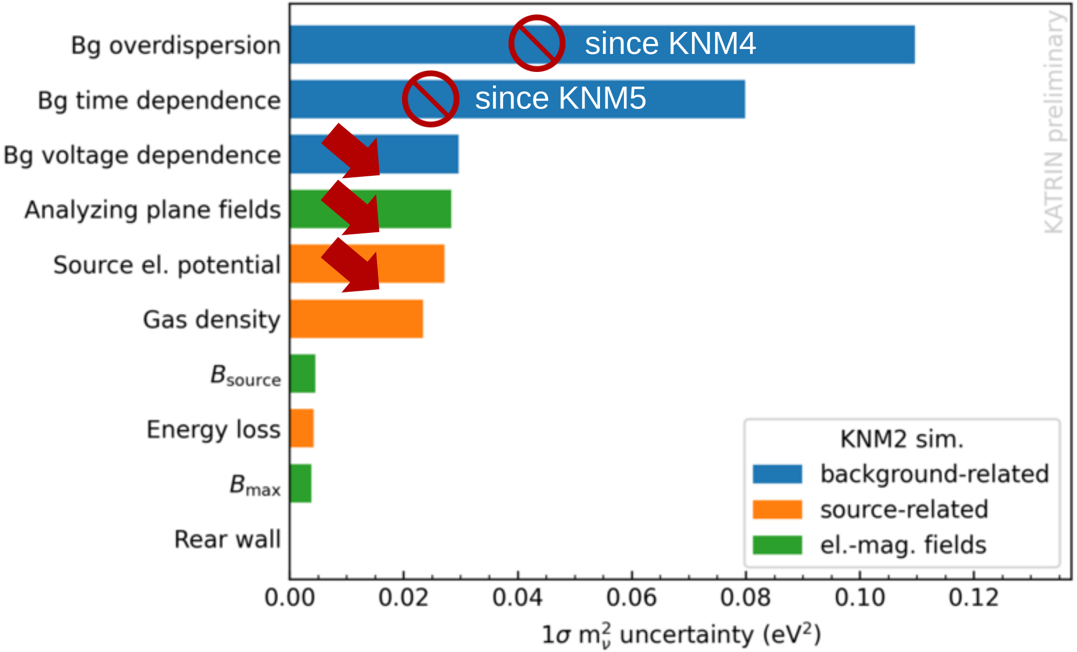


counter measures implemented for data taking

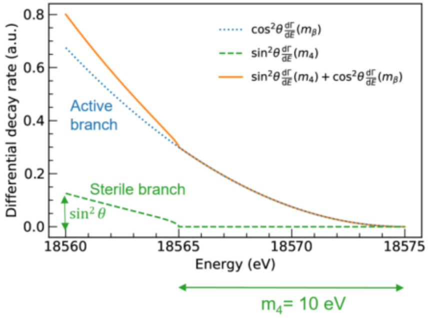
decrease due to new calibration measurements

“Beyond neutrino mass” in KATRIN

high statistics and
precise β spectrum

“Beyond neutrino mass” in KATRIN

search for sterile neutrinos



high statistics and precise β spectrum

Aker et al., 2022 *Phys. Rev. D* **105** 072004
Aker et al., 2021 *Phys. Rev. Lett.* **126** 091803
Mertens et al., 2015 *J. Cosmol. Astropart. Phys.* **JCAP02**(2015)020
etc.

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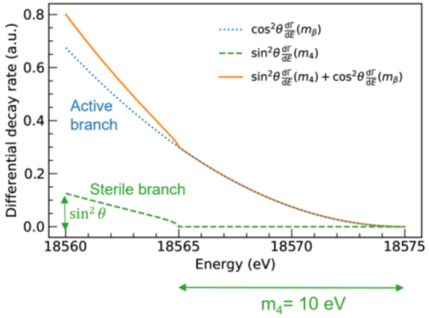

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high statistics and precise β spectrum

search for exotic interactions

Arcadi et al., 2019 *J. High Energy Phys.* JHEP01(2019)206
Fengler et al., 2024 *PoS, DISCRETE2022* **011**
etc.

