Assessment of systematic effects in KATRIN's neutrino-mass measurement with a calibration photoelectron source

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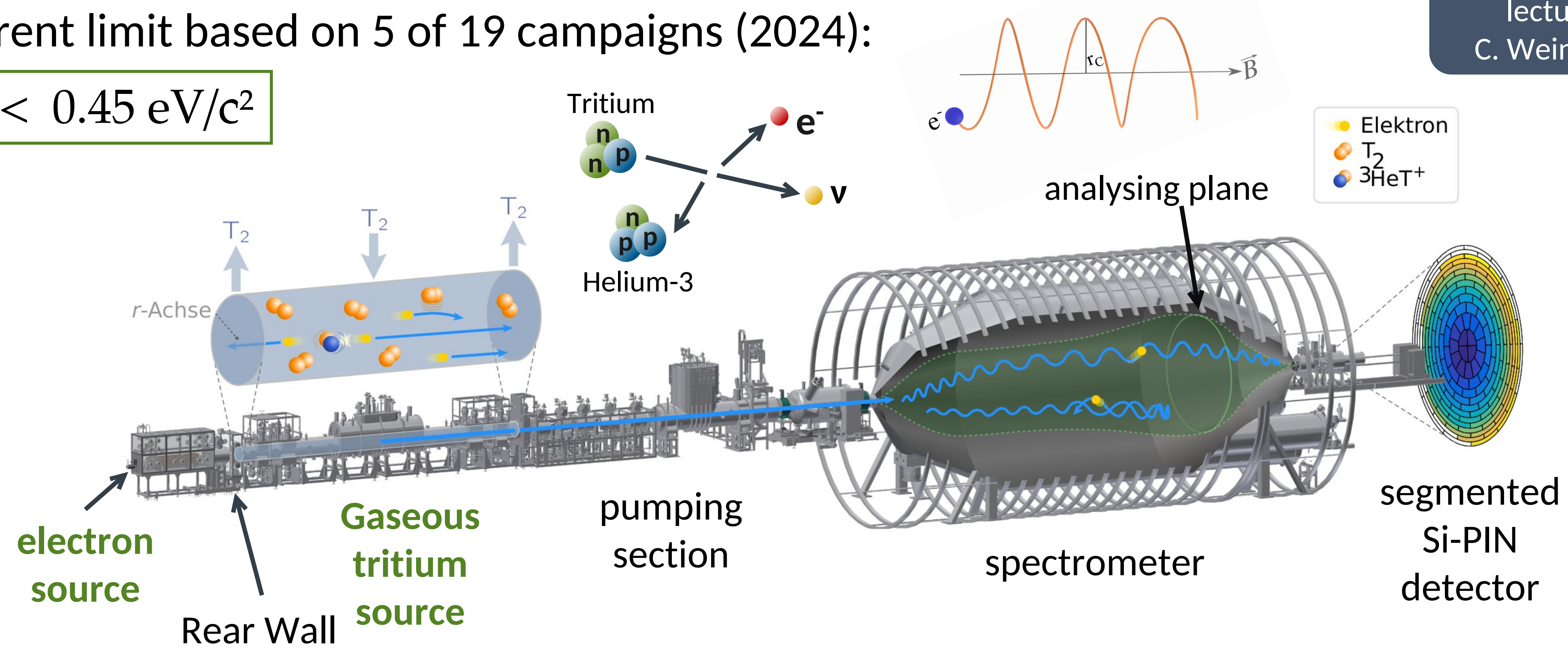
Karlsruhe Tritium Neutrino (KATRIN) experiment

Goal: Determination of neutrino mass with sensitivity ≤ 0.3 eV/c² (90 % C.L.)

Current limit based on 5 of 19 campaigns (2024):

$$\boxed{m_\nu < 0.45\ \mathrm{eV/c^2}}$$

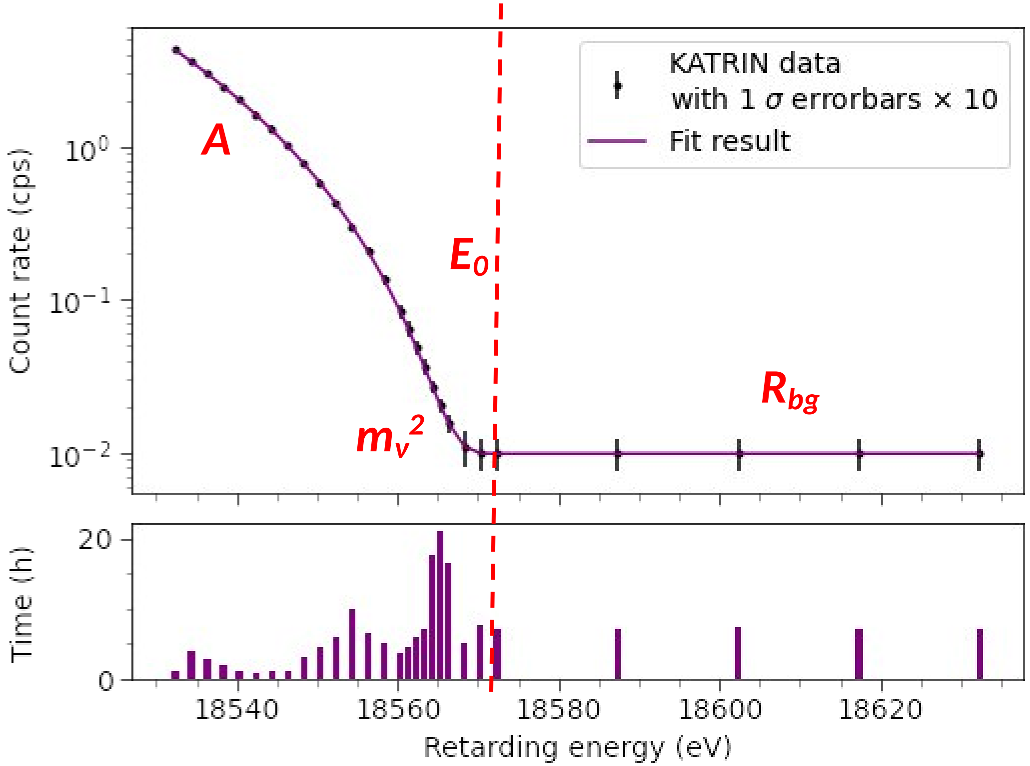
See KATRIN lecture by C. Weinheimer



KATRIN Coll. Science 388 (2025) 180–185

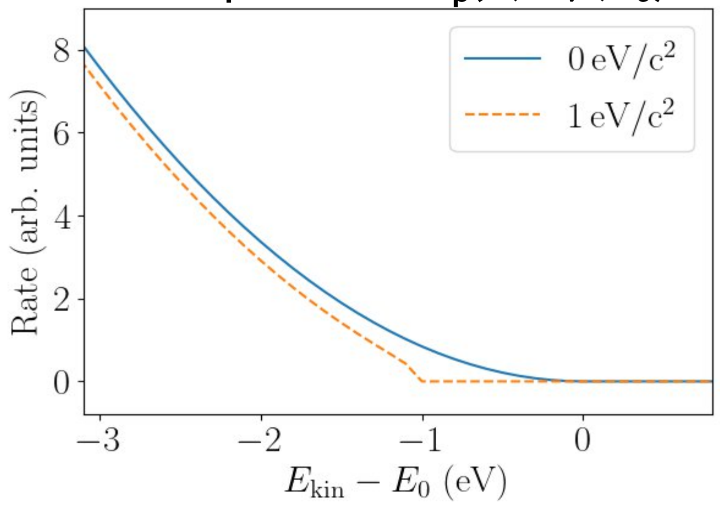
Karlsruhe Tritium Neutrino (KATRIN) experiment

$$R(qU) = A \cdot \int_{qU}^{E_0} R_\beta(E; m_\nu^2, E_0) \cdot f(qU, E)\, dE + R_{bg}$$

