Universität Münster

Details of the latest KATRIN data analysis

Neutrino Oscillation Workshop 2024 – 06.09.2024

Richard Salomon for the KATRIN collaboration

KATRIN
Karlsruhe Tritium Neutrino Experiment

Graduiertenkolleg 2149
Research Training Group

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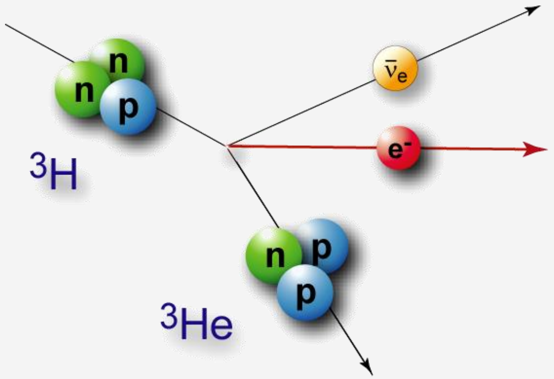
University of Münster
Institute of Nuclear Physics

KATRIN Experiment

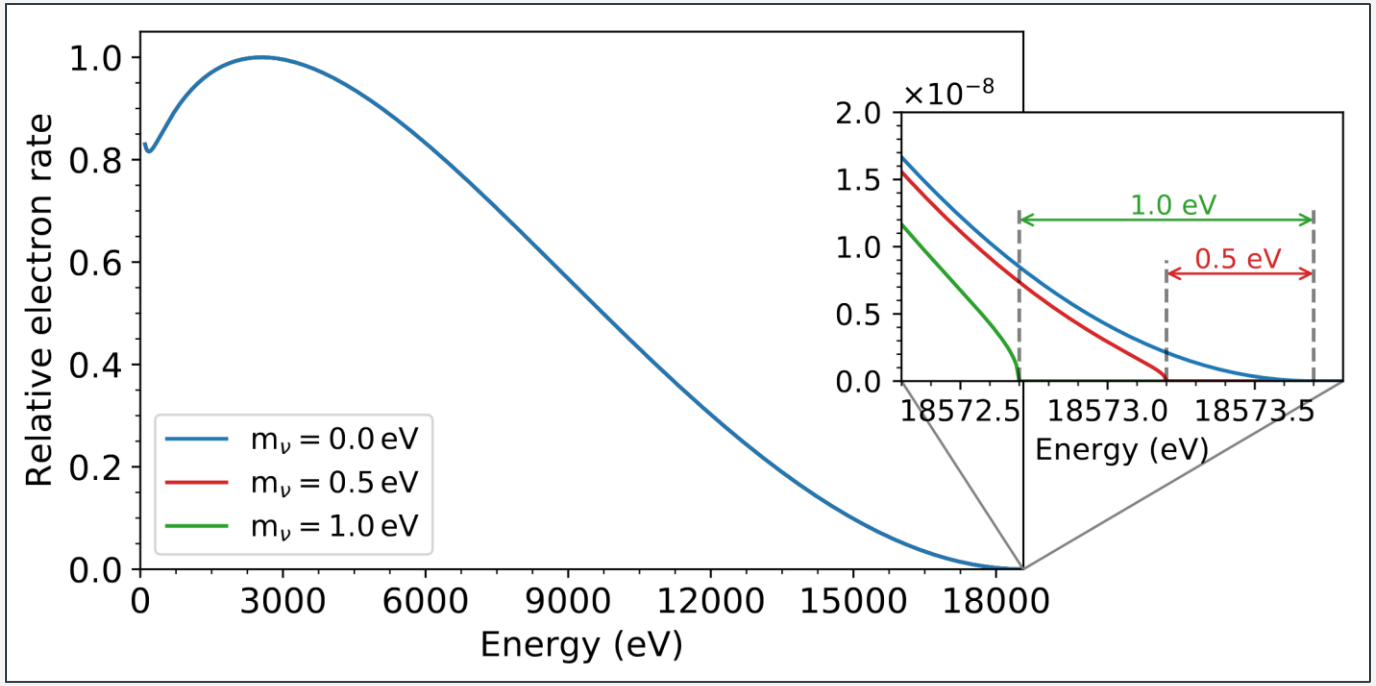
Spectrum from tritium beta decay is sensitive to neutrino mass m_ν^2