“Beyond neutrino mass” in KATRIN

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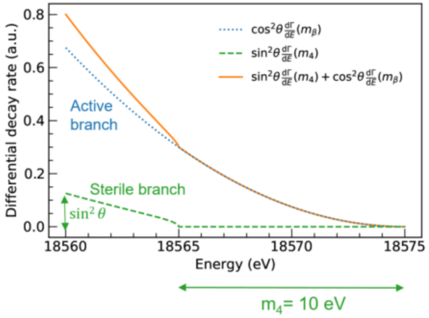

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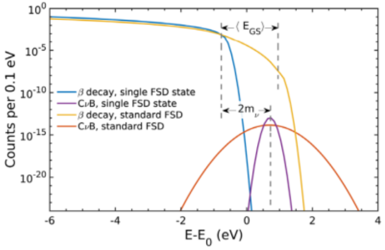
set constrains on local density of cosmic relic neutrinos

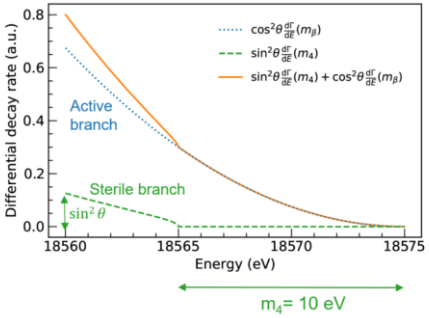
Aker et al., 2022 *Phys. Rev. Lett.* **129** 011806



“Beyond neutrino mass” in KATRIN

high statistics and precise β spectrum

search for sterile neutrinos



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Aker et al., 2021 *Phys. Rev. Lett.* **126** 091803
Mertens et al., 2015 *J. Cosmol. Astropart. Phys.* **JCAP02**(2015)020
etc.

search for Lorentz invariance violation

Aker et al., 2023 *Phys. Rev. D* **107** 082005

search for exotic interactions

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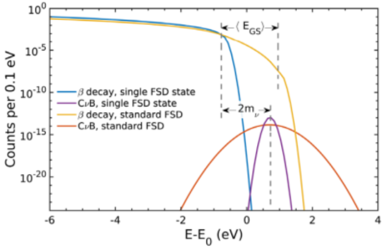
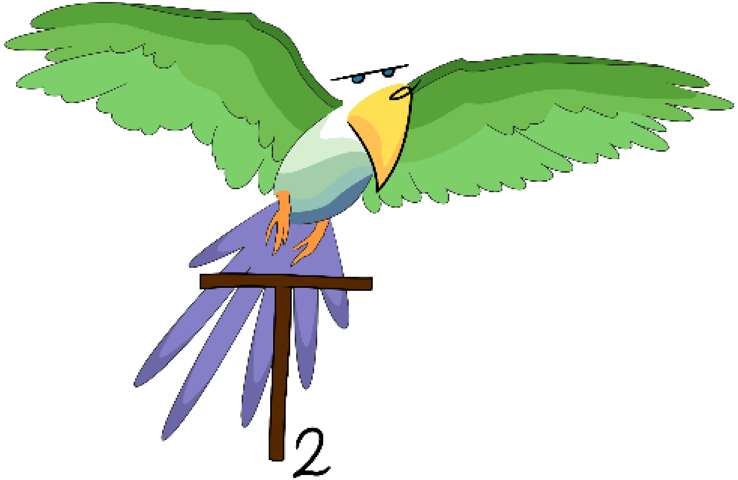


Summary and outlook

- first direct neutrino-mass measurement with sub-eV sensitivity

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

- combination of first five campaigns
  - significant improvement of systematics and statistics
  - sensitivity: $m_\beta < 0.5$ eV (90% CL)
- multiple physics searches beyond the neutrino mass



Thank you for your attention!

Back-up

Tests of new physics – light sterile neutrinos

- eV-scale sterile neutrino motivated by anomalies in short-baseline neutrino oscillation experiments

Aguilar et al., Phys. Rev. D 64, 112007 (2001)

Aguilar-Arevalo et al., , Phys. Rev. Lett. 121, 221801 (2018)

