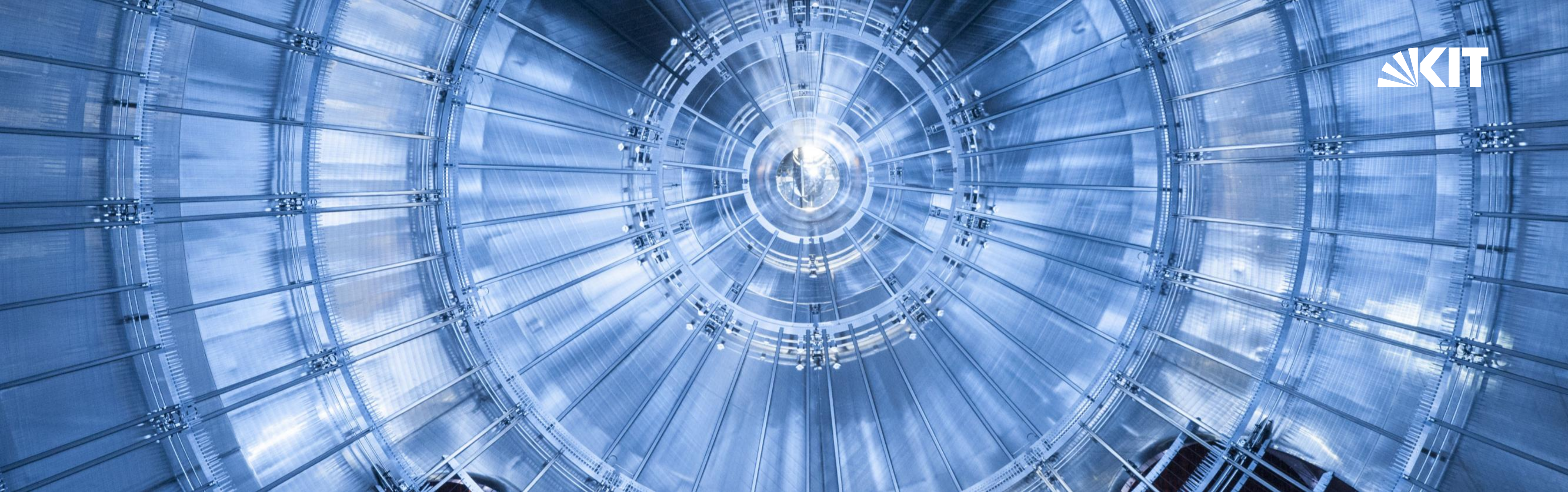


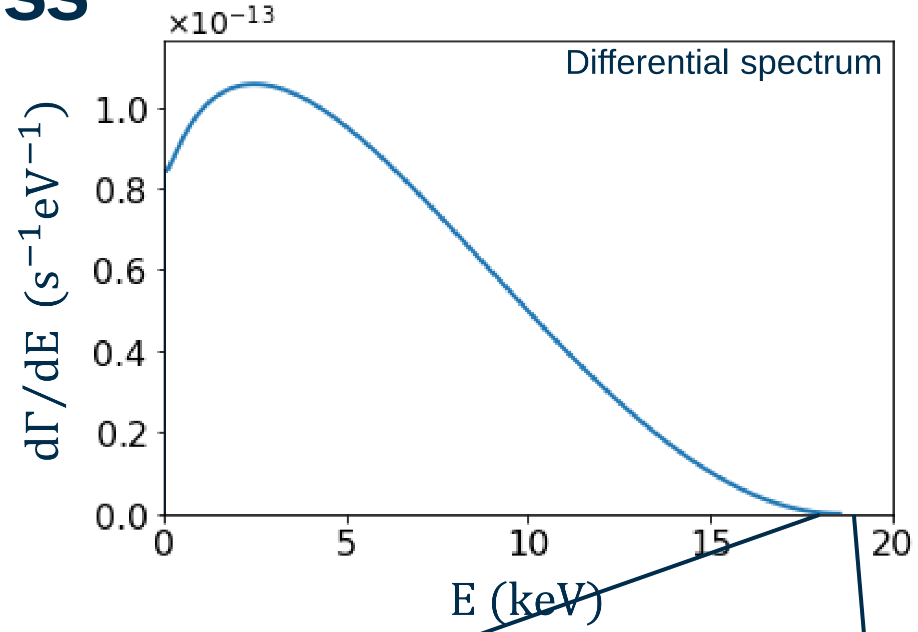
Uncertainty optimizations for the Neutrino Mass Analysis of the KATRIN Experiment using Krypton-83m

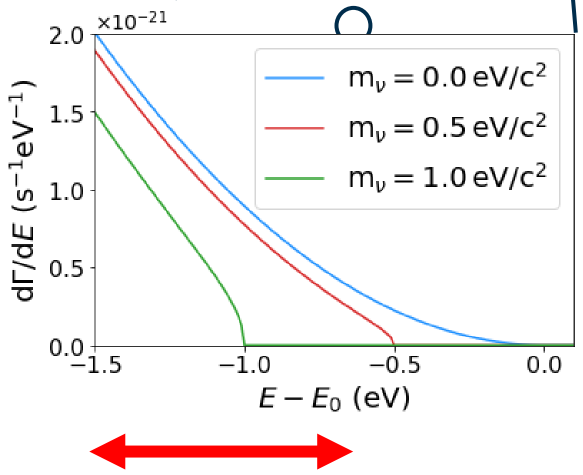
Karo Erhardt (Karlsruhe Institute of Technology)
for the KATRIN collaboration

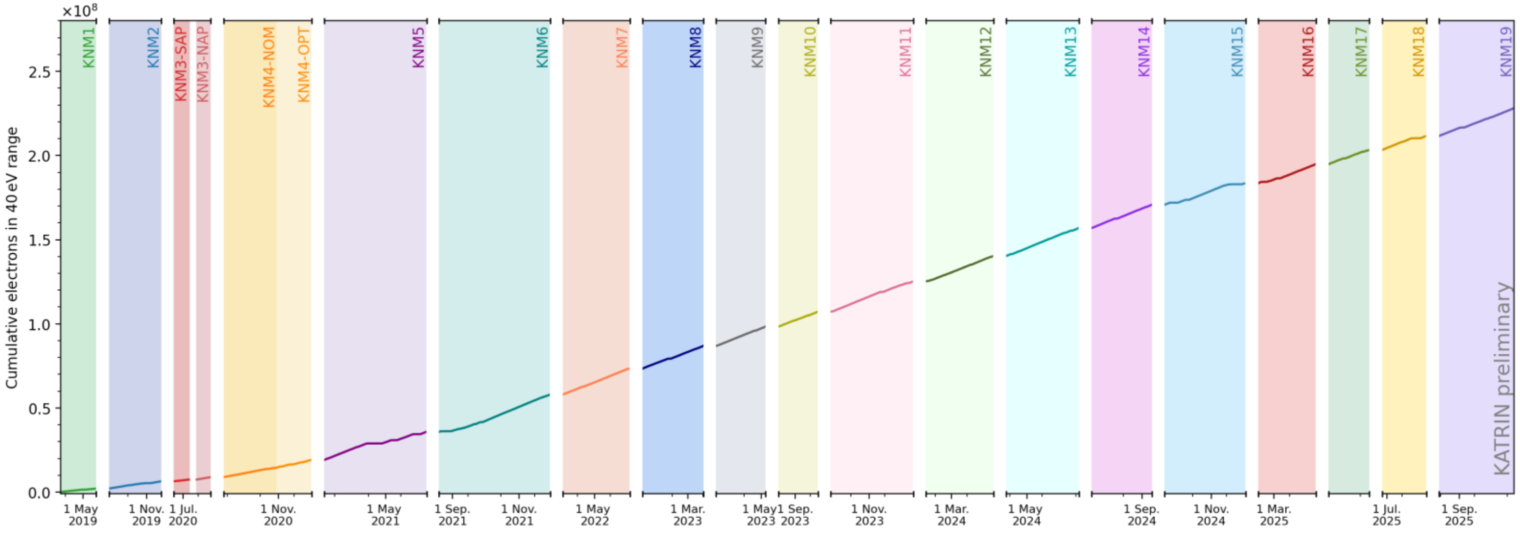
International School of Nuclear Physics, Erice, 2026

Direct measurement of neutrino mass

- Determination by kinematic method
- Tritium beta decay
  - $T_2 \rightarrow {}^3\mathrm{HeT}^+ + e^- + \bar{\nu}_e + Q(T_2)$
- Low statistics, long measurement
- Analysis is ongoing!
- Description of systematic effects