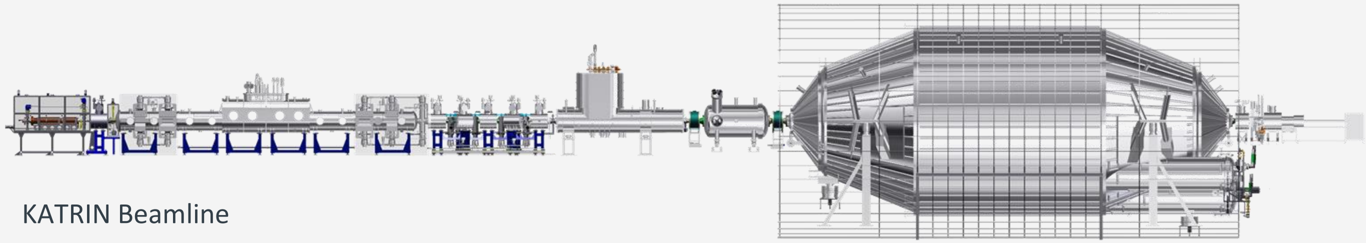
→ Precisely measure spectral shape near the endpoint



Fermi's Golden Rule:

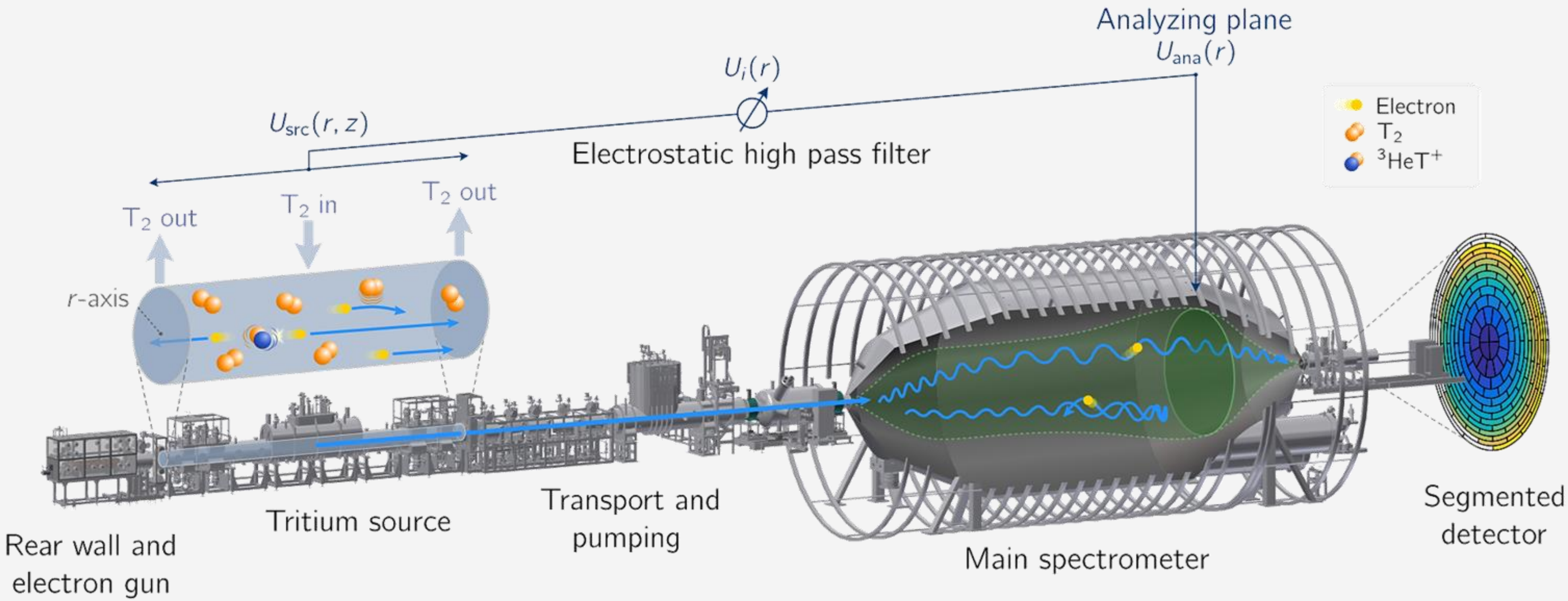
$$\frac{dN}{dE} = K \cdot F(E,Z) \cdot p \cdot E_{tot} \cdot (E_0 - Ee) \cdot \sum_i |U_{ei}|^2 \cdot \sqrt{(E_0 - E_e)^2 - m^2(\nu_i)}$$