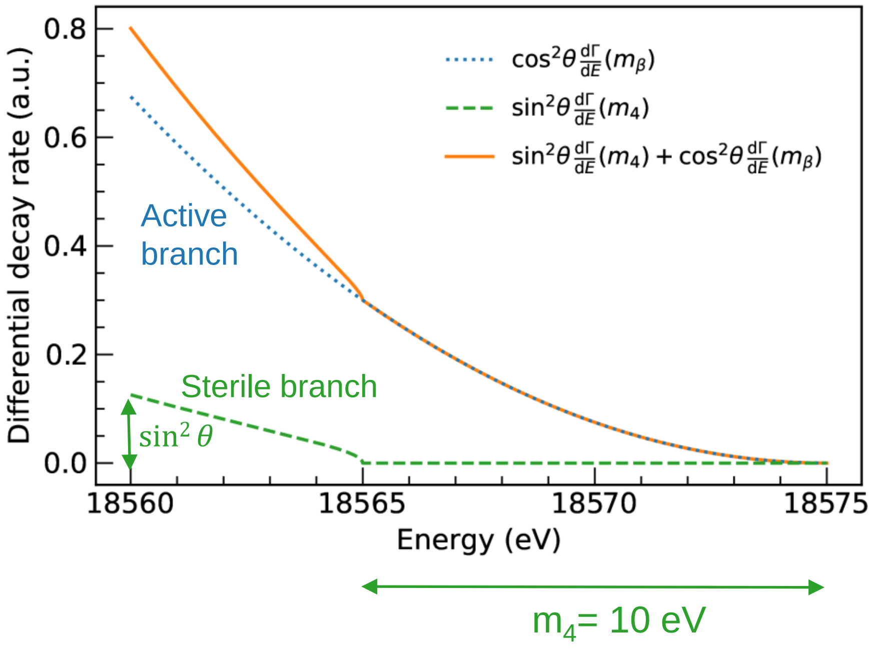
Hampel et al., Phys. Lett. B 420, 114 (1998)

Abdurashitov et al., Phys. Rev. C 80, 015807 (2009)

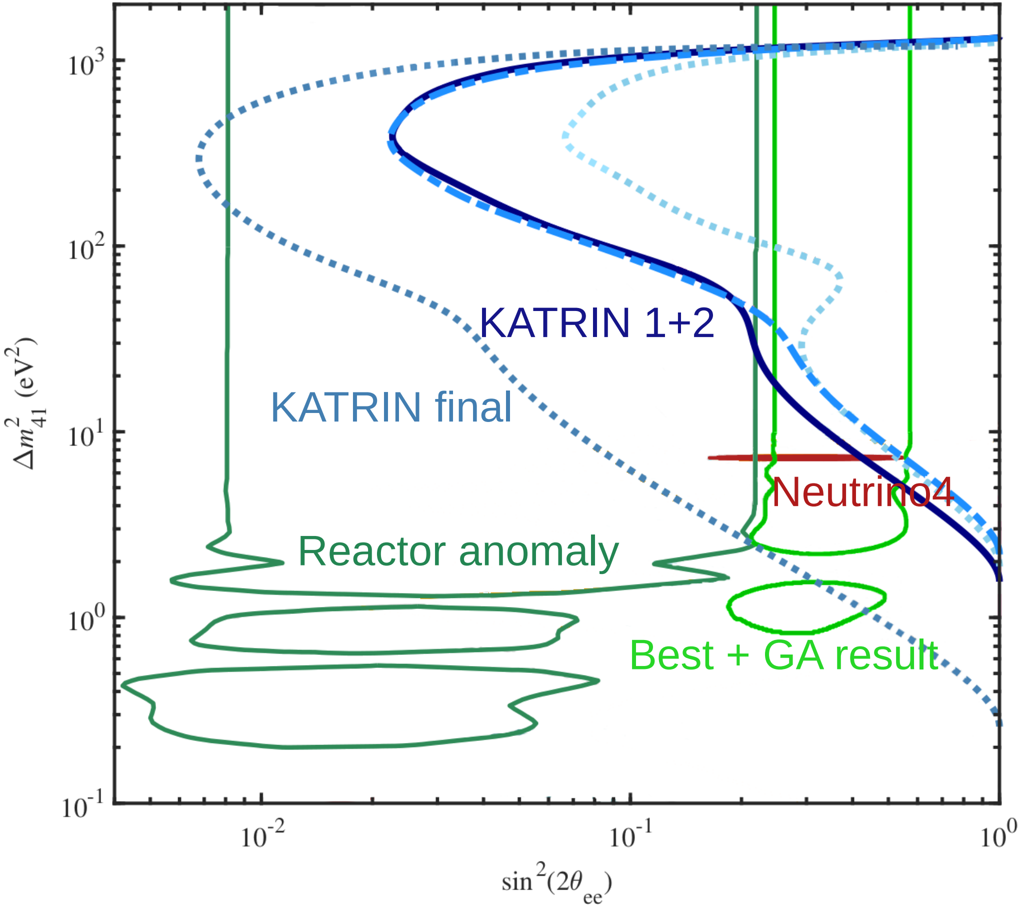
Barinov et al., Phys. Rev. Lett. 128, 232501