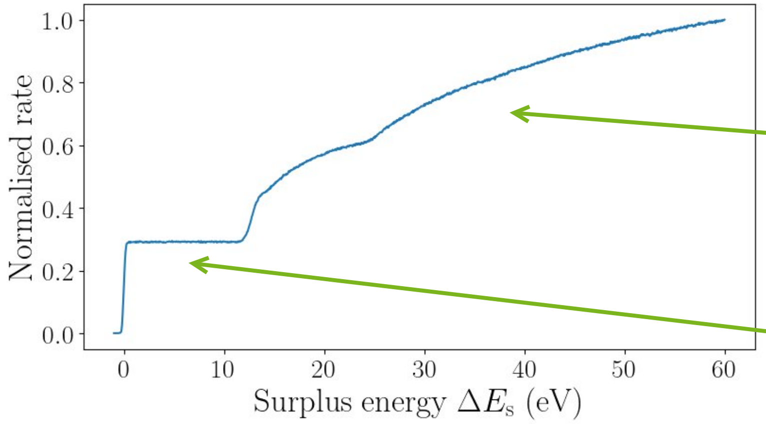


$\otimes$

Tritium spectrum: $R_\beta(E;m_\nu^2,E_0)$



Experimental response: $f(qU, E)$

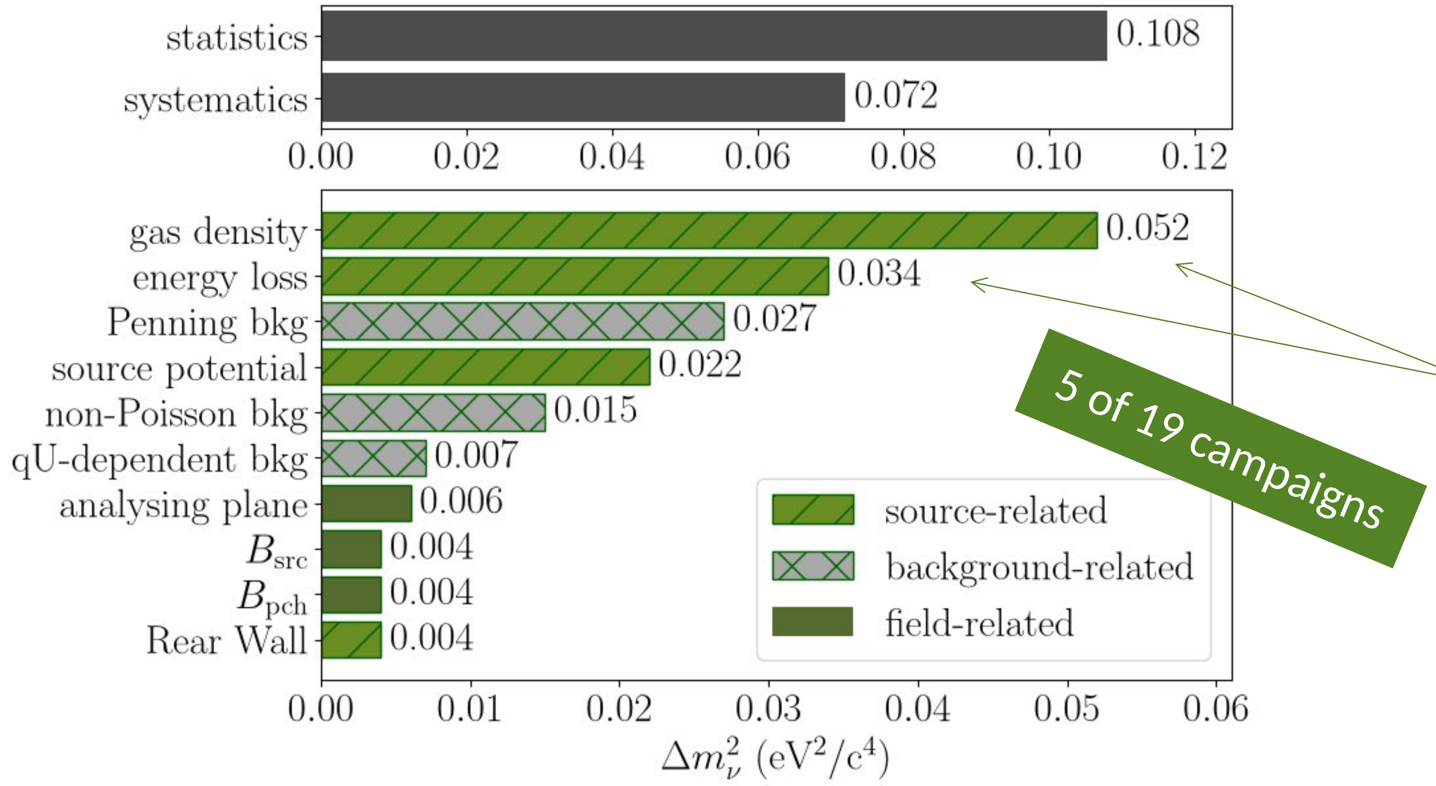


$=E_{start} - qU$

also scattered electrons

unscattered electrons only

Systematic uncertainties in KATRIN analysis



Source-related uncertainties

dominant

measurement with calibration photoelectron source

based on Science 388 (2025) 180–185

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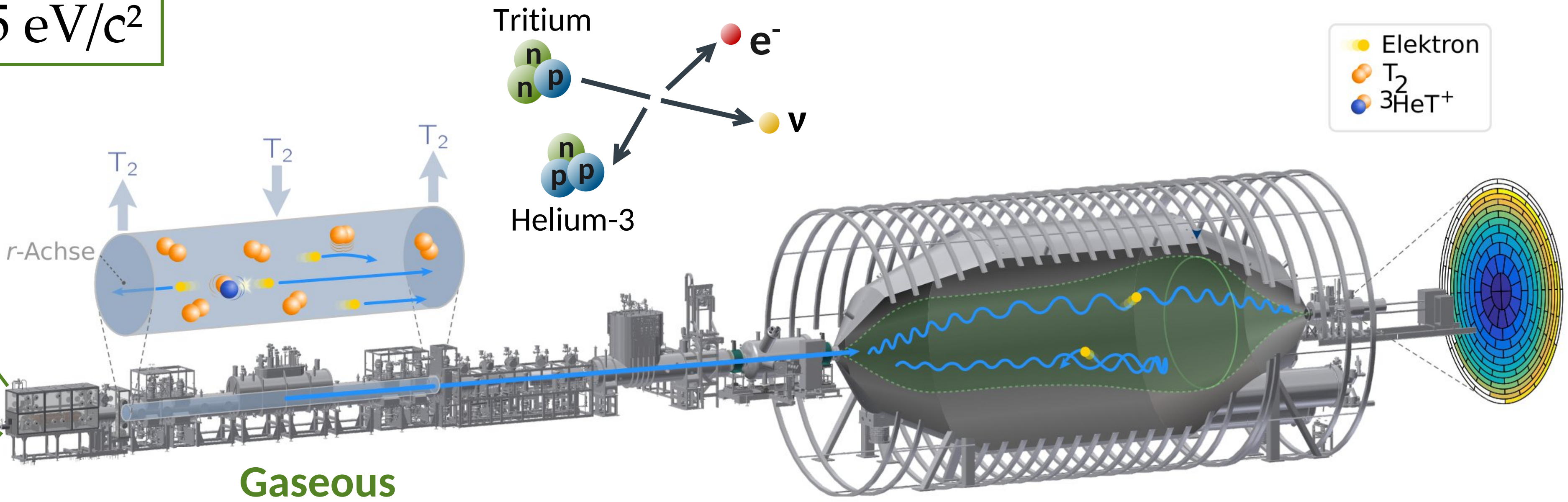

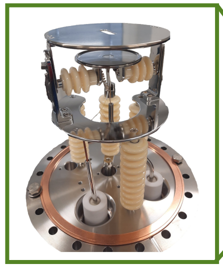

electron source

Gaseous tritium source

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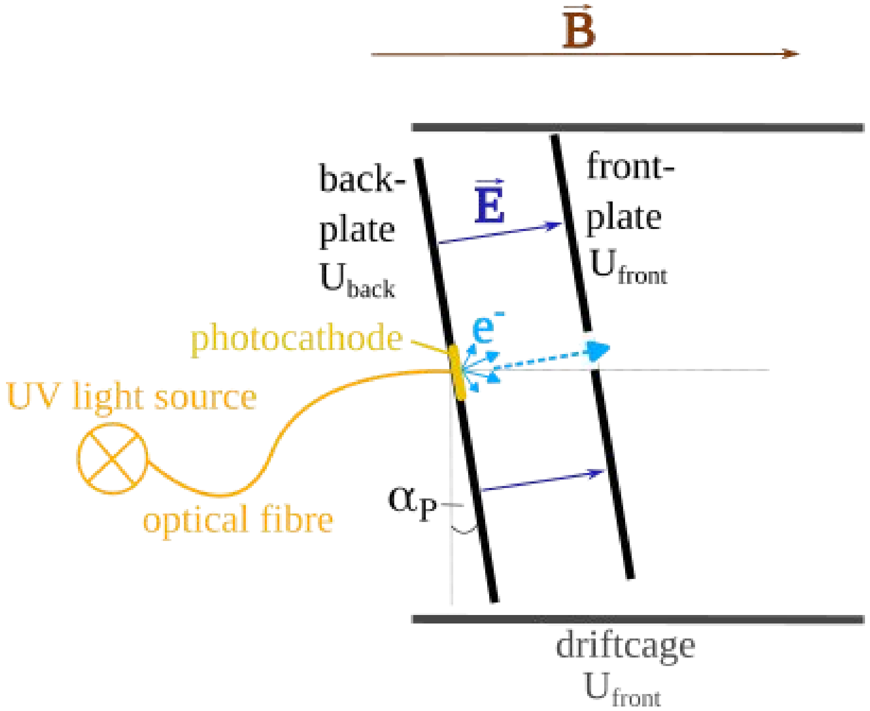
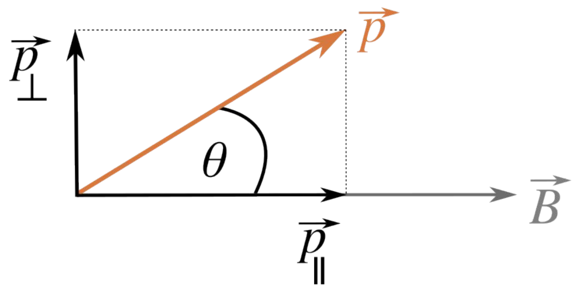
KATRIN photoelectron source (e-Gun)





- Backplate potential
  → final energy
- Tilt angle α_P +
  ratio of electric and magnetic-field strength
  → final angle θ with respect to magnetic-field lines

Emission of photoelectrons with small energy (~0.1eV) and isotropic angular distribution