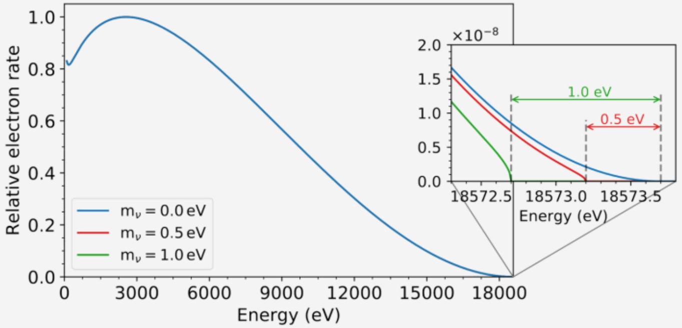
KATRIN Beamline

KATRIN Experiment

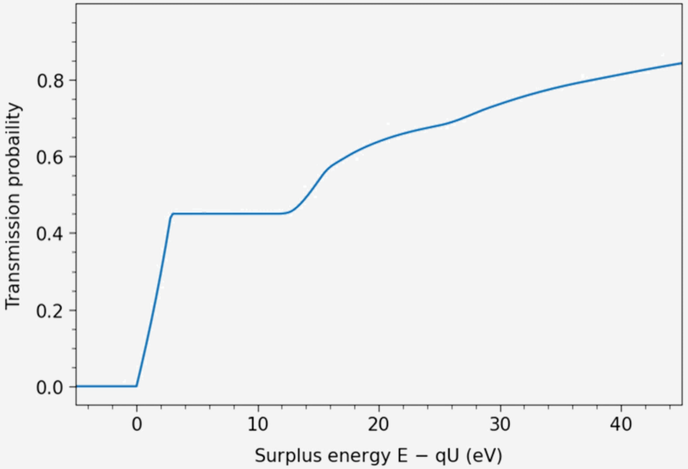


The Experimental Spectrum

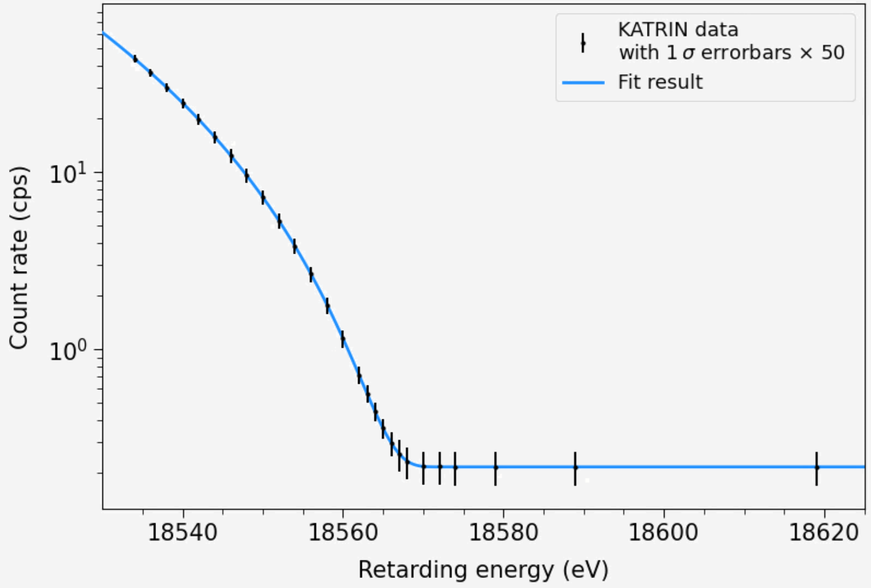
1) Differential Beta-decay Spectrum $R_\beta(E, m_\nu^2)$



2) Response function $f(E - qU)$



Convolution of beta spectrum and response function



Integral spectrum:

$$R(qU) = A_s \cdot N_T \int_{qU}^{E_0} R_\beta(E, m_\nu^2, E_0) \cdot f(E - qU)\mathrm{d}E + R_{bg}$$