Mention et al., Phys. Rev. D 83, 073006 (2011)

Serebrov et al., Pis’ma Zh. Eksp. Teor. Fiz. 109, 209 (2019)



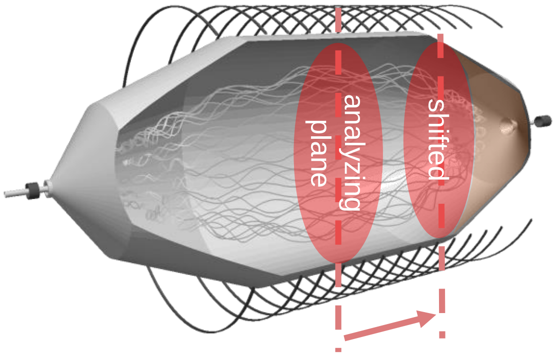
Tests of ne



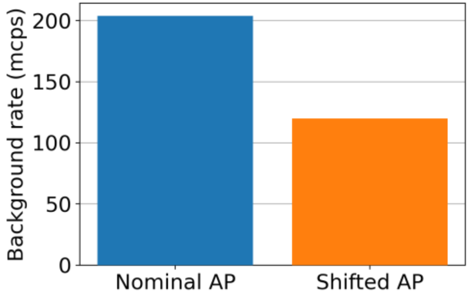
KATRIN 1+2
KATRIN final
Neutrino4
Reactor anomaly
Best + GA result
Δm^2_{41} (eV^2)
$\sin^2(2\theta_{ee})$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0

Background reduction

- dominating background contribution is produced in the main spectrometer
- volume-dependent background rate
  - sensitive to volume between analyzing plane and detector
  - adjusted electromagnetic field layout in main spectrometer
  - significant reduction of background rate



Lokhov et al., *Eur. Phys. J. C* 82, 258 (2022).

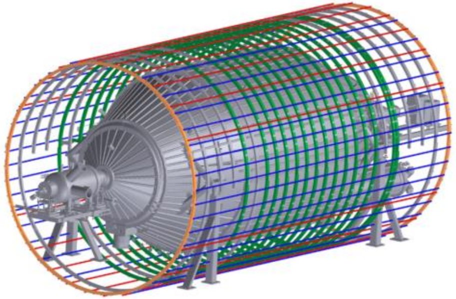


Main spectrometer as MAC-E filter

- fine-tuned drop of magnetic field in combination with electrostatic retarding potential (MAC-E filter principle) allows main spectrometer energy resolution of