Velocity

Quasi-monoenergetic, angular-selective electron source

non-adiabatic acceleration by $\vec{E}$

Lorentz force:

$$F_L = q \cdot (\vec{E} + \vec{v} \times \vec{B})$$

adiabatic transport by $\vec{B}$:

$$\boxed{\frac{sin^2\theta_1}{B_1} = \frac{sin^2\theta_2}{B_2}}$$

J. Behrens et al., EPJC 77 410 (2017)

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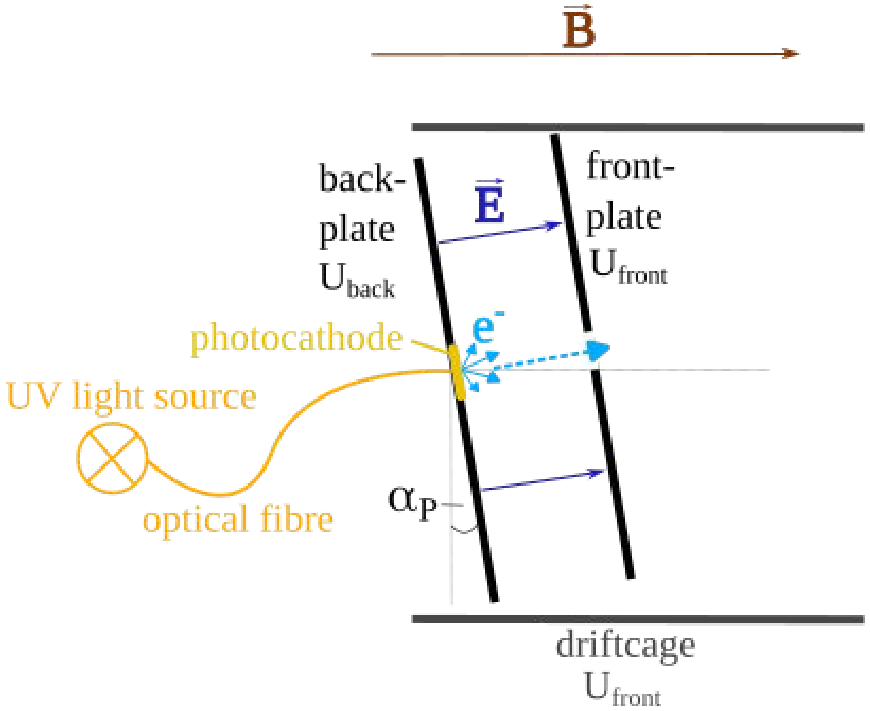

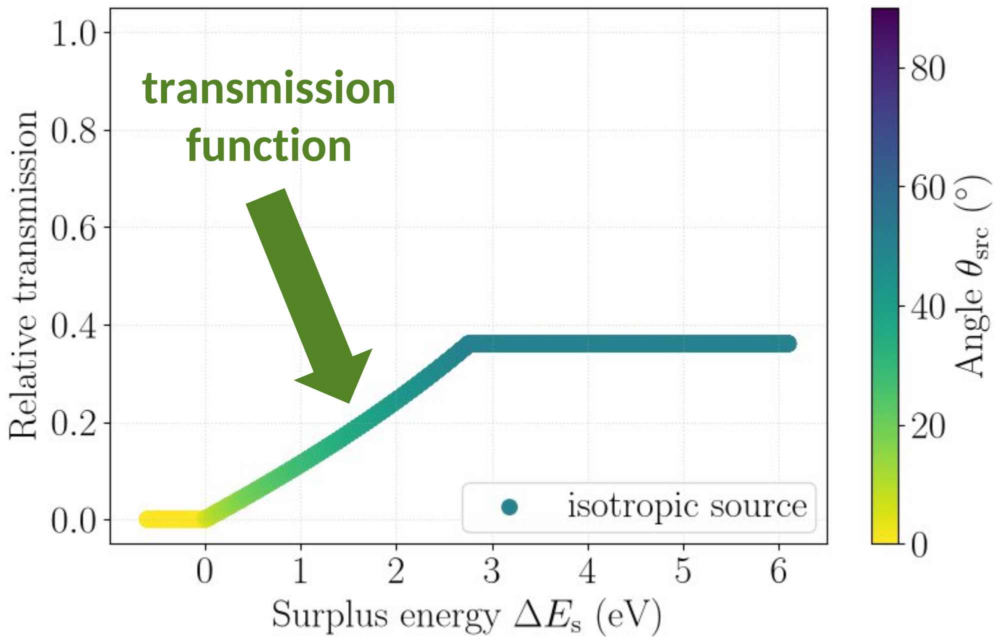

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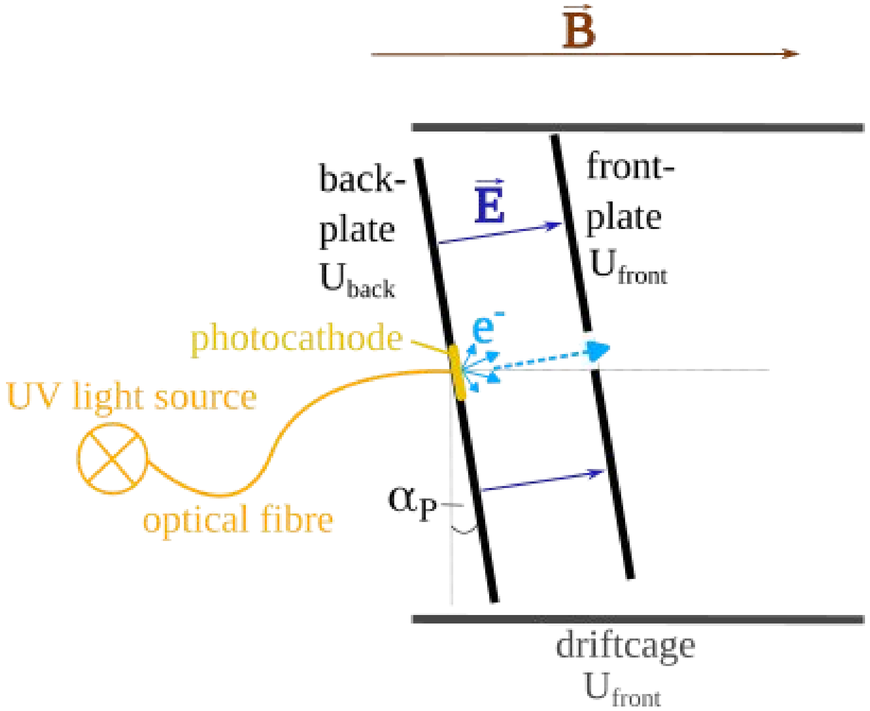

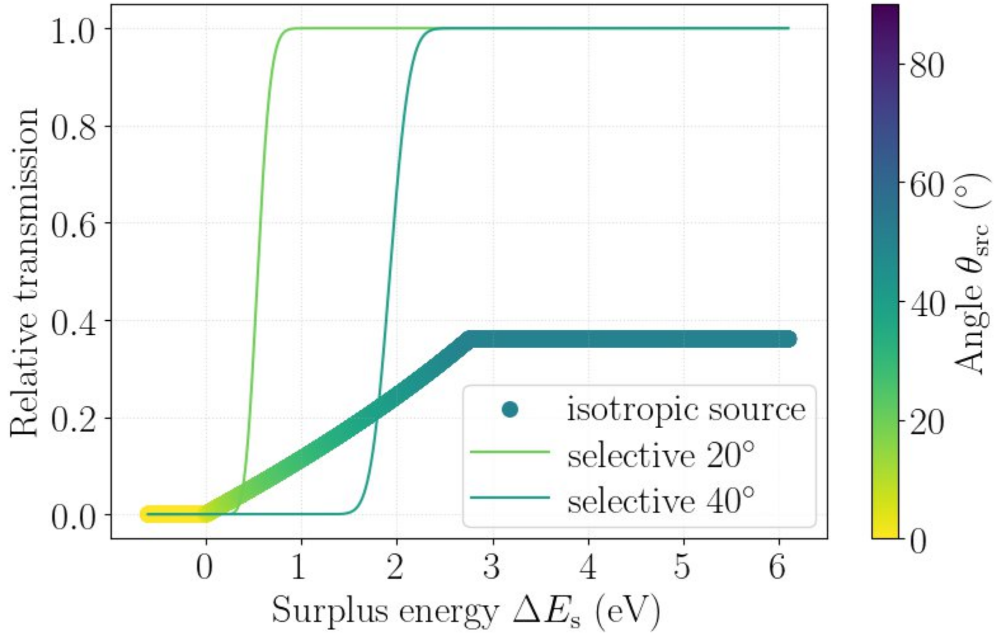

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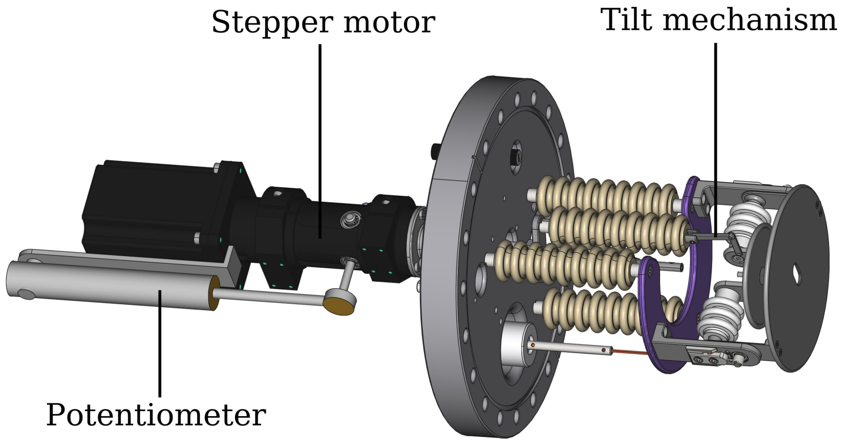
J. Behrens et al., EPJC 77 410 (2017)