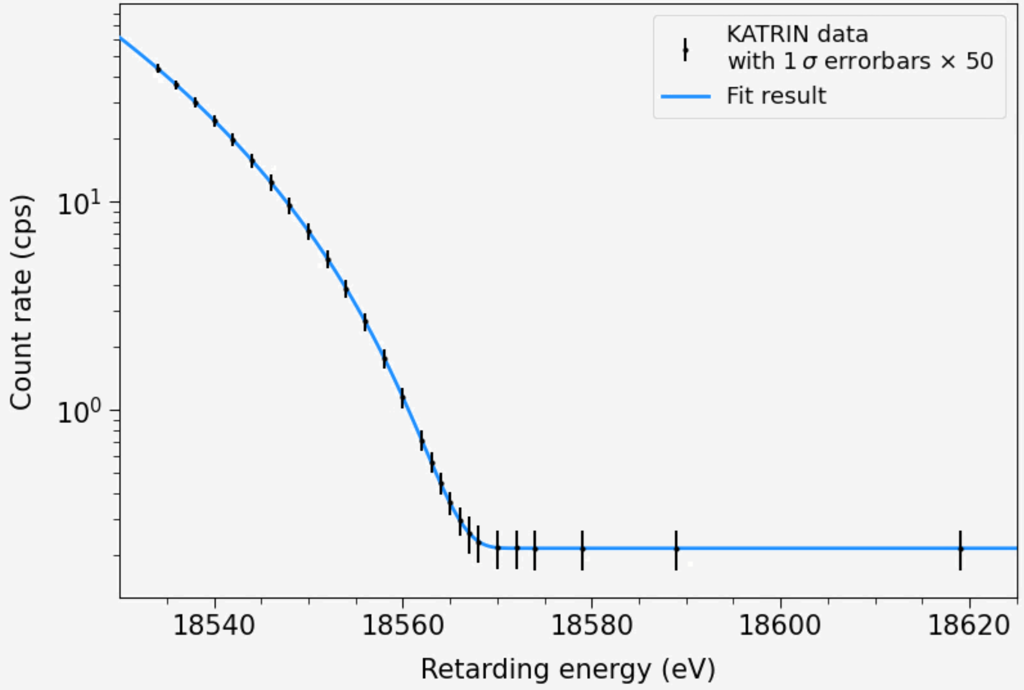
Measurement and Analysis Strategy

- Scan spectrum in several retarding voltage steps
  Measured interval: $[E_0 - 300\text{ eV}, E_0 + 135\text{ eV}]$

  → 2-3 hours per measurement of full spectrum
  → Measure $\mathcal{O}(100)$ spectra per campaign

- Blinding procedure involving multiple steps
  → Establish analysis strategy on Asimov twins
  → First analysis of the data using model blinding

- Two independent analysis methods
  → KaFit (fast direct model evaluation)
  → Netrium (neural network)
  EPJ C **82**, 439 (2022)