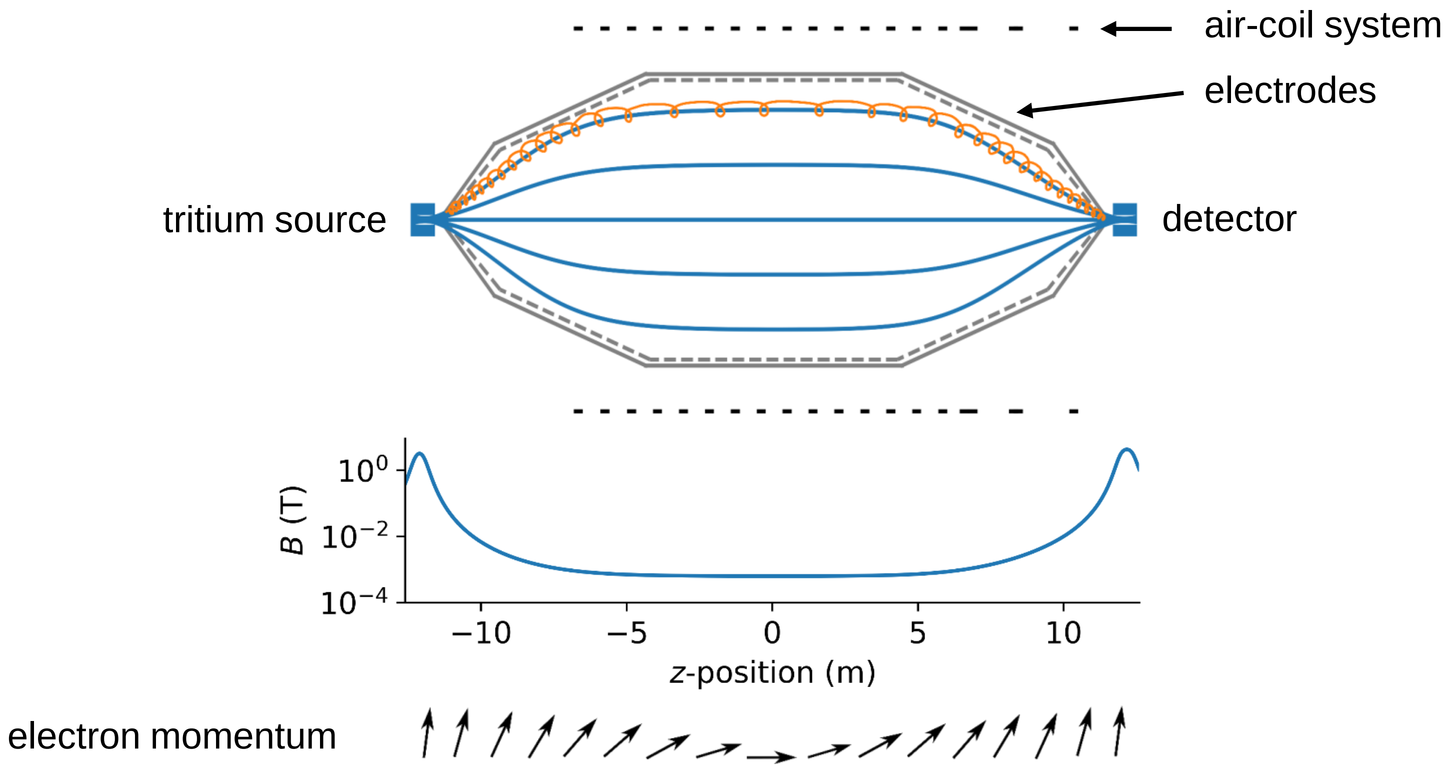
$$\Delta E = 1 \text{ eV (at 18.6 keV)}$$

- air-coil system and inner electrode system allow fine-tuning of electromagnetic field configuration
- high-voltage system can provide up to -40 kV