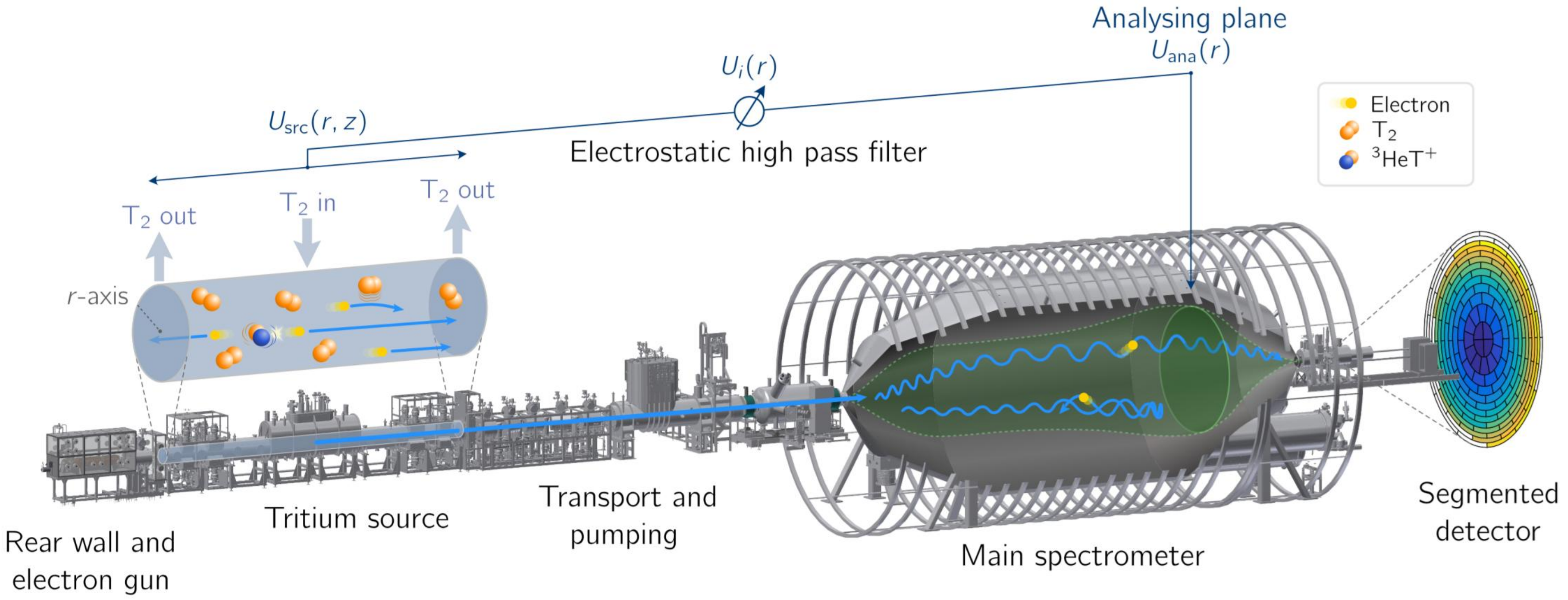






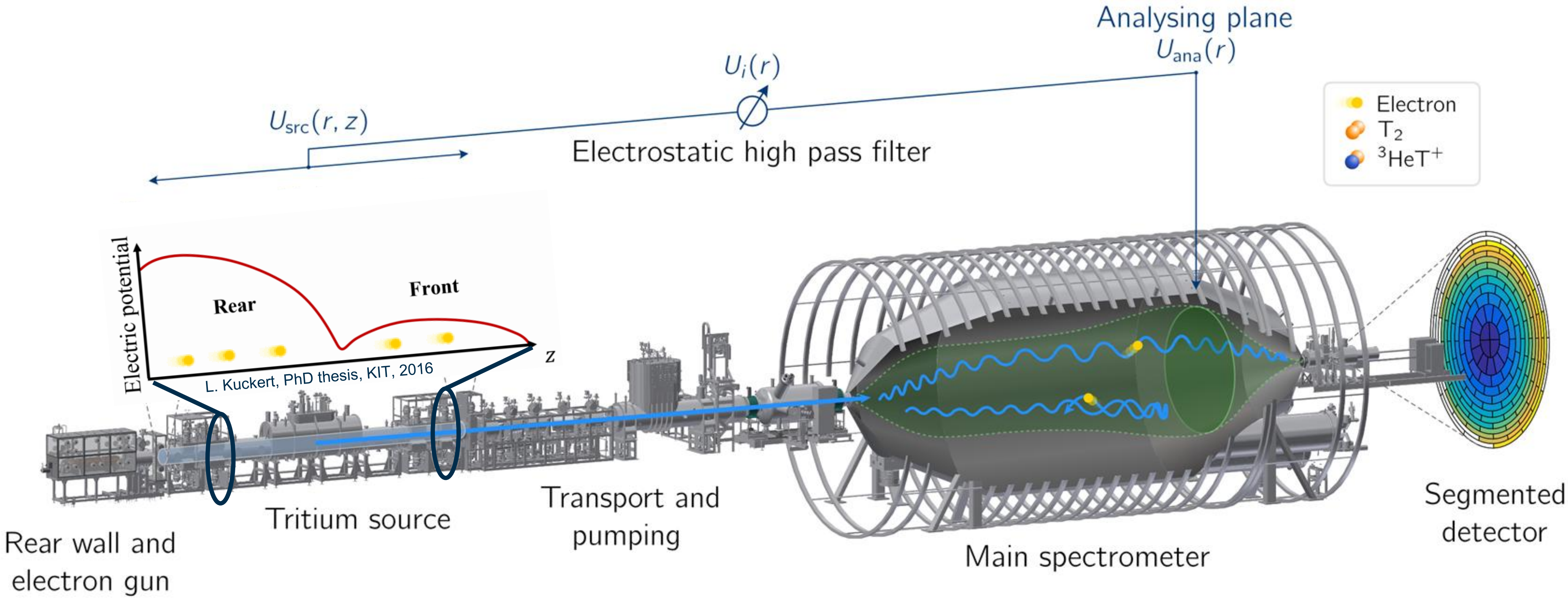
KATRIN experiment

- Energy measurement by electrostatic filter
- Cold gaseous tritium source → Plasma

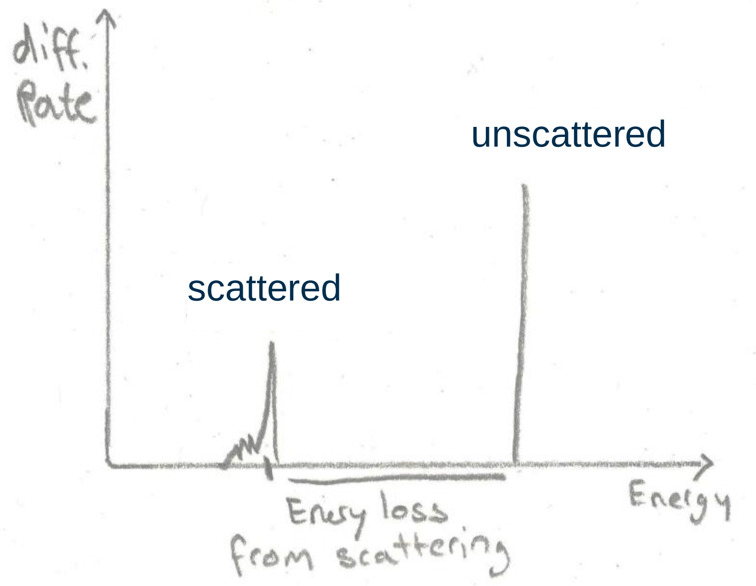


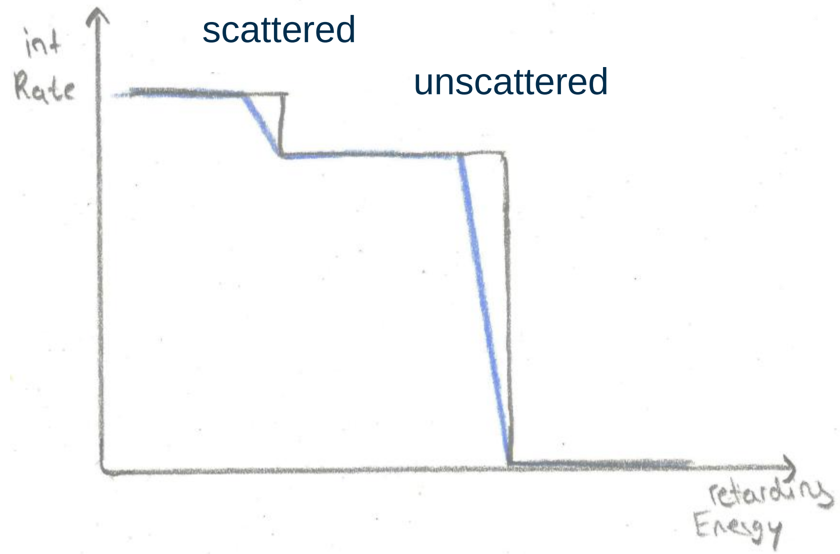
KATRIN experiment

- Plasma → inhomogeneous source potential → different energy thresholds for different z



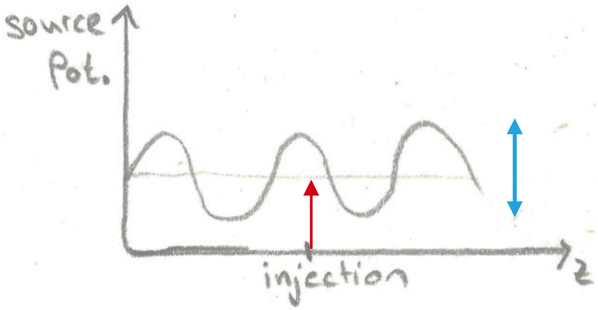
Monoenergetic electrons in the KATRIN Beamline

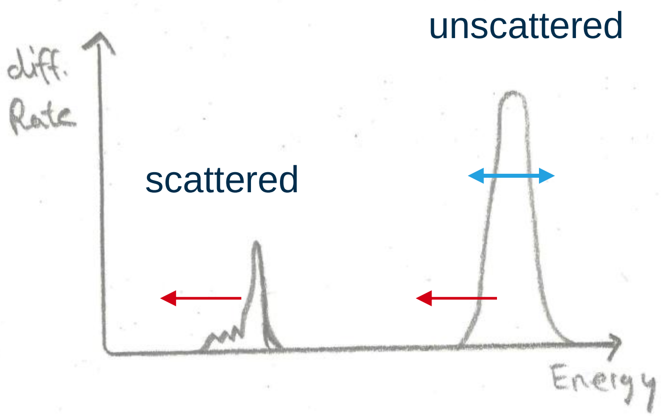


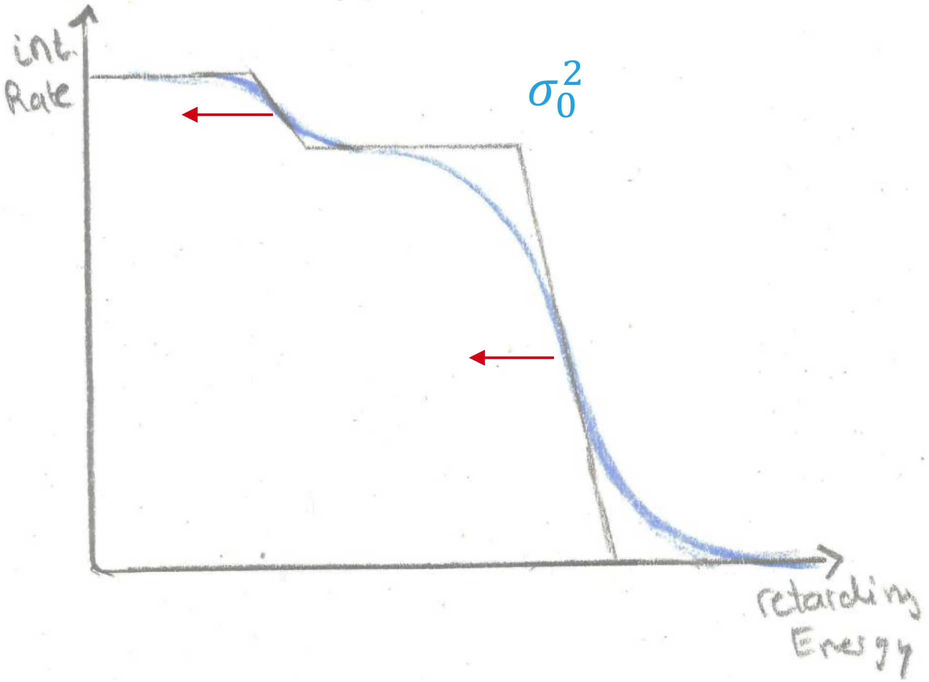


- Scattering of electrons in the source
- Integrated spectrum
- Finite Energy resolution

Monoenergetic electrons in the KATRIN Beamline

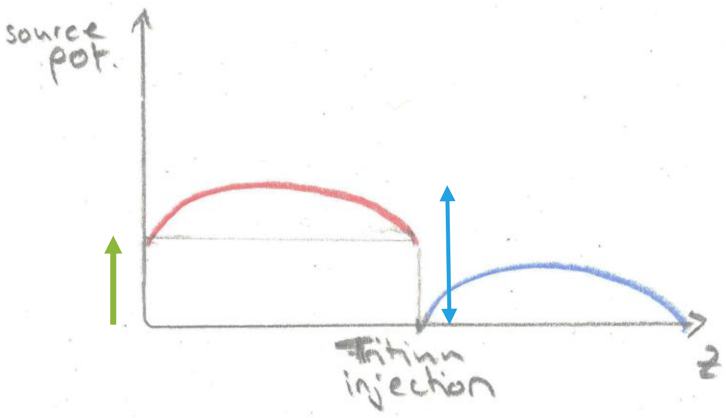


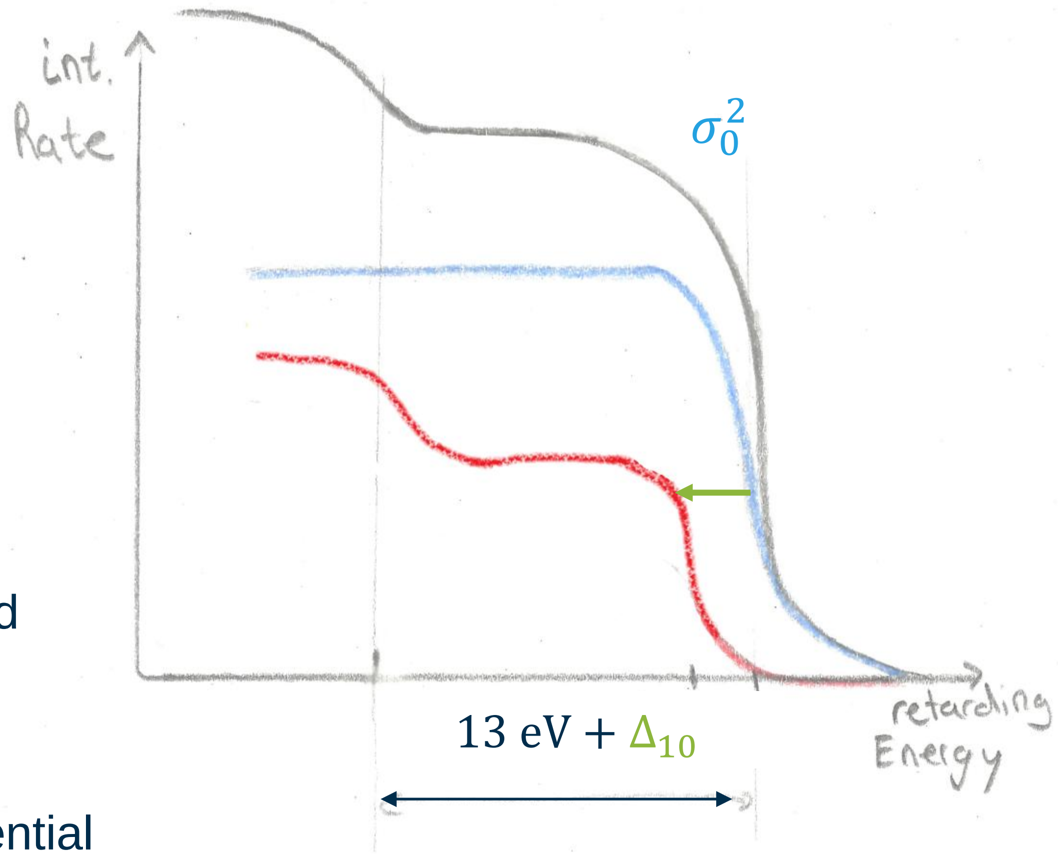




- Overall shift
- Broadening of Lines σ_0 from inhomogeneous potential

Monoenergetic electrons in the KATRIN Beamline



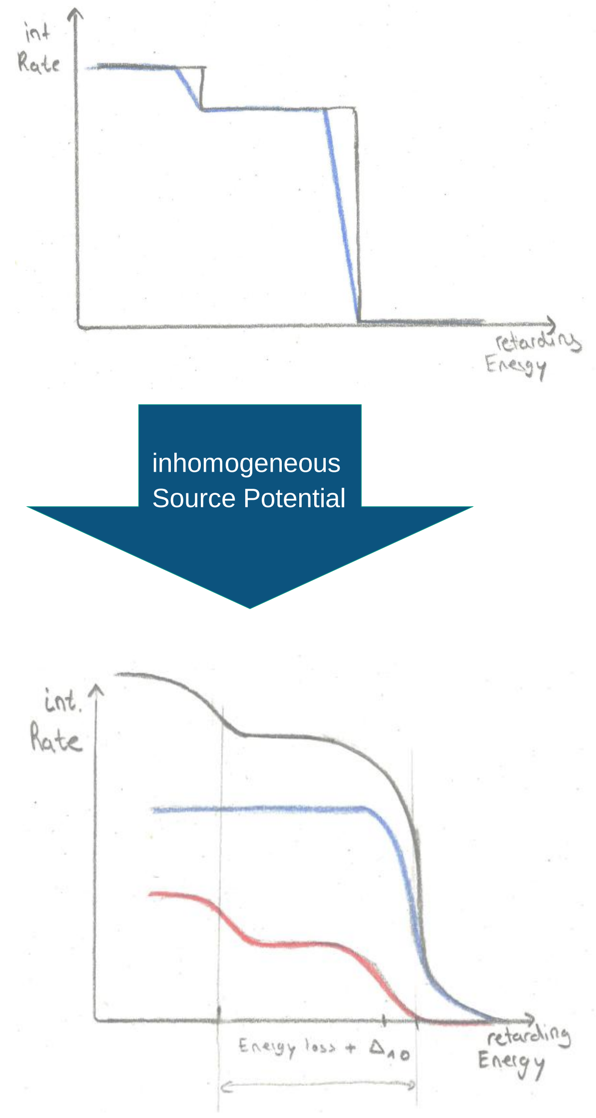


- Back and front section of the source have a different potential
- Contribution from the front mostly unscattered
- Contribution from the back scattered and unscattered
- Broadening σ_0 of unscattered electrons is increased
- Scattered electrons are shifted extra by Δ_{10}
- Δ_{10} and σ_0 describe the inhomogeneous source potential

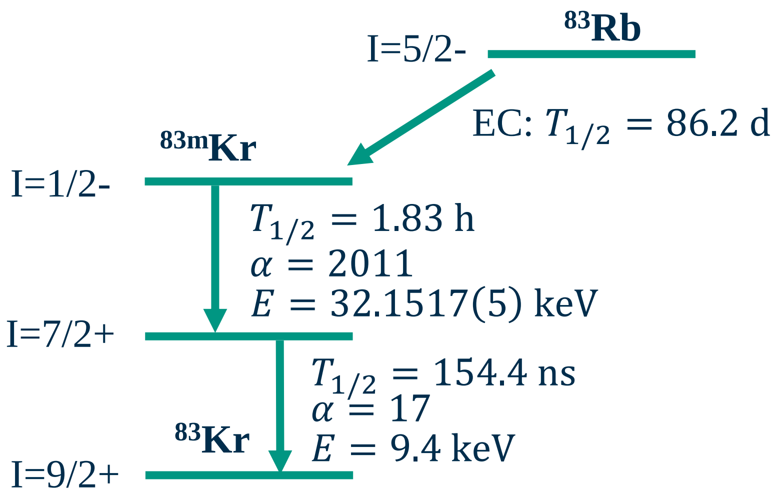
Bias on the Neutrino Mass Analysis

- Direct impact on neutrino mass
  - σ_0^2 : Broadening bad
  - Δ_{10} : Shape deformation worse

- Calibration measurement to find σ_0^2 and Δ_{10}
- Source of electrons
- Krypton-83m conversion electrons
- Tritium and Krypton are co-circulated in the source



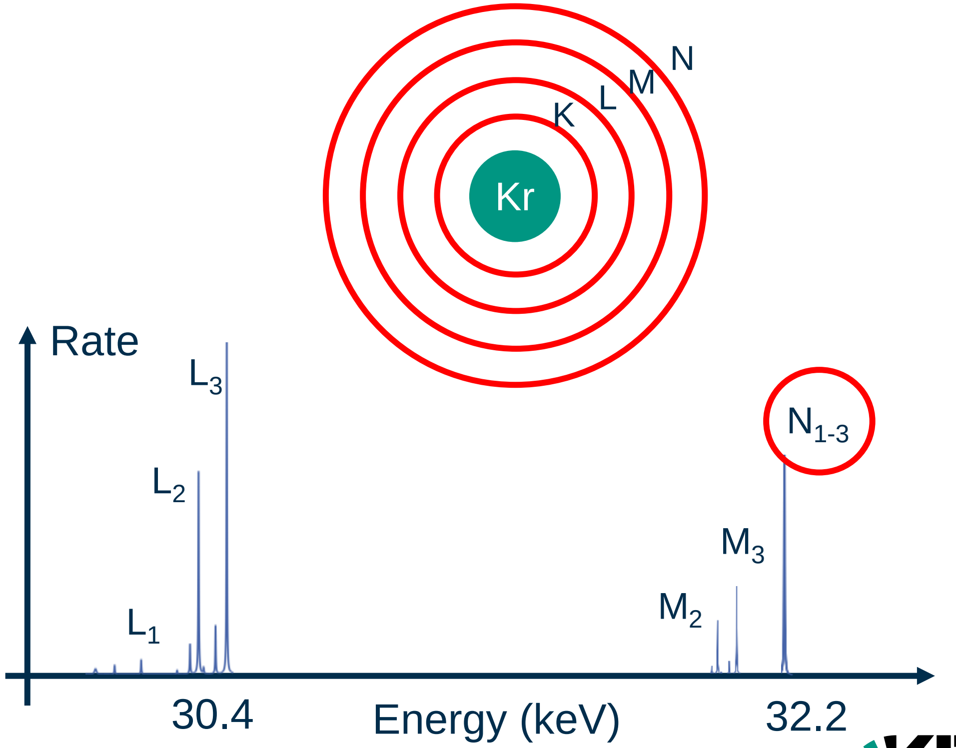
Krypton electron conversion source

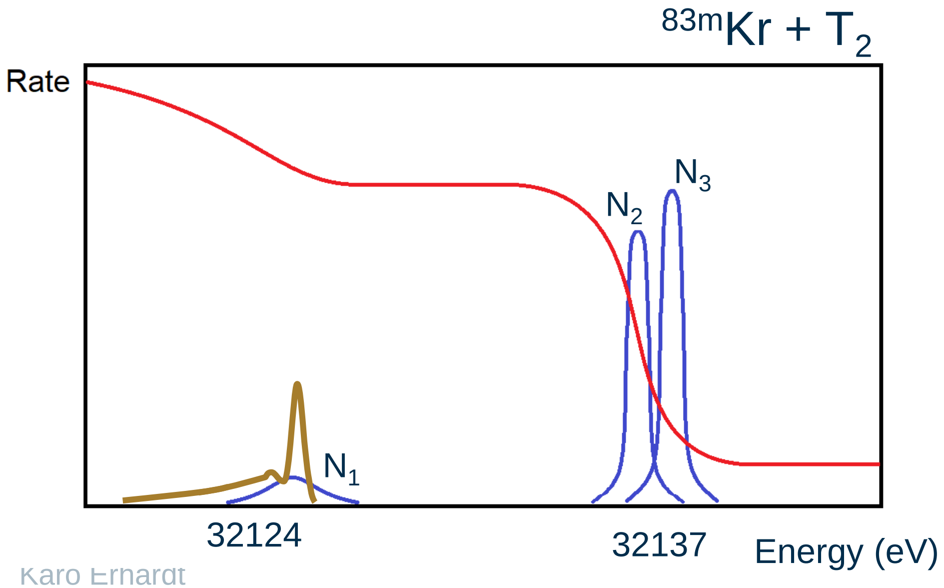


Krypton-83m because

1. *Gaseous* – mix krypton with tritium and obtain the same spatial distribution
2. Probe the potential spatial dependence in the *entire source volume*
3. *Decays* fast – no contamination

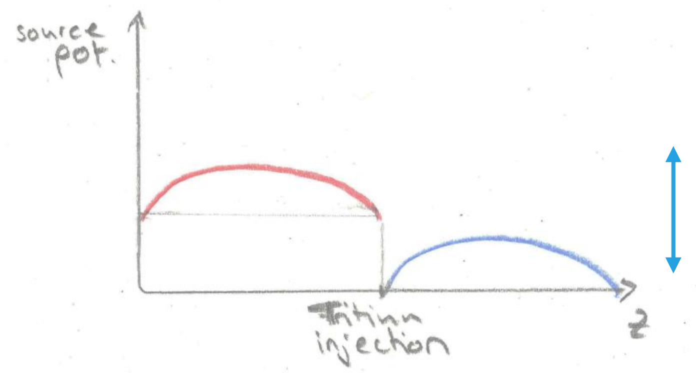
- 32 keV N lines have *negligible line widths*
  - Ideal quasi-monoenergetic isotropic calibration source

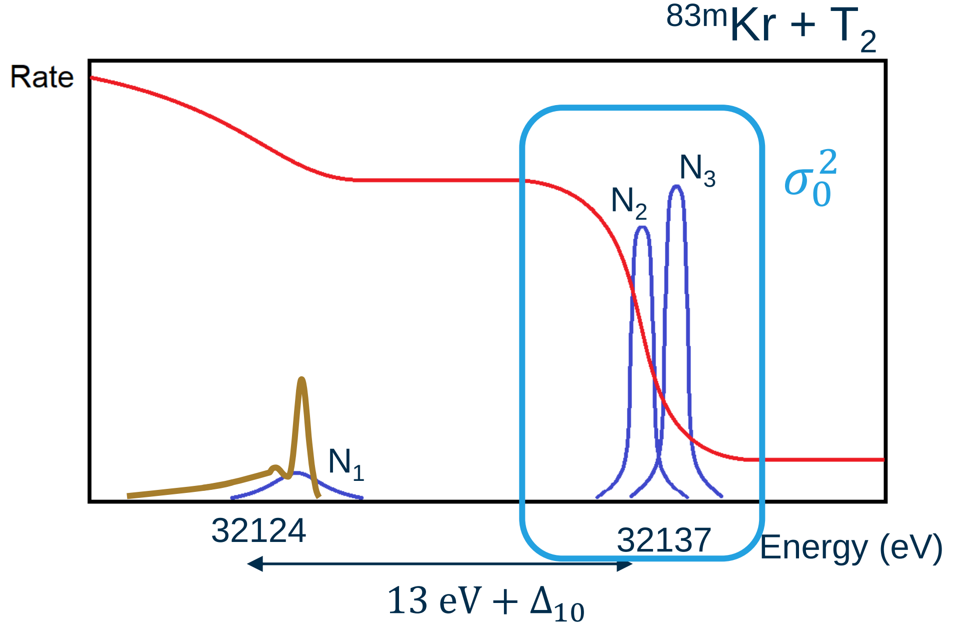




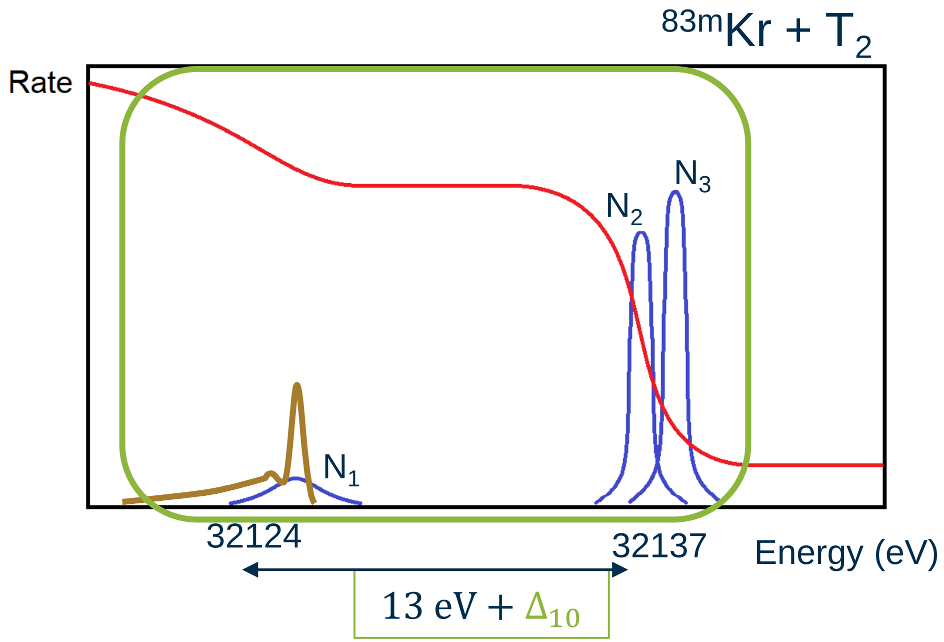
Analysis of $N_{2,3}$ lines

- Region of interest for broadening σ_0^2 is unscattered electrons from $N_{2,3}$ lines
- Indirect measurement of front-back inhomegeniety and Δ_{10}: upper limit on absolut value
- Results from $N_{2,3}$-Line Analysis
  - $\Delta m_\nu^2 \approx$ (-0.2 ± 22) x 10^{-3} eV   Eur. Phys. J. C (2025) 85: 757
  - uncertainty from front-back inhomogeniety
- One of the biggest systematics





Direct measurement of Δ_{10}

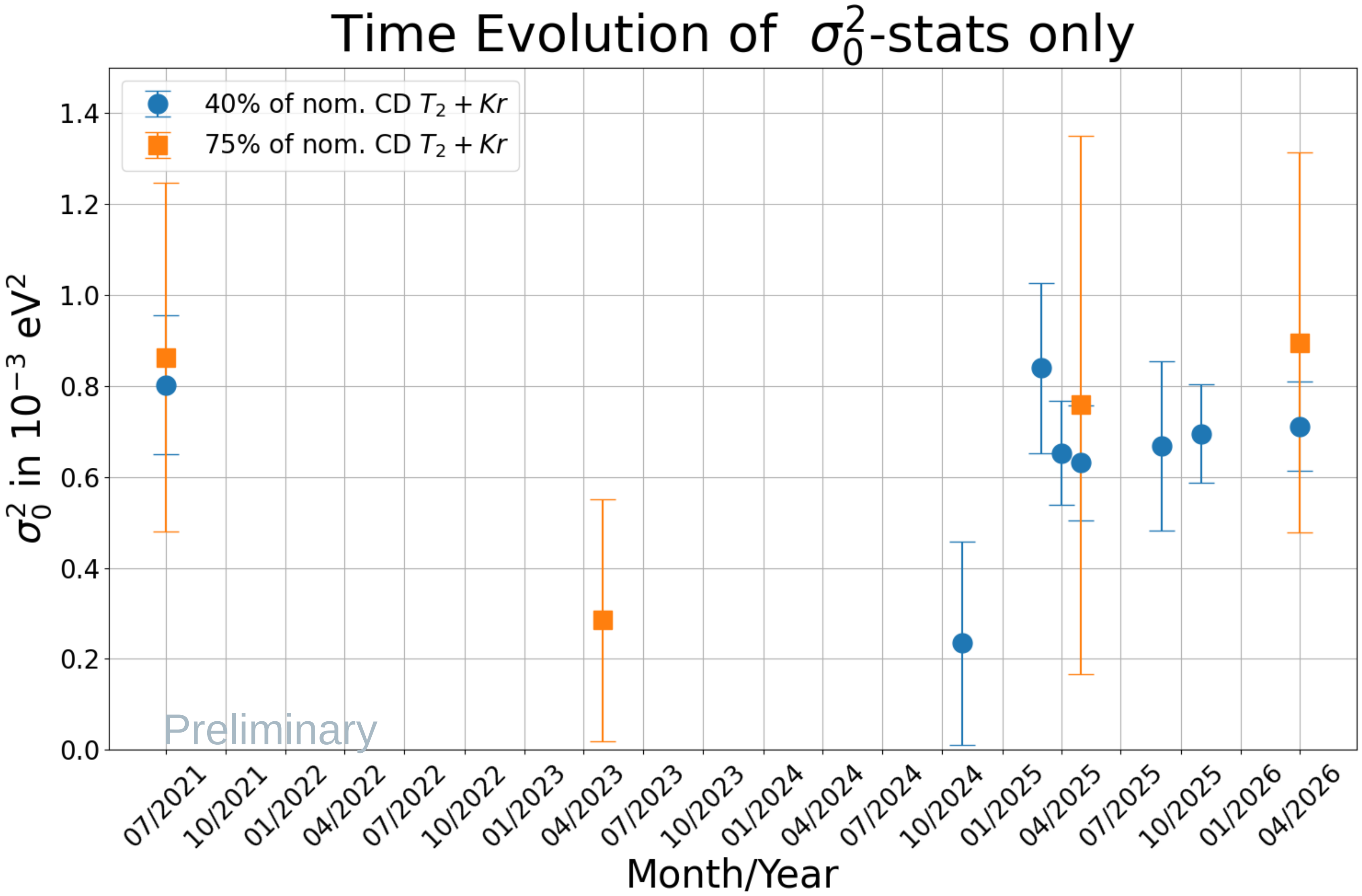


- Inlcude the scattered electrons in the analysis
- Direct measurement of Δ_{10} to improve current bounds
- Extend the model
  - Krypton spectrum
  - Energy loss when scattering on T_2
  - Number of scatterings, so T_2 gas density and cross-section

- N_1 line overlaps with scattered electrons
  - Shape and Position of N_1 line needs to be determined with separate measurement
  - Use He: energy loss from scattering is larger (~21eV)
  - Analysis of He+Kr data ongoing, prelim. results

→ Dependent on inputs

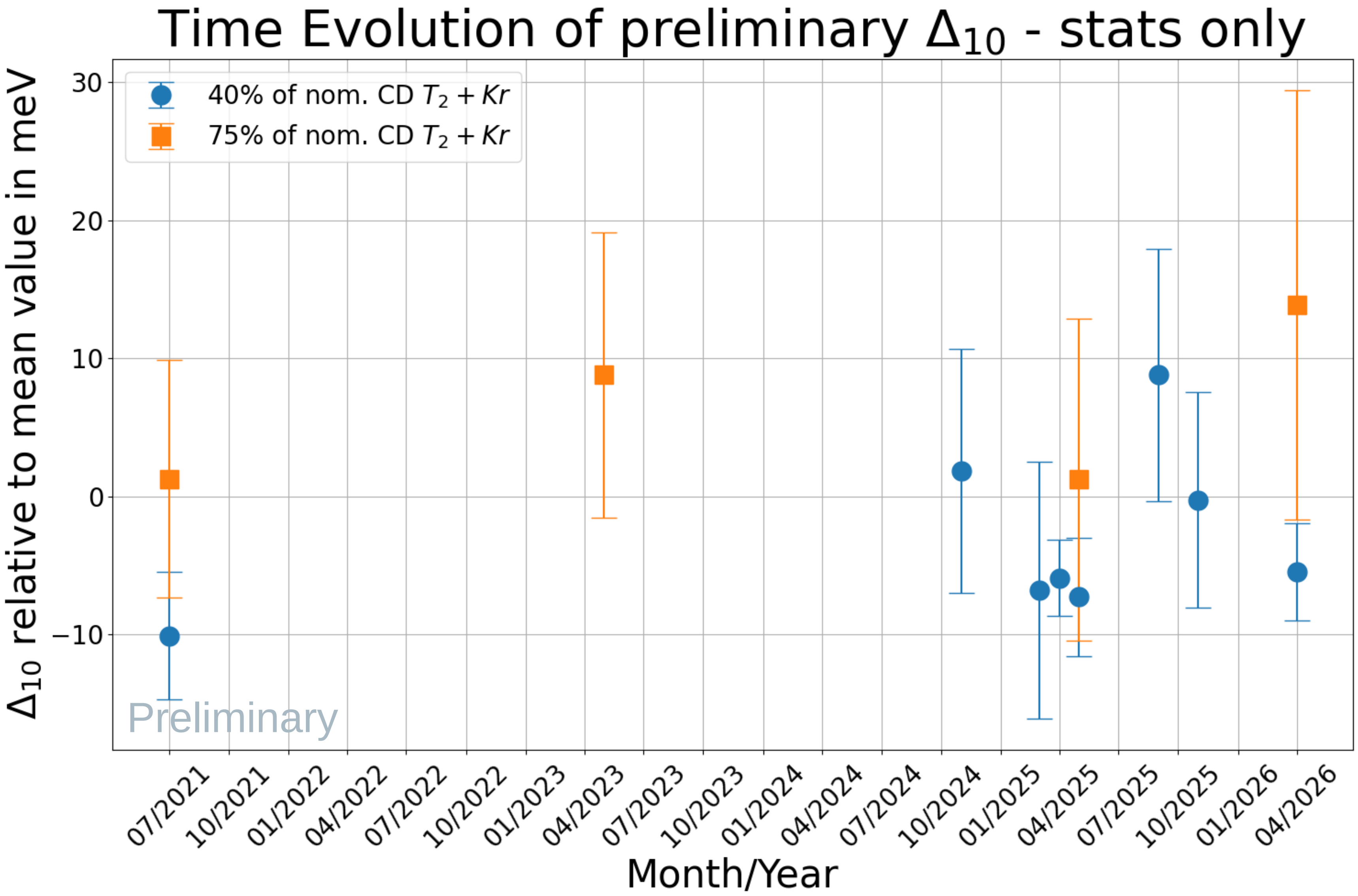
Analysis of T_2+Kr Data: Results for σ_0



Consistent values throughout the measurements and modes

Crucial update: gas density as a free parameter, expected to change between measurements

Analysis of T_2+Kr Data: Results for Δ_{10}



No indication of temporal evolution

40% and 75% have different means

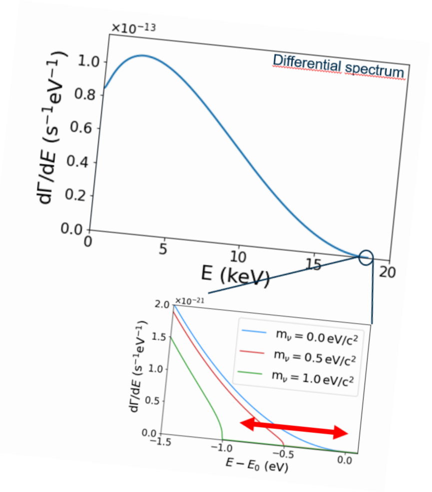
Could come from
- different systematics in the measurement modes
- different Plasma potentials in two modes

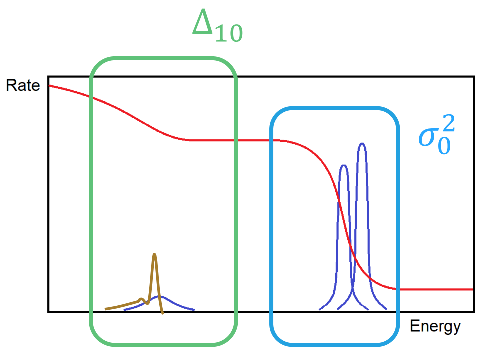
Summary

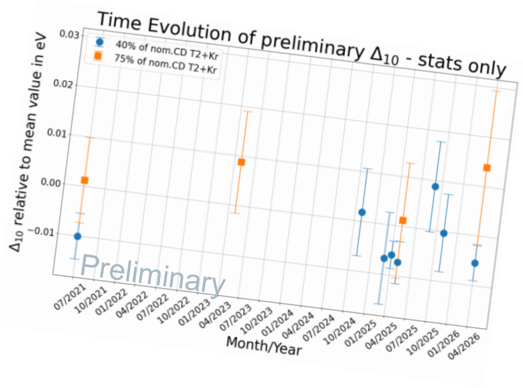
- KATRIN perfoms precision measurement of tritium beta spectrum
- inhomogeneous source potential can deform the spectrum
- σ_0^2 and Δ_{10} determined by measurement ^{83m}Kr monoenergetic electrons
- Previously: Upper limit on Δ_{10} with large uncertainty
- Direct measurement of Δ_{10} requires inputs from scattering and additional Krypton Lines
- No indication of time evolution for σ_0^2 and Δ_{10}

- Repeat analysis with final inputs and systematic error propagation

→ Neutrino Mass Inputs







Backup

Bias on the Neutrino Mass Analysis

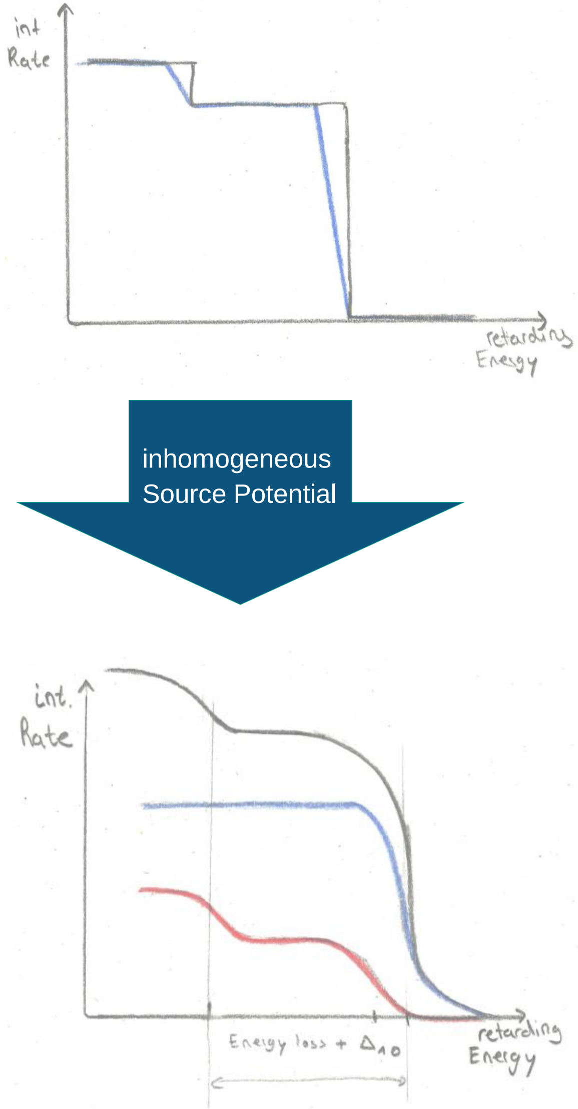
- Direct impact on neutrino mass
  - σ_0^2 : Broadening bad
  - Δ_{10} : Shape deformation worse

$$\Delta m_\nu^2 = -2\sigma_0^2 - \epsilon\Delta_{10}$$

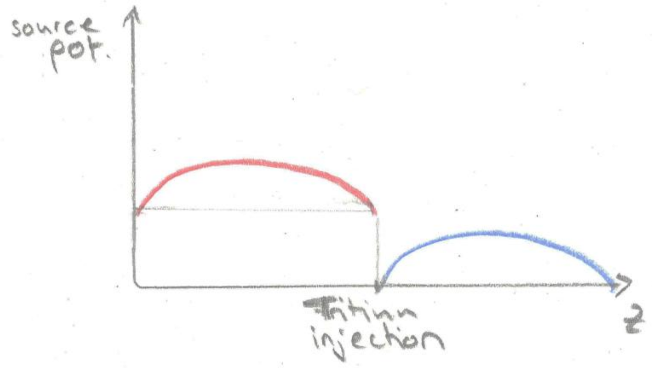
$\epsilon \sim 1.2$ eV

Eur. Phys. J. C (2025) 85: 757

- Calibration measurement to find σ_0^2 and Δ_{10}
- Source of electrons
- Precise knowledge of our source
- Precise knowledge of the energy loss probability needed
- Krypton-83m conversion electrons
- Tritium and Krypton are co-circulated in the source



Analysis of $N_{2,3}$ lines



- Region of interest for broadening σ_0^2 is just $N_{2,3}$ lines
- Indirect measurement of Δ_{10} with upper limit through an inequality

$$|\Delta_{10}| \leq \kappa\, \sigma_0$$

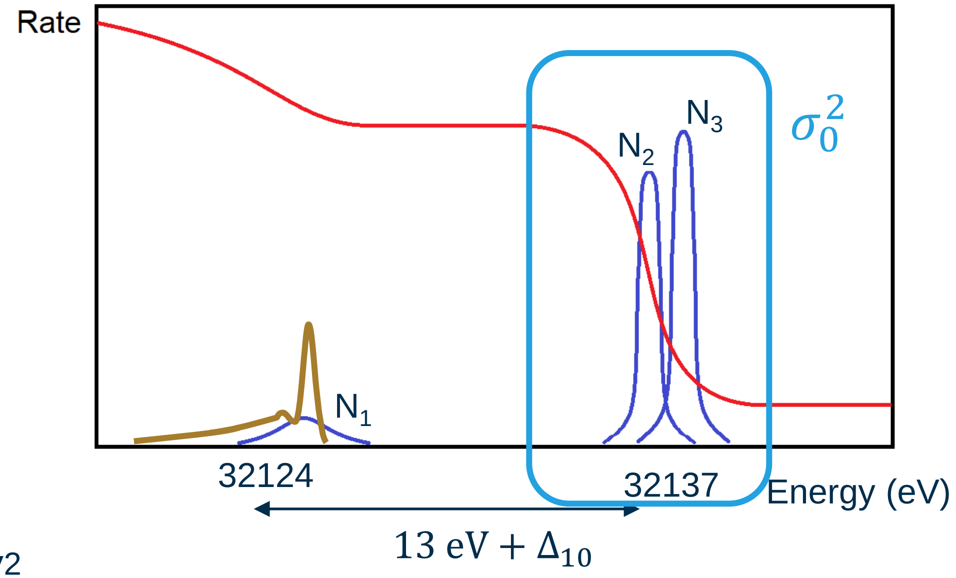
$\kappa \sim 0.7$ eV

arXiv:2506.13829

- Results from $N_{2,3}$-Line Analysis
  - Δ_{10} = 0 ± 22 meV
  - σ_0^2= (1.0 ± 0.3) x 10^{-3} eV^2
  - Δ_{10} dominant

$$\Delta m_\nu^2 = -2\sigma_0^2 - \epsilon\Delta_{10}$$

$\epsilon \sim 1.2$ eV



- Systematic effect on neutrino mass measurement $\Delta m_\nu^2 \approx 2 \times 10^{-2}$ eV^2
- One of the biggest systematics

Eur. Phys. J. C (2025) 85: 757

Electron scattering off tritium molecules

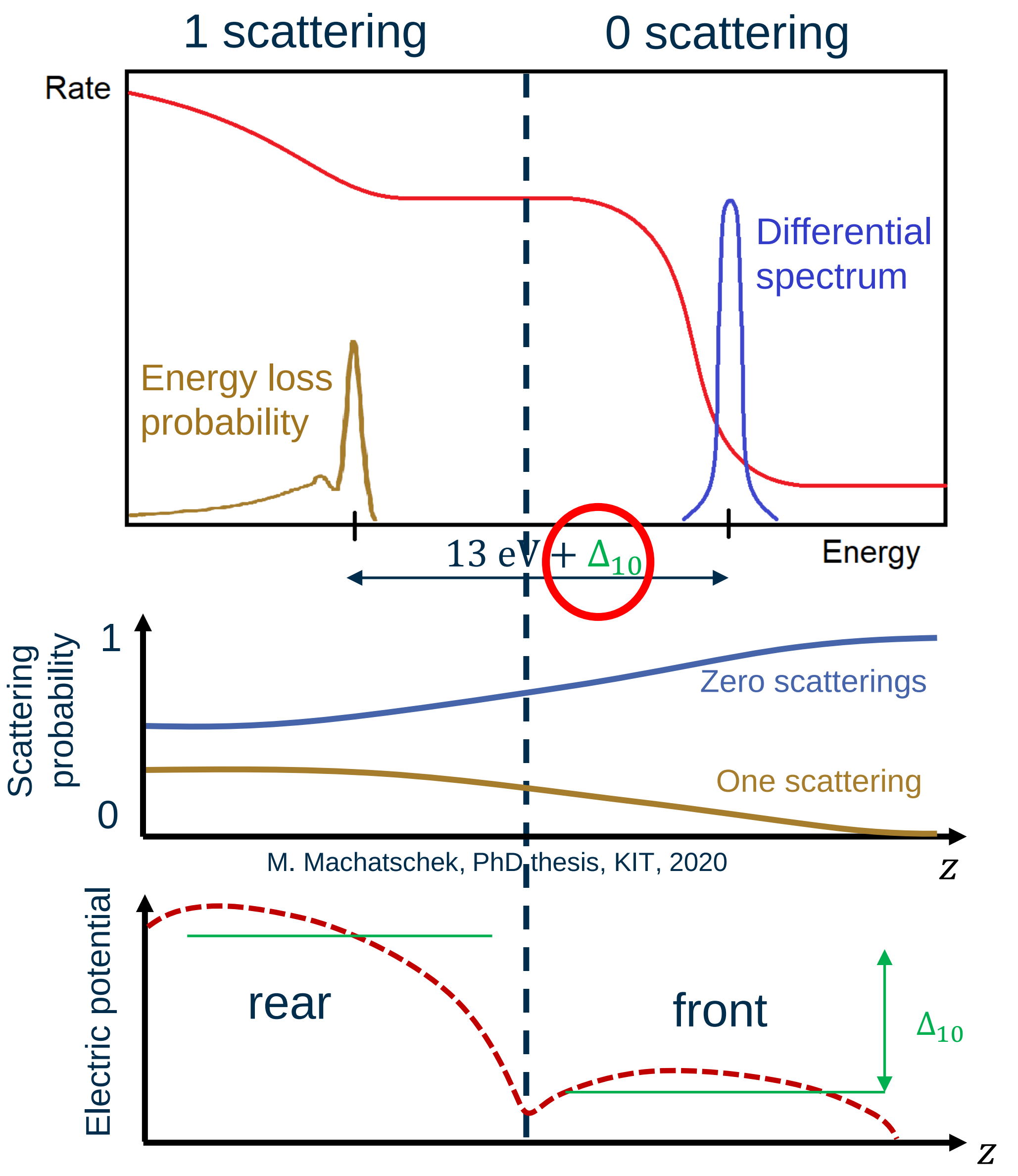
- Direct probe of the rear source potential
- Electron scattering on T_2 leads to minimum loss of 13 eV
- Difference of rear and front potentials: Δ_{10}
  - Direct impact on neutrino mass shift

$$\Delta m_\nu^2 = -2\sigma_0^2 - \epsilon\Delta_{10}$$

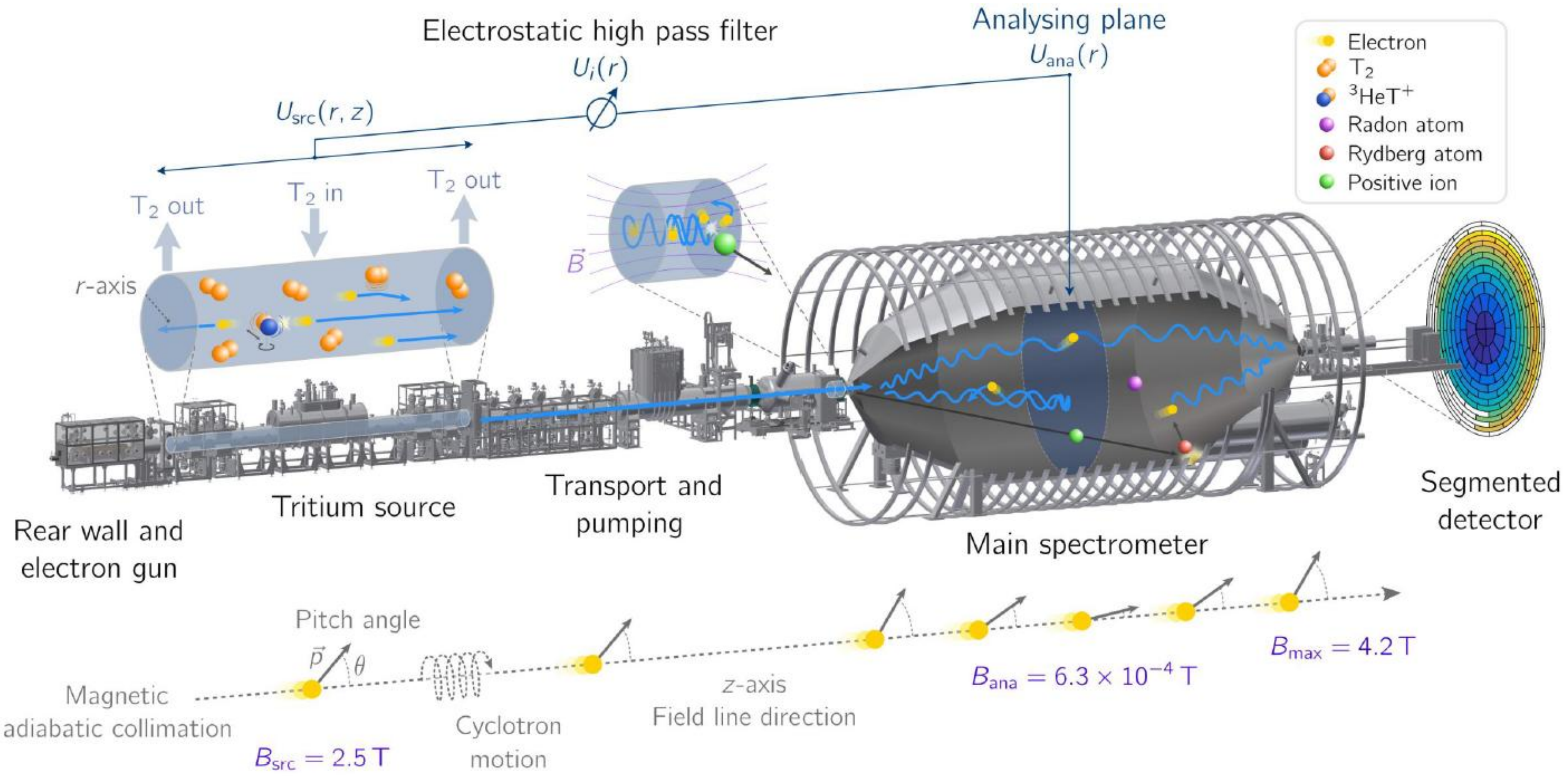
$\epsilon \sim 1.2$ eV

arXiv:2503.13221

  - Δ_{10} sensitivity ~ 10 mV needed
- Precise knowledge of the energy loss propability and krypton spectrum needed



Backup



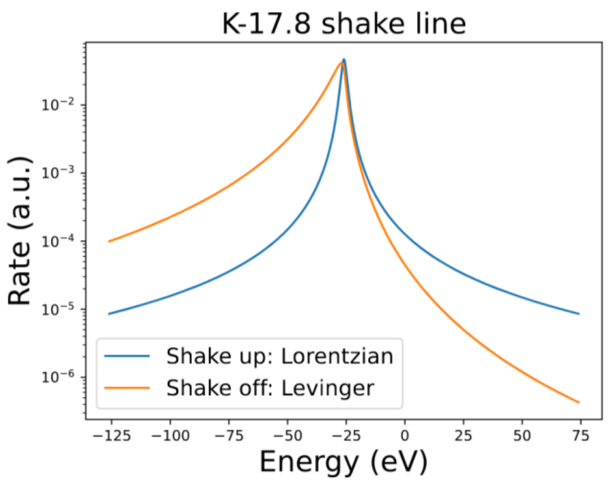
Electrostatic high pass filter
$U_i(r)$
Analysing plane
$U_{ana}(r)$
$U_{src}(r, z)$
Electron
T_2
$^3HeT^+$
Radon atom
Rydberg atom
Positive ion
T_2 out
T_2 in
T_2 out
r-axis
$\vec{B}$
Rear wall and
electron gun
Tritium source
Transport and
pumping
Main spectrometer
Segmented
detector
Pitch angle
$\vec{p}$
θ
Magnetic
adiabatic collimation
$B_{src} = 2.5\,T$
Cyclotron
motion
z-axis
Field line direction
$B_{ana} = 6.3 \times 10^{-4}\,T$
$B_{max} = 4.2\,T$

Krypton + Helium

Work by Jaroslav Storek

- No scattering contribution in the N_1 line region
- New challenge: $N_{2,3}$ shake region
  - Sparse literature information about shake up/off structure D. Vénos *et al JINST* **13** T02012 (2018)
  - Description by 2 Lorentzians or Levinger shakeoff distribution J. S. Levinger, Phys. Rev. **90**, 11 (1953)
  - Levinger distribution successfully used for description of the K line

R. G. Hamish Robertson and Vedantha Venkatapathy, Phys. Rev. C **102,** 035502 (2020)



$$S(E) = A\left[\frac{1}{\pi}\arctan\left(\frac{2W}{\Gamma}\right)+\frac{1}{2}\right]\cdot\,(1\,-\,e^{-2\pi\kappa})^{-1}\kappa^{8}(\kappa^{2}+1)^{-4}e^{-4\kappa\,\arctan(1/\kappa)}$$

^{83m}Kr + He