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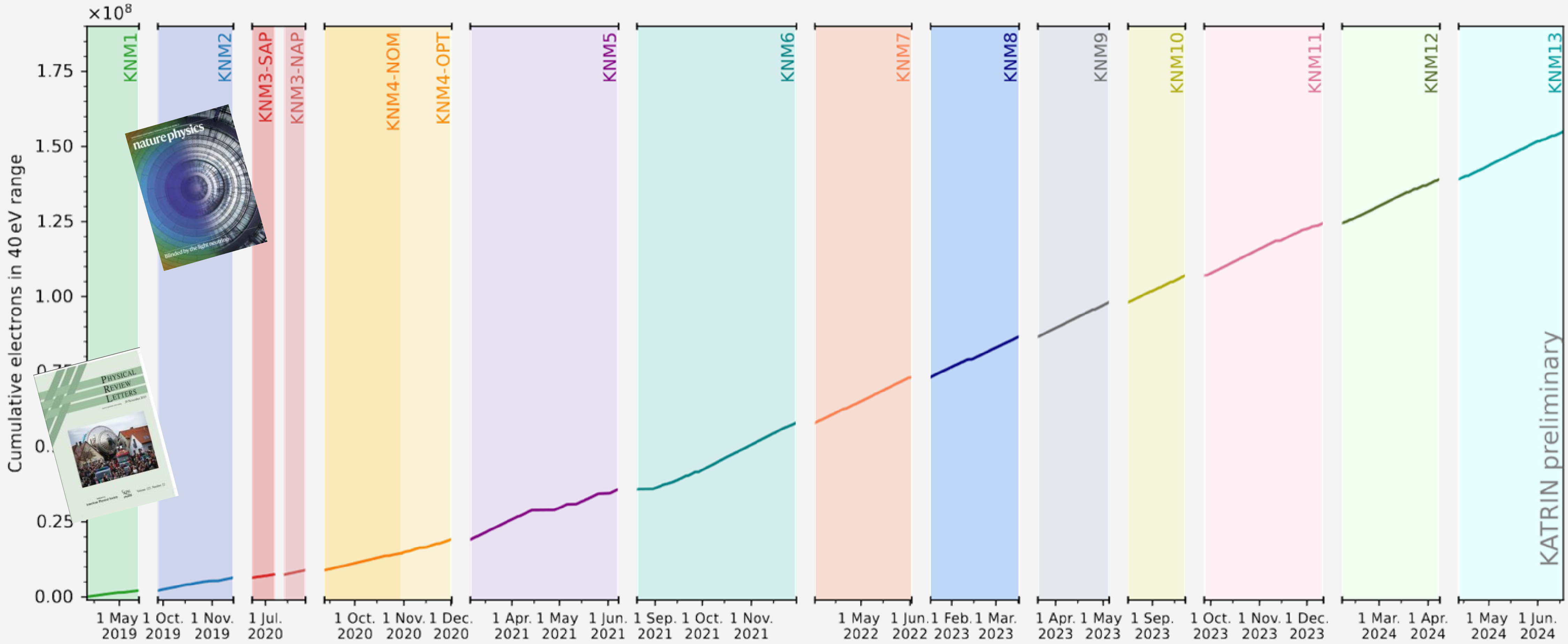
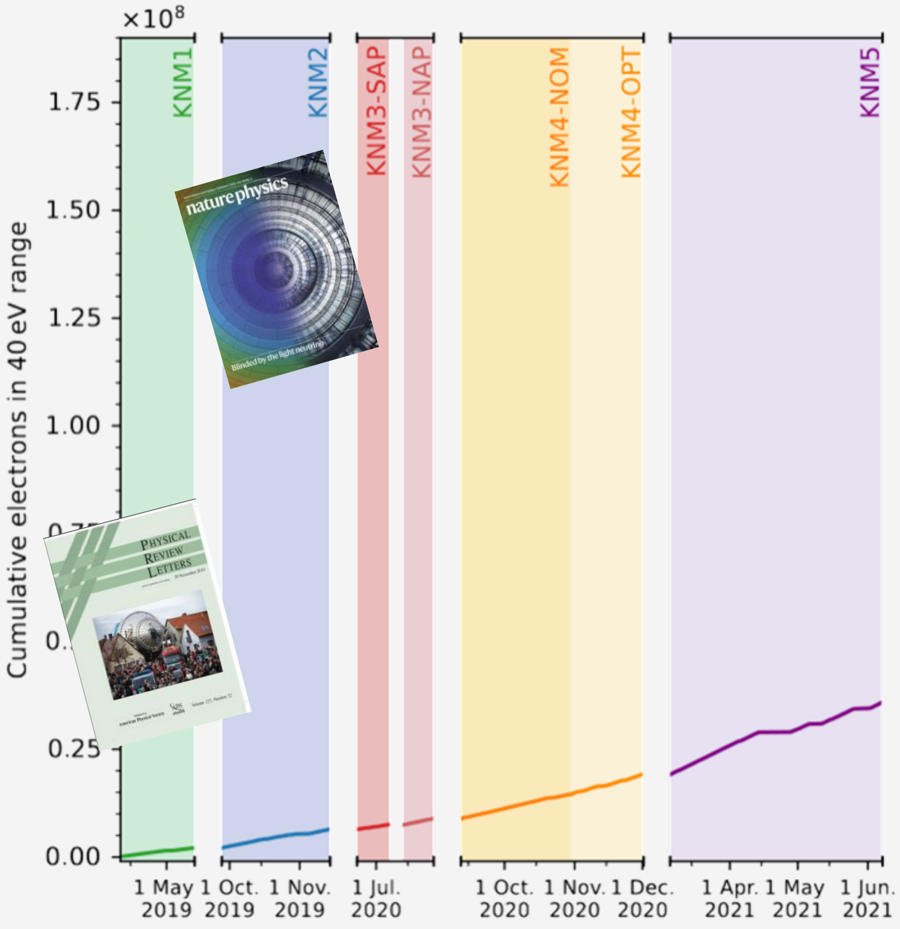
Measurement Campaigns



Measurement Campaigns



KNM1: $m_\nu < 1.1\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$

PRL 123 (2019) 221802

KNM1-2: $m_\nu < 0.8\ \mathrm{eV}\ (90\%\ \mathrm{C.L.})$

Nature Phys. 18 (2022) 160

KNM1-5 Key Points:

- 259 measurement days
- 36 million electrons in 40 eV analysis window $[E_0 - 40\ \mathrm{eV}, E_0 + 135\ \mathrm{eV}]$
- Expected sensitivity $m_\nu < 0.5\ \mathrm{eV}$