The KATRIN collaboration, 2021 *JINST* 16 T08015

Main spectrometer as MAC-E filter



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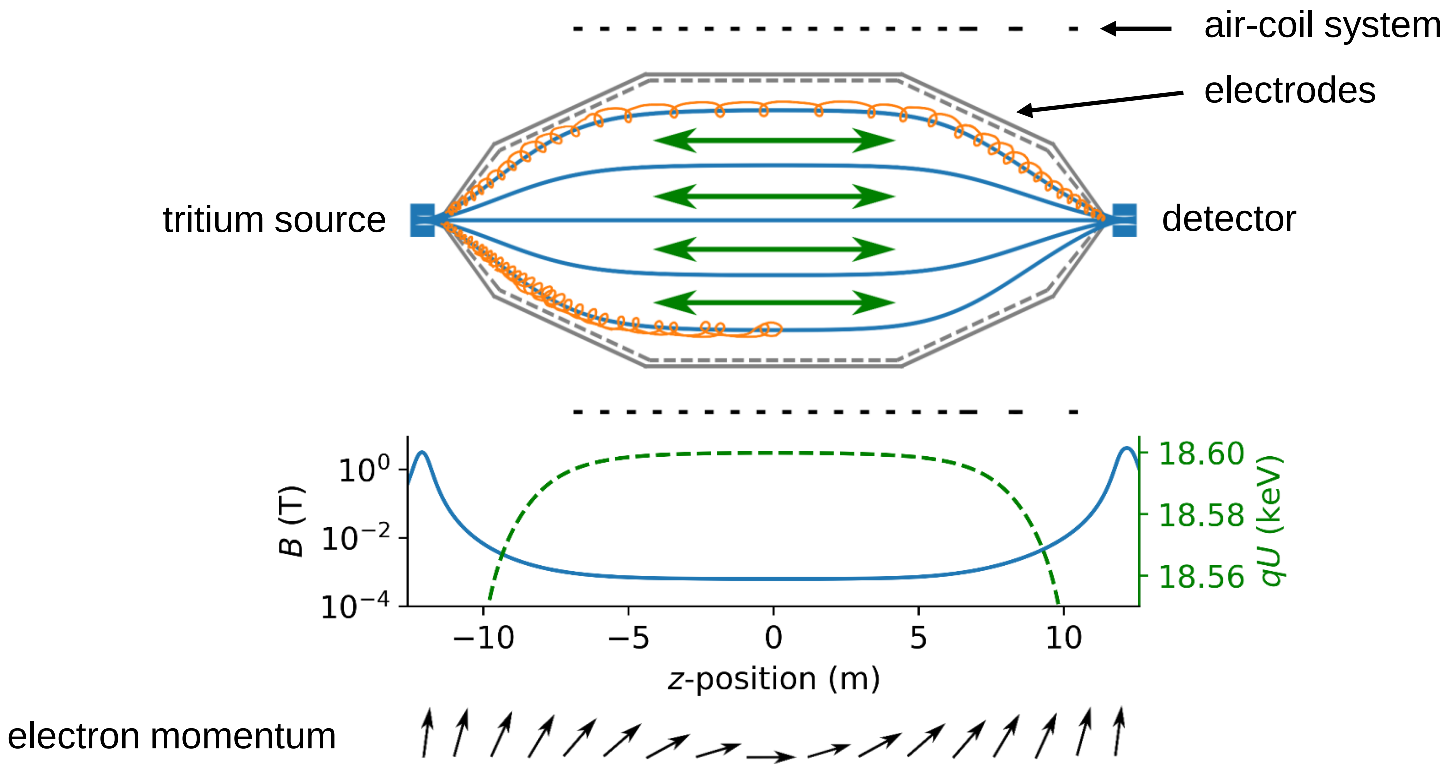

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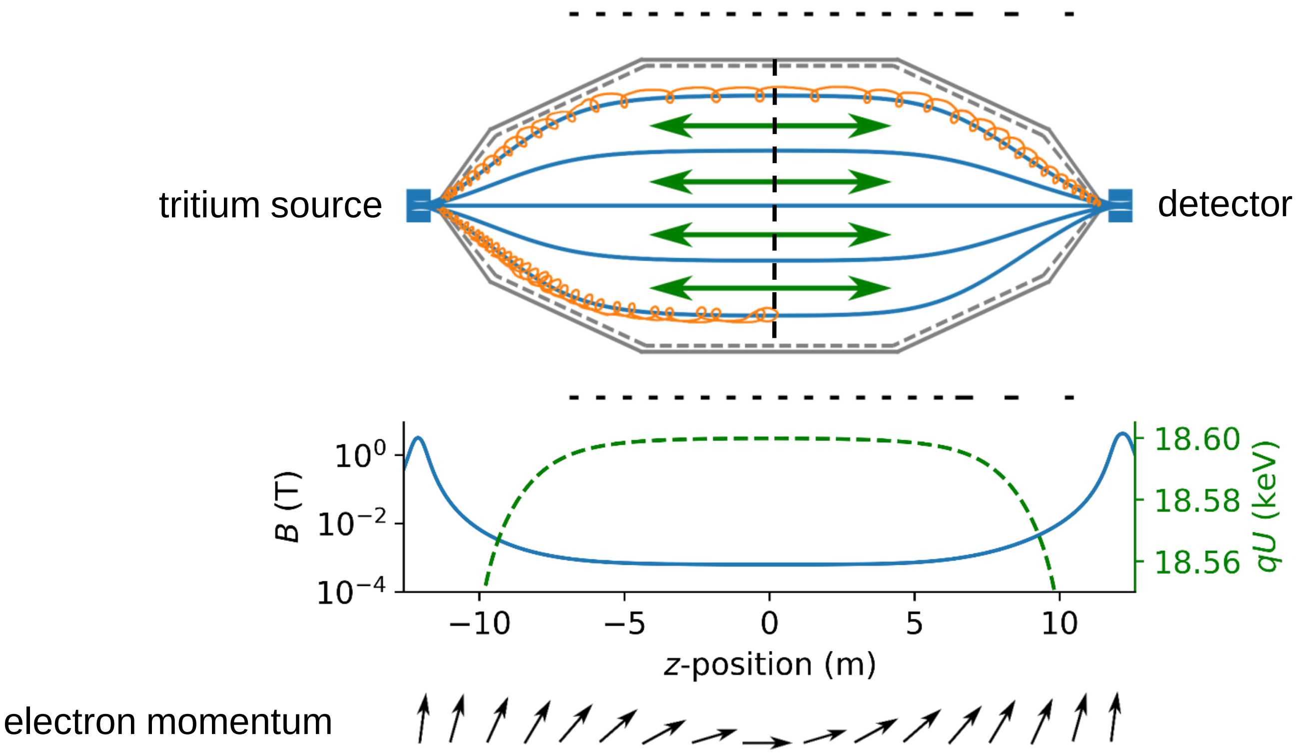