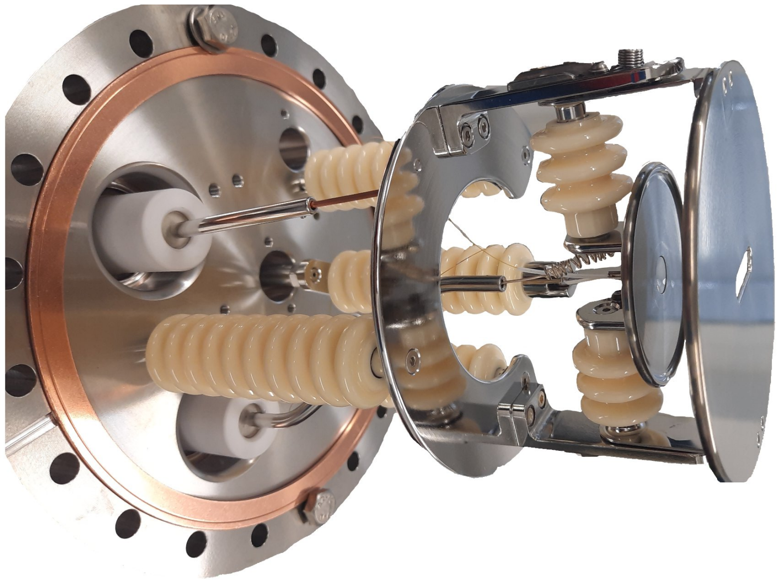
KATRIN photoelectron source (e-Gun)

Photoelectron source upgrade in 2022:

- Extended energy range of 32keV instead of 20keV
  ➜ Enables comparison of measurements with photoelectron source and krypton source (energy of $N_{2,3}$ lines: 32keV)
- Precise and reproducible adjustment of electron angle
  ➜ essential for determination of gas density in tritium source
- 10 times higher electron rate at same UV wavelength
  ➜ improved statistics in all measurements

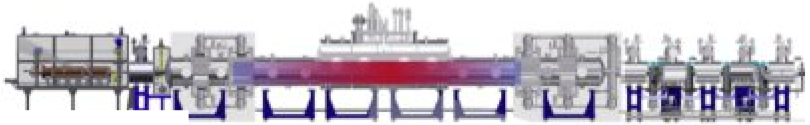
S. Schneidewind et al., EPJC 86 773 (2026)

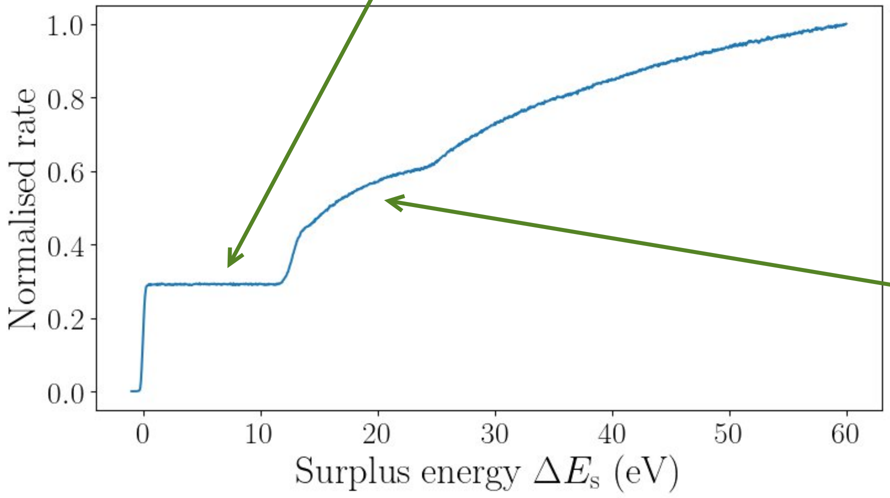




Source-related systematics

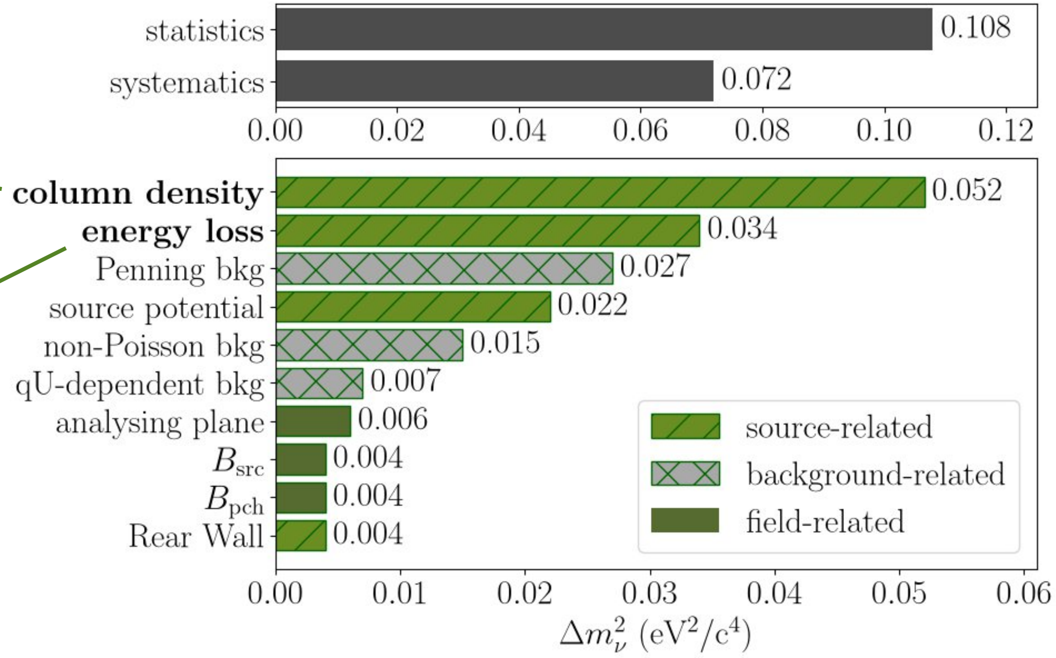
Scattering: β-decay electrons scatter off tritium molecules





How often
do electrons scatter?

How much energy
do they lose
when they scatter?



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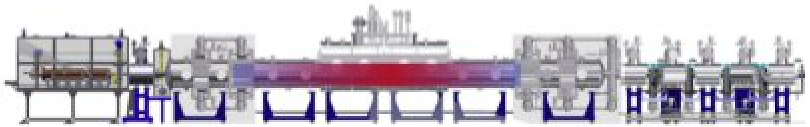

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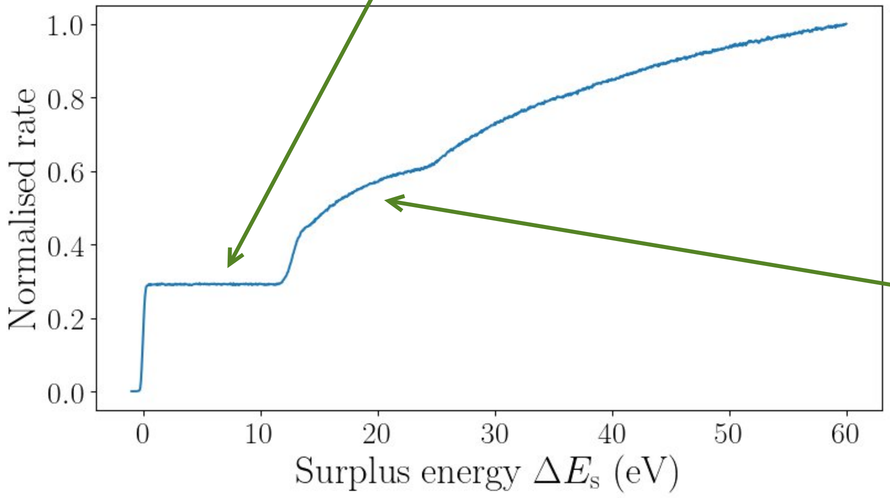
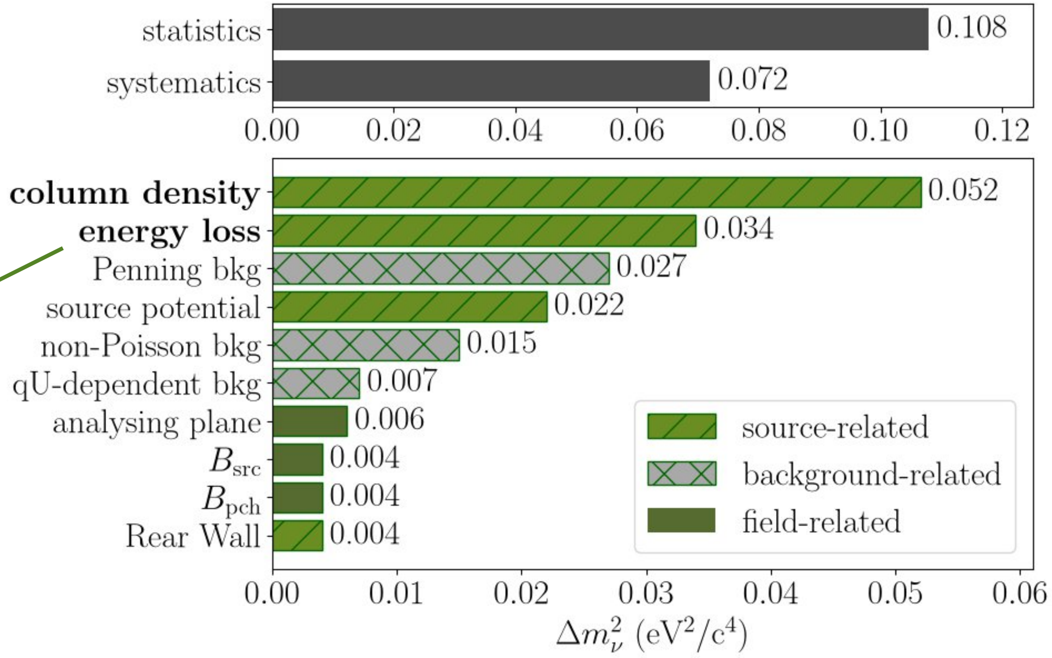
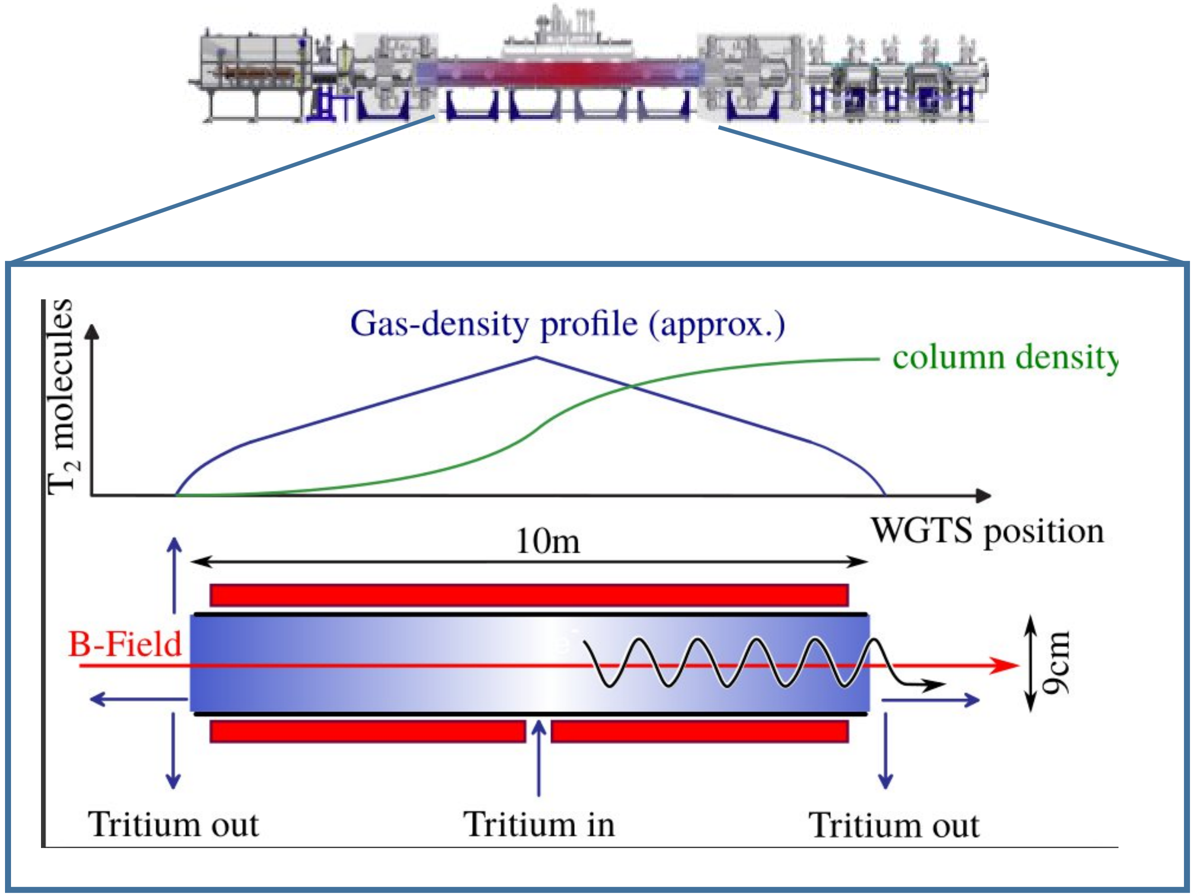




Column-density determination



- Column density: number of tritium molecules along beam tube axis per area
- Higher column density:
  → higher luminosity / statistics
  → higher scattering probability
- Typical value: $\rho d = 3.8 \cdot 10^{17} \frac{\text{molecules}}{\text{cm}^2}$

  Source scattering depending on:
  - column density
  - electron path
  - inelastic cross section

0° electron scatters on average roughly 1.4 times

Column-density determination

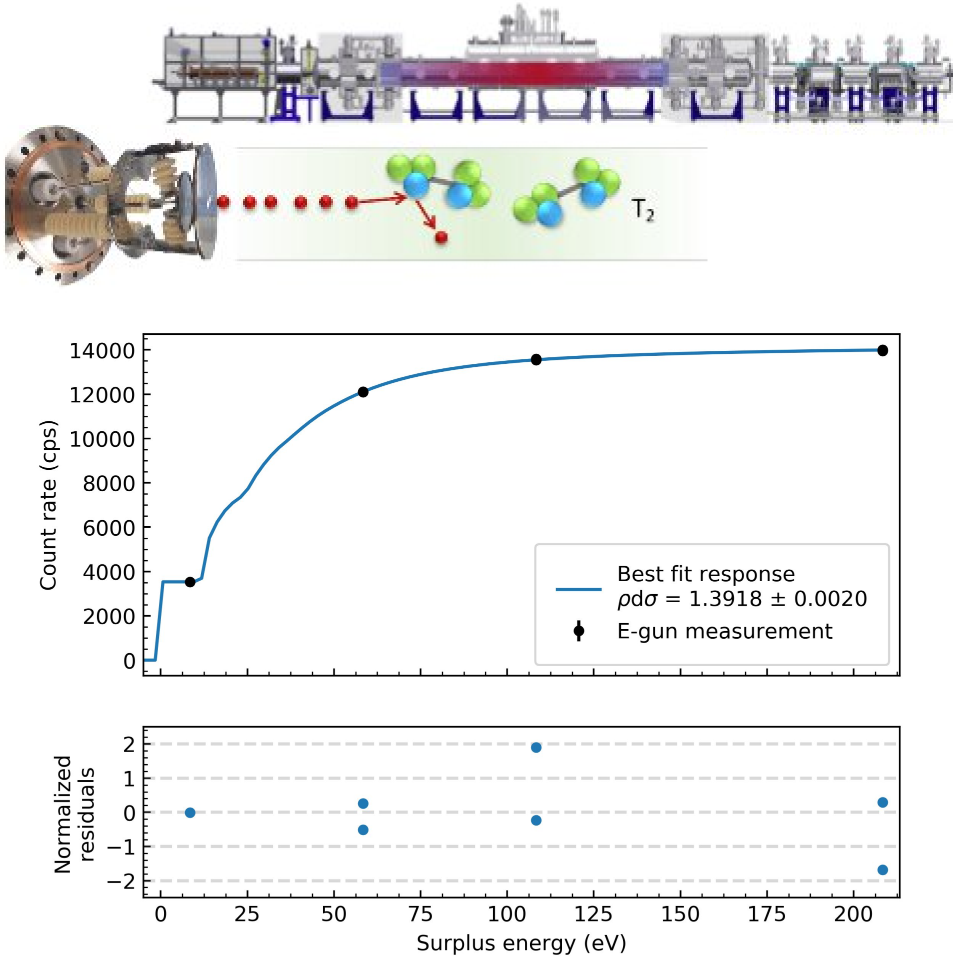
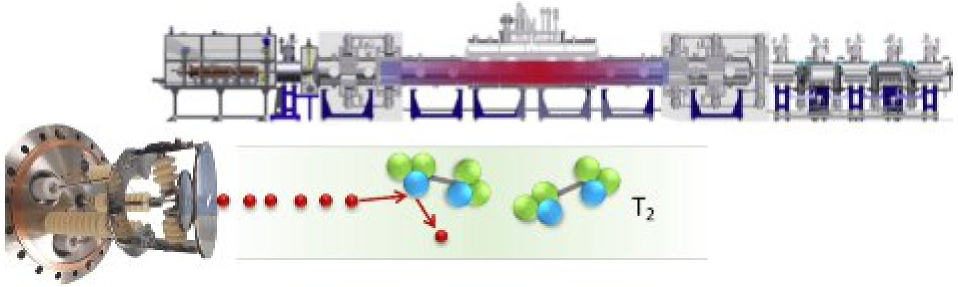
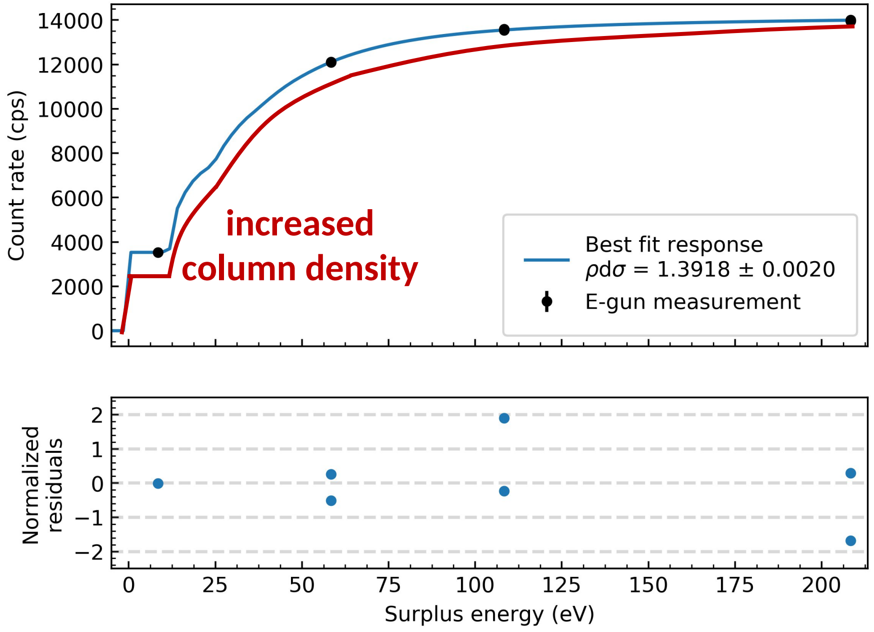


Figure: C. Köhler

- Measurement with e-Gun at several different surplus energies
- Two-parameter fit:
  - electron rate
  - ρdσ
- around 1h measurement once per week in between neutrino-mass measurements

Column-density determination





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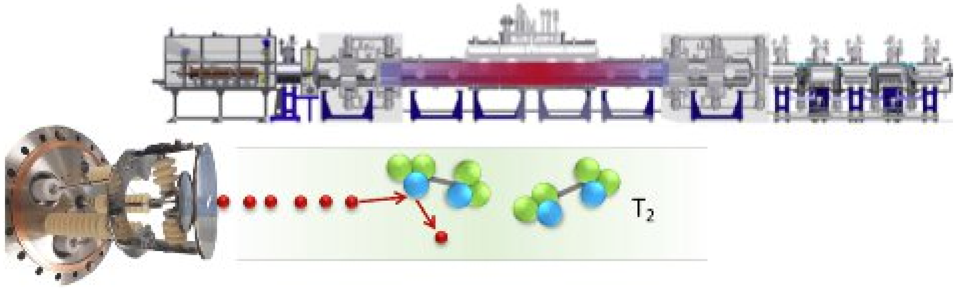

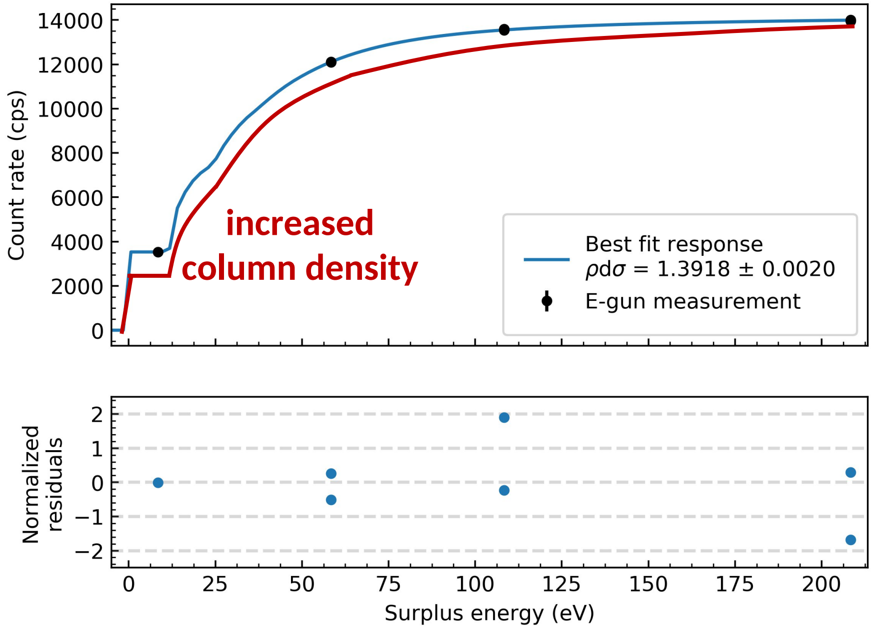

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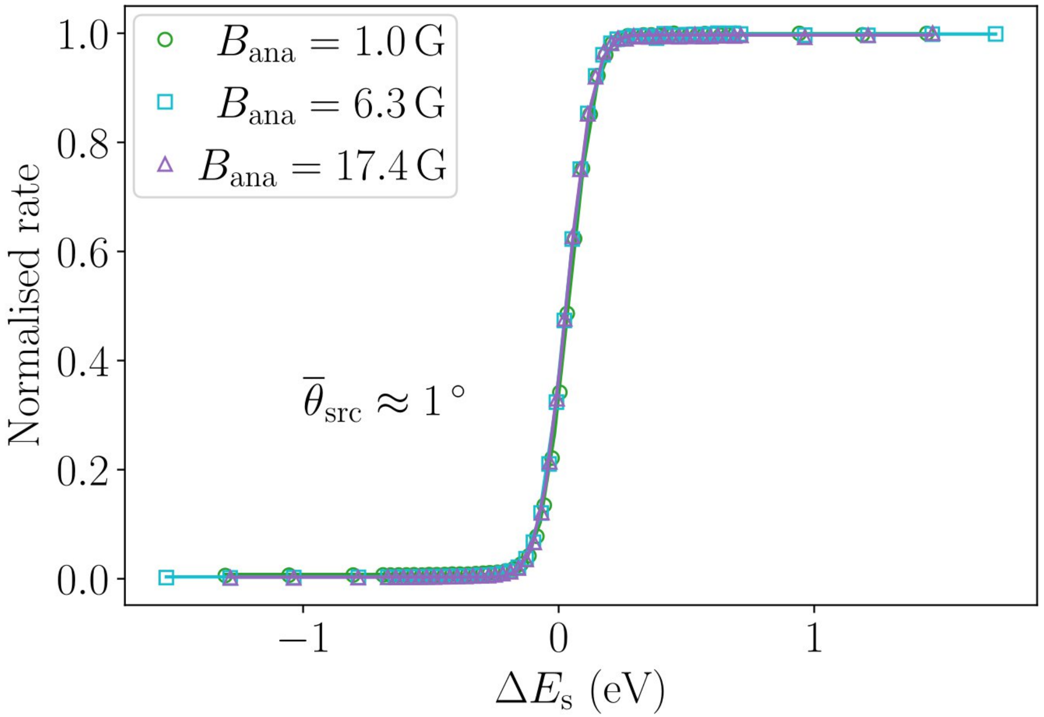
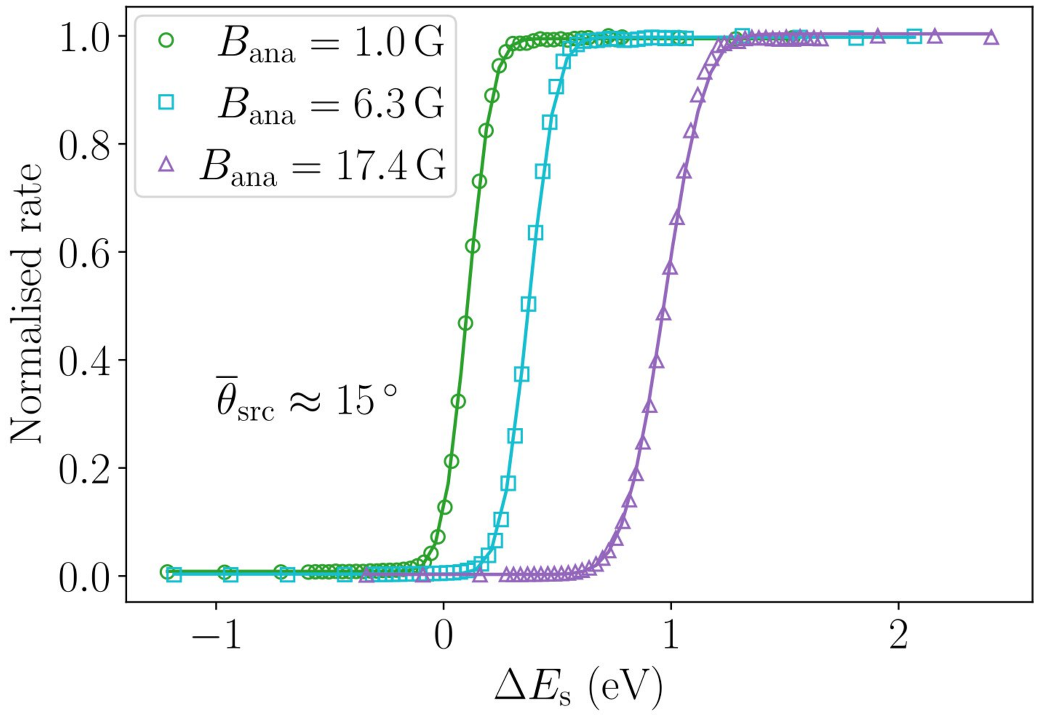
For precise measurement:
Very good knowledge on e-Gun parameters required!
Most important: Electron angle

e-Gun electron angle determination

- Make use of dependence of transmission function on magnetic field in spectrometer:
  Increase of magnetic field B_{ana} → higher sensitivity to electron pitch angle θ



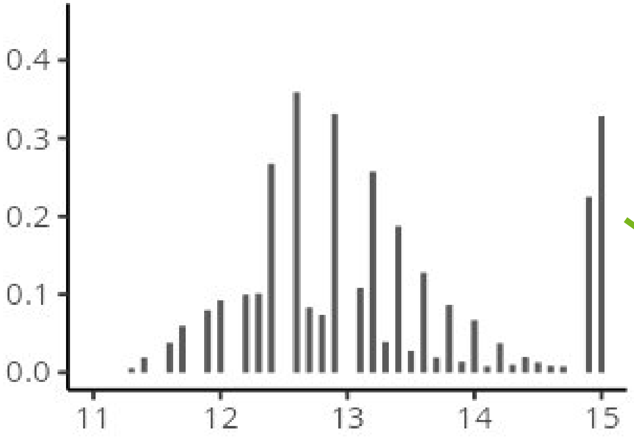


S. Schneidewind et al., EPJC 86 773 (2026)

Angle determination possible with $\mathcal{O}$(0.5°) uncertainty

Determination of energy-loss function

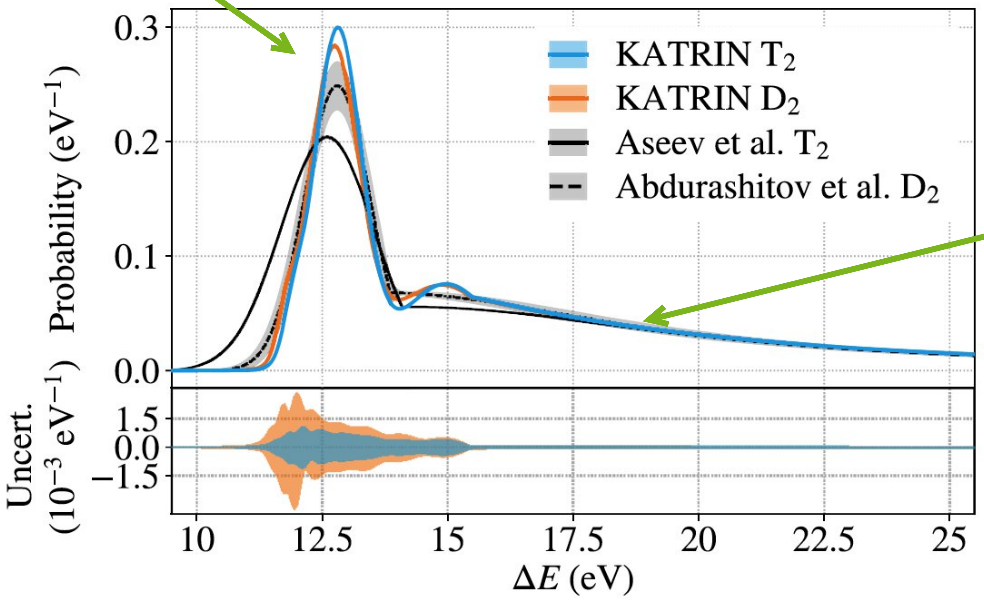
Energy-loss function $f(\Delta E)$: Description of inelastic scattering of electrons off tritium molecules



Electronic excitations in combination with rotational and vibrational molecular excitations

Energy-loss model KATRIN 2021:

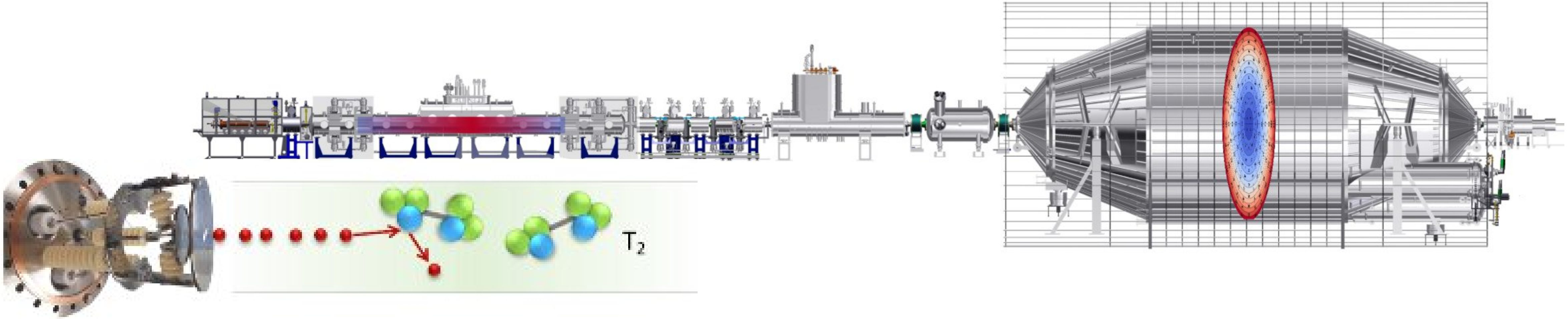
$$f(\Delta E) = \begin{cases} \sum_{i=1}^{3} a_i \exp\left(-\frac{(\Delta E - m_i)^2}{2\sigma_i^2}\right), & \Delta E \leq E_{\text{ion}} \\ \frac{f(E_{\text{ion}})}{f_{\text{BED}}(E_{\text{ion}})} \cdot f_{\text{BED}}(\Delta E), & \Delta E > E_{\text{ion}} \end{cases}$$



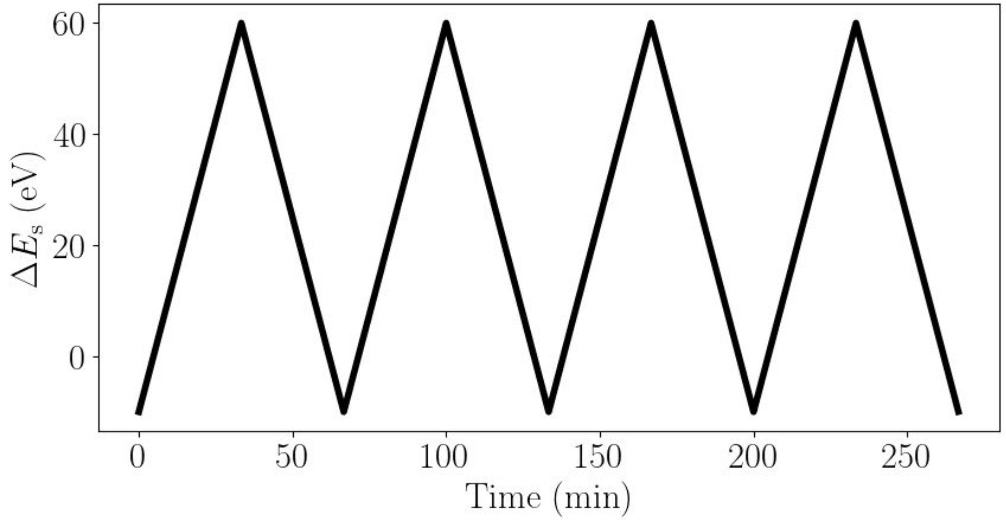
Ionisation above E_{ion} = 15.4eV

M. Aker et al.,
Eur. Phys. Journal C 81, 579 (2021)

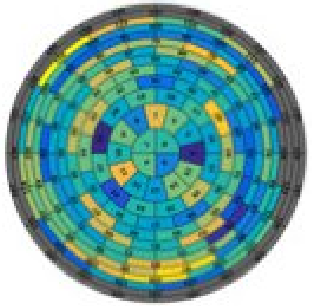
Determination of energy-loss function



Continuous variation of surplus energy

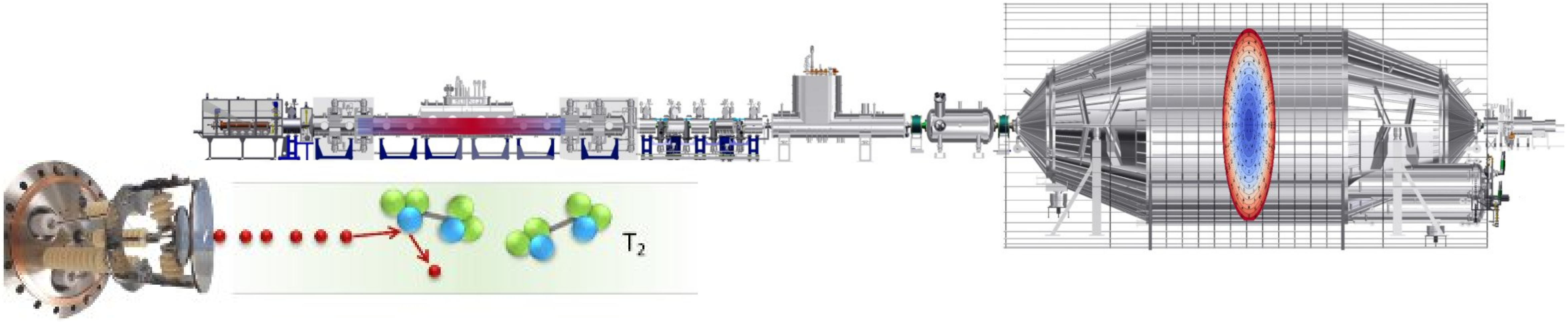


Measurement of transmitted electrons
as function of surplus energy

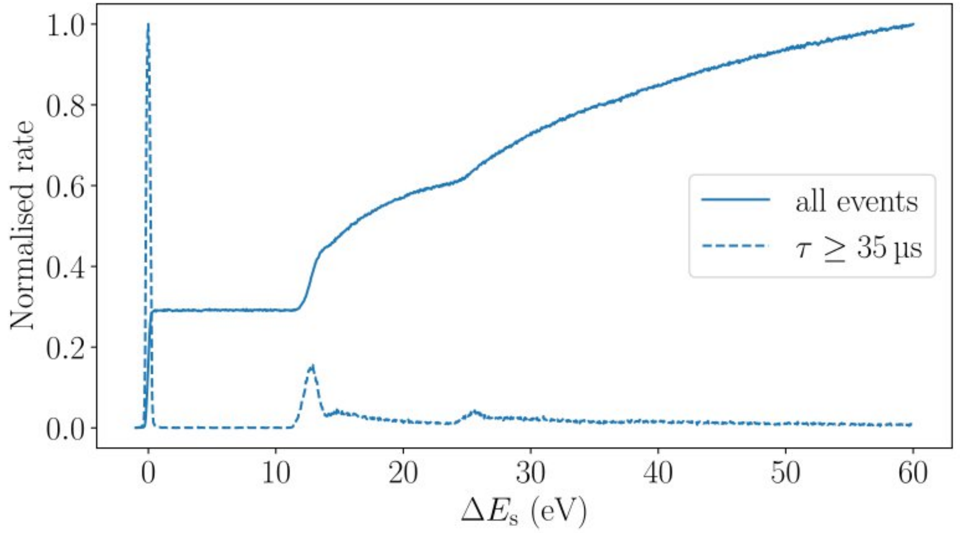


several days to weeks
of high-statistics measurements

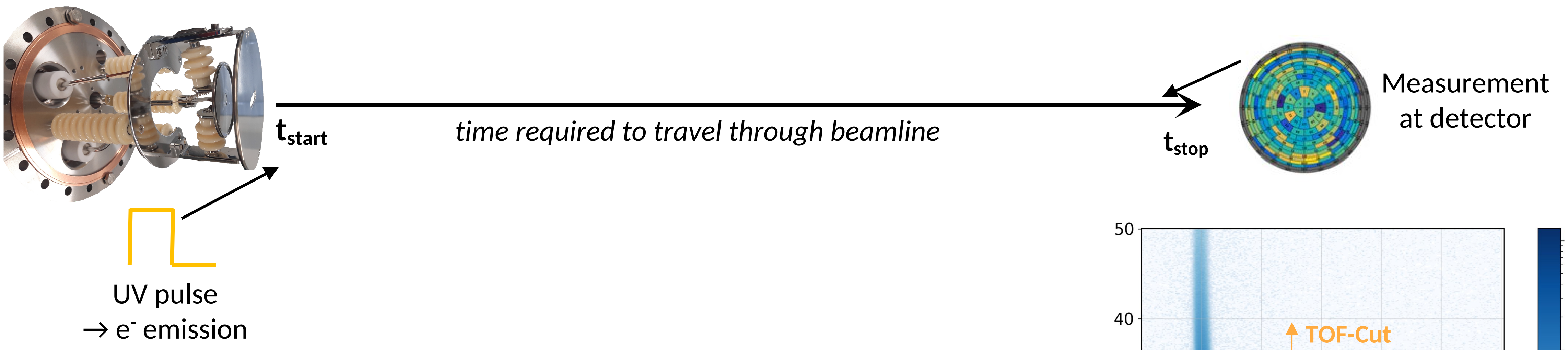
Determination of energy-loss function



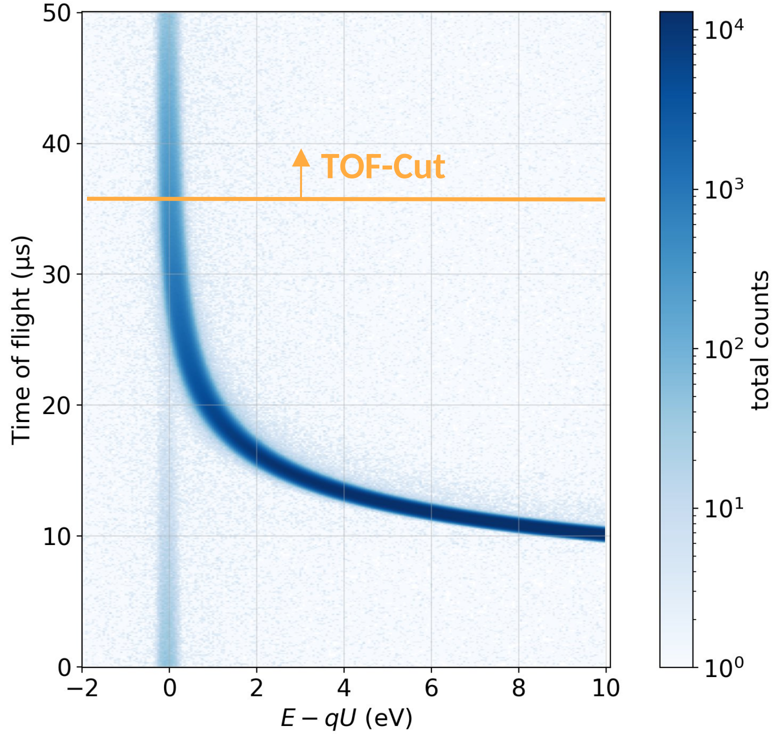
- Two measurement modes:
  - integral, with time-continuous light source (LDLS)
  - differential time-of-flight (TOF) mode with pulsed UV laser



e-Gun time-of-flight mode

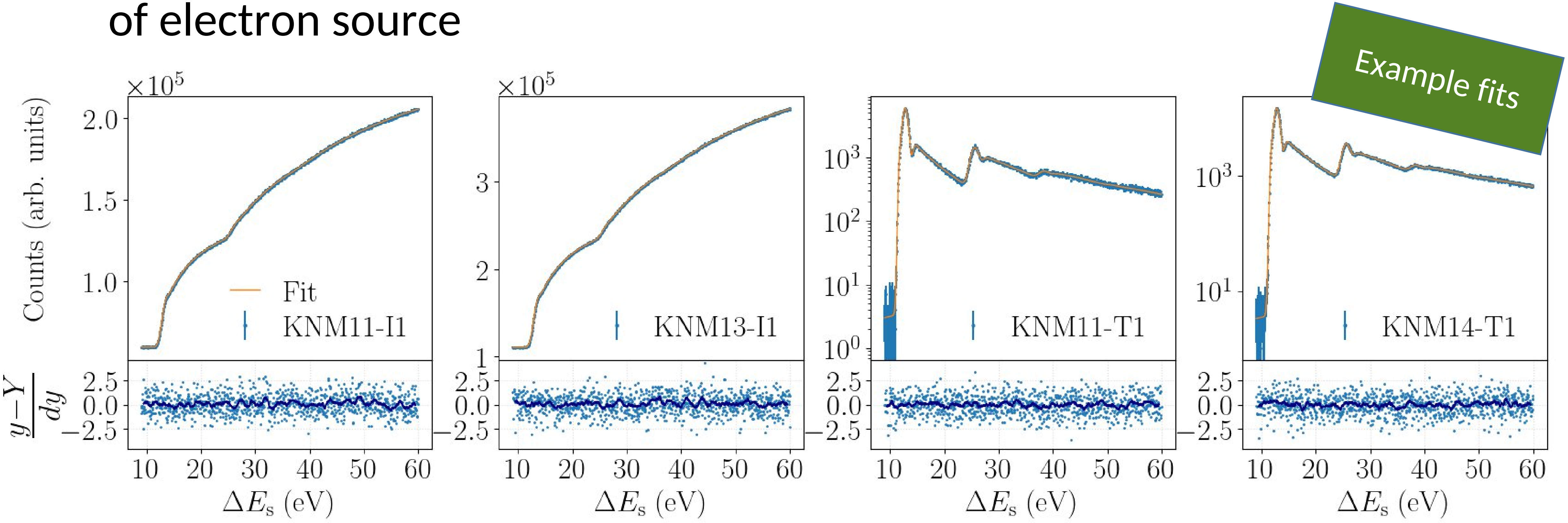


- KATRIN spectrometer acts ass **high-pass filter**
- Electron flight time τ decreases with increasing surplus energy
  → time-of-flight-cut as additional **low-pass filter**
- **Band-pass filter** by combination of spectrometer and flight-time
  → Differential measurement possible



Determination of energy-loss function

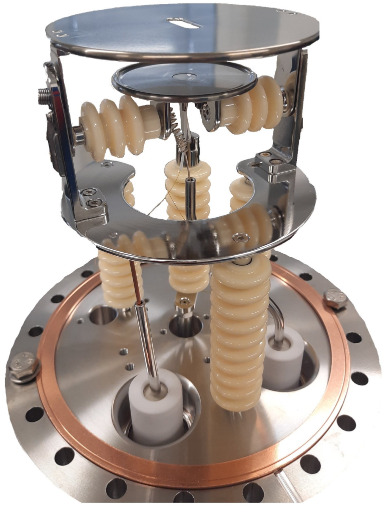
- Analysis: Fit of integral and/or TOF data with energy-loss model, taking into account multiple scatterings and experimental response of electron source



Summary & Outlook

KATRIN's photoelectron source…

- Quasi-monoenergetic, angle-adjustable electron beam
- Key tool for precise determination of systematic effects:
  - Column density →Scattering probability
  - Energy-loss function → Energy distribution of scattered electrons
- Upgrade in 2022:
  - Higher energies up to 32keV
  - Very good control of electron angle
  - Factor 10 higher statistics



Electron source will be a well-characterised calibration tool also for the TRISTAN phase of KATRIN!

keV sterile neutrino search with KATRIN