Beta Spectrum Analysis with KaFit

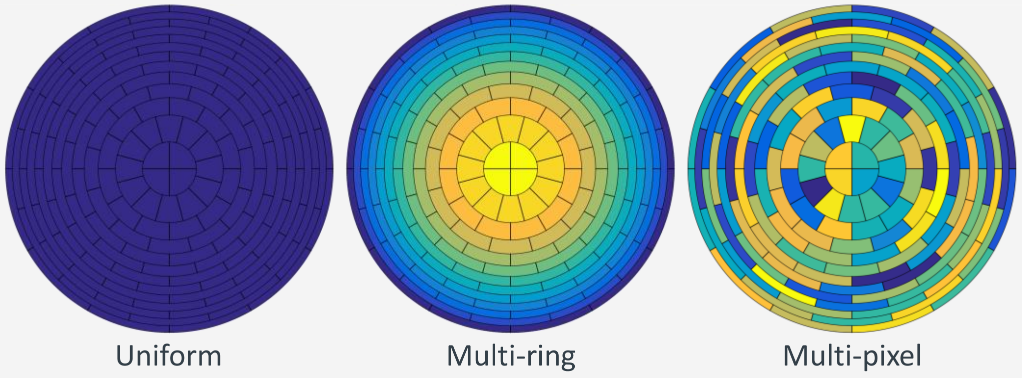
- **Gradient descend minimization using MINUIT**
- **Minimize one combined likelihood**

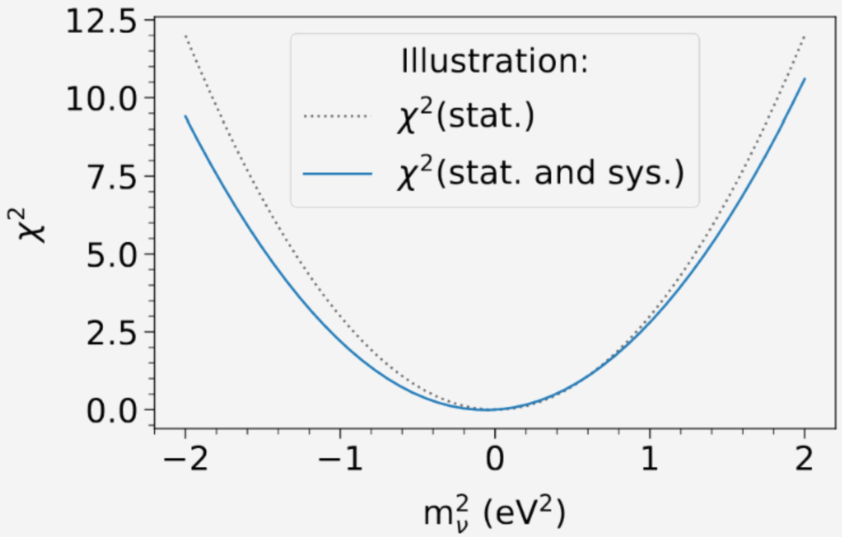
$$-\log \mathcal{L} = \sum_i -\log \mathcal{L}_i \left(m_\nu^2, E_{0_i}, A_{s_i}, R_{bg_i} \right)$$

$$-2\log \mathcal{L} = \chi^2$$

- **Include systematics via pull-terms**

$$\chi^2 \left(m_\nu^2, E_{0_i}, A_{s_i}, R_{bg_i}, \theta_1, \ldots \right) + \underbrace{\left(\hat{\vec{\theta}} - \vec{\theta} \right) C^{-1} \left(\hat{\vec{\theta}} - \vec{\theta} \right)^T}_{\text{Multivariate gaussian penalty}}$$

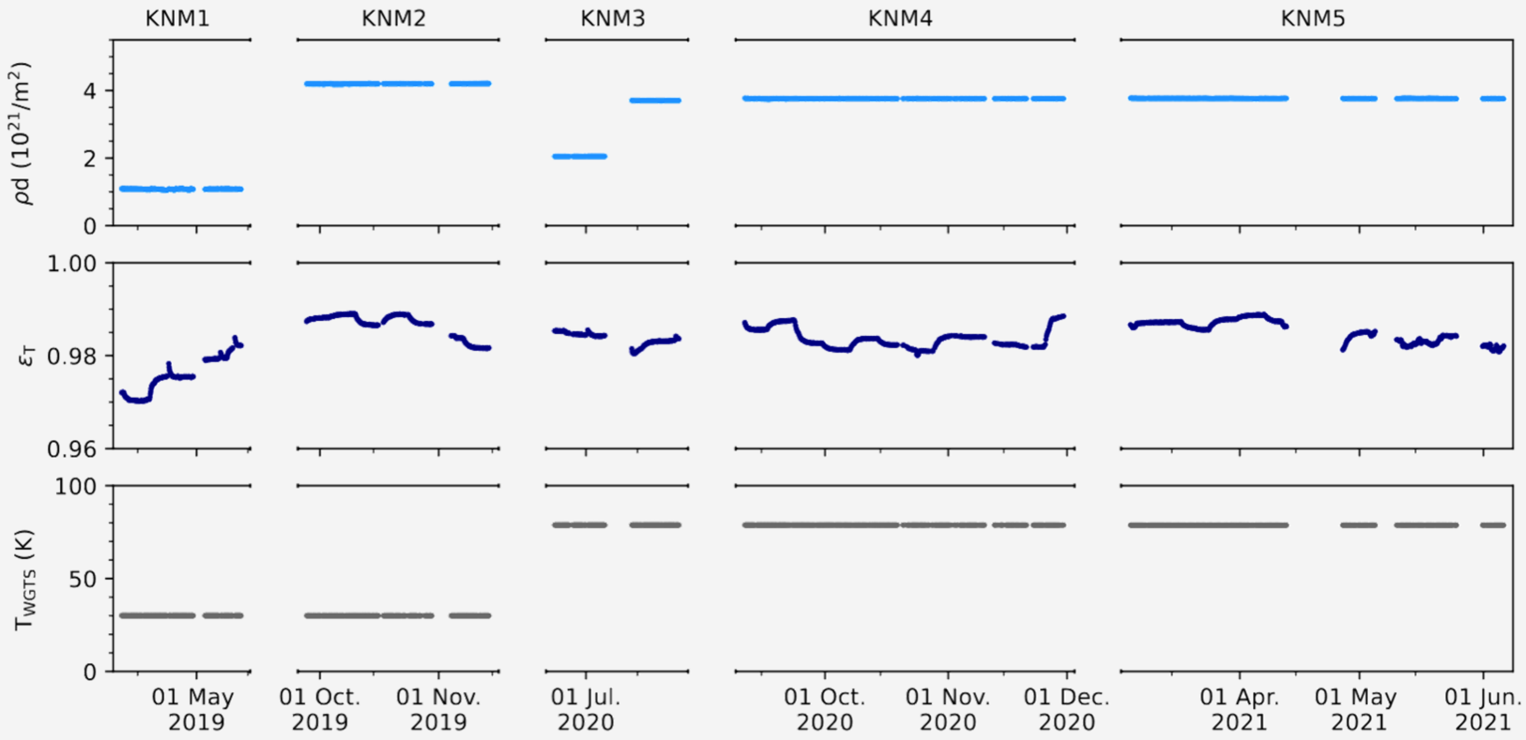




Data Combination

- Stack data with same measurement conditions

  → Average slow control parameters
  → Stack counts
  → Correlate systematic parameters within and between campaigns



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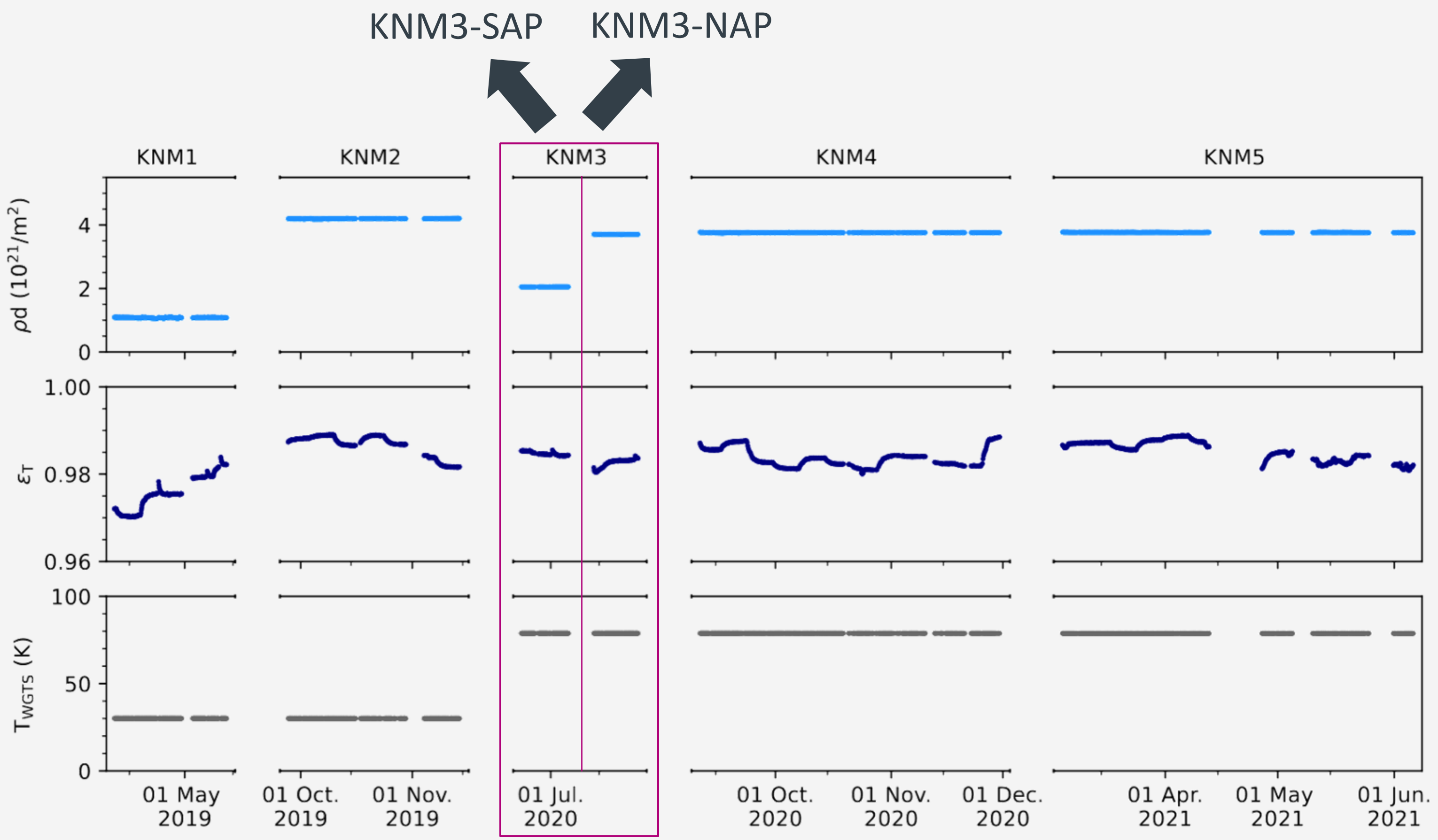
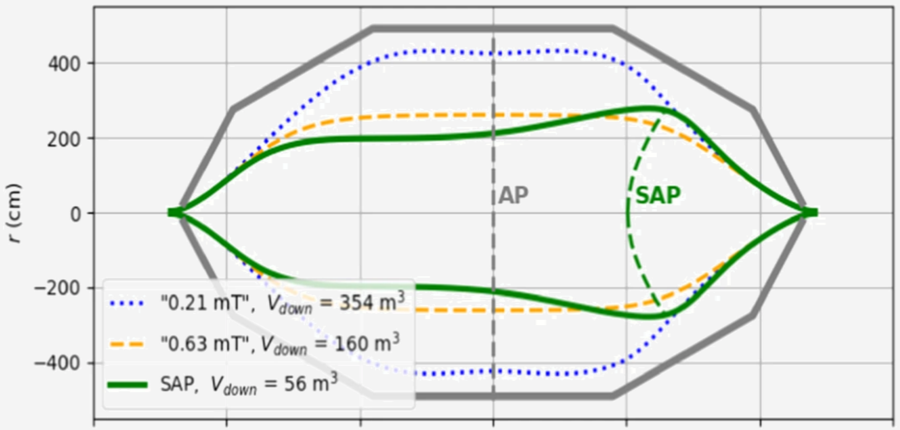
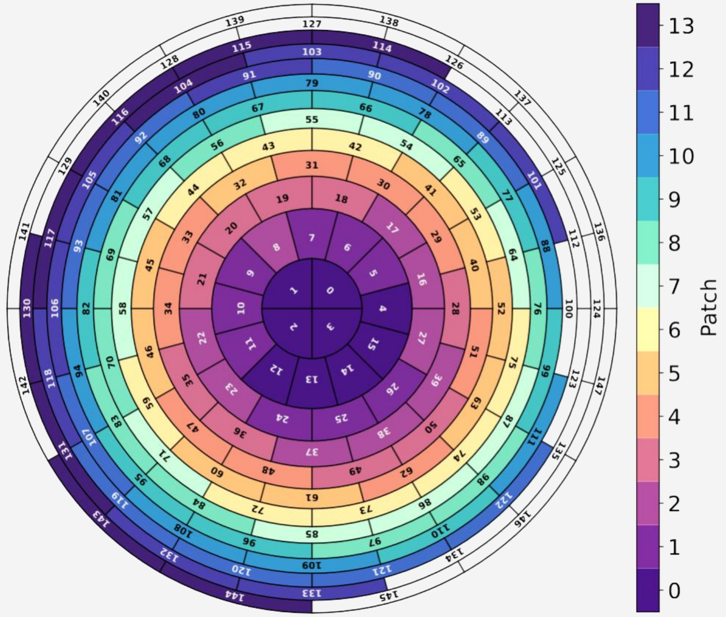


Shifted Analyzing Plane Setting

- Adapt electromagnetic fields in main spectrometer
  → Move point of highest potential