analyzing plane:
- minimal B
- maximal qU

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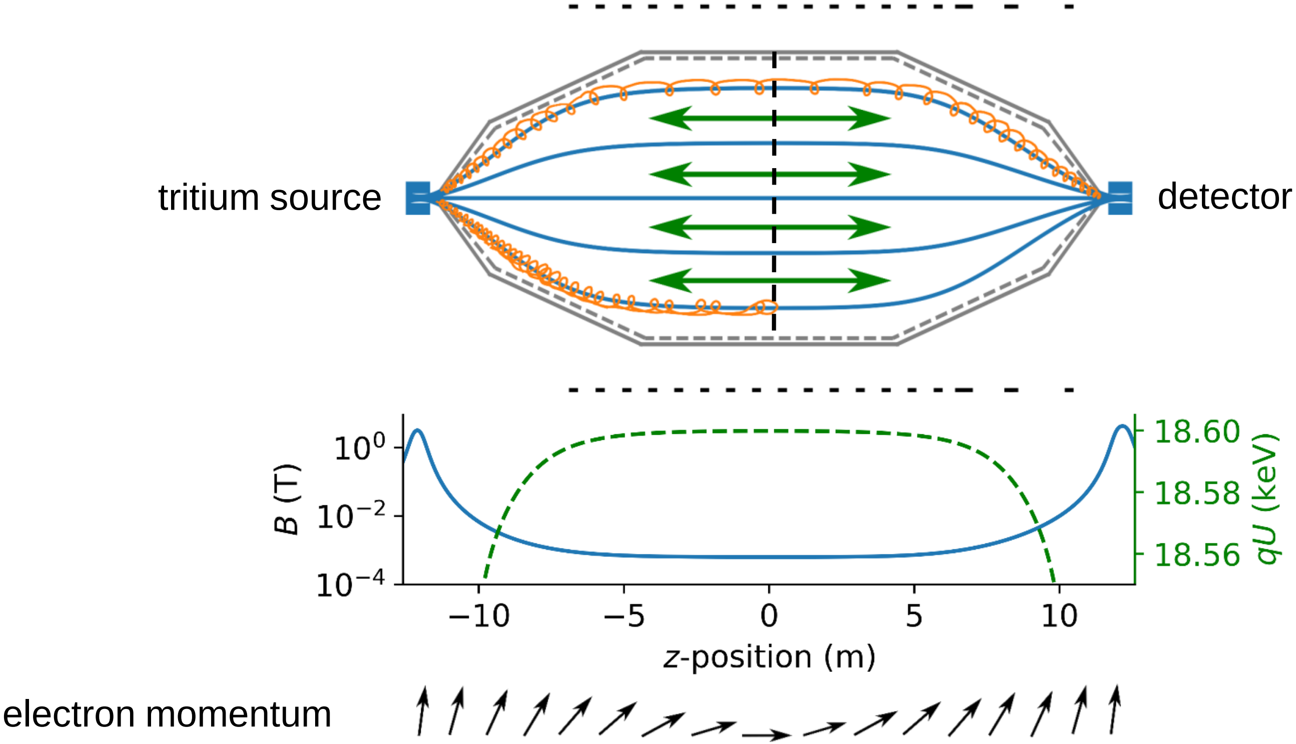

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described in transmission function $T(E,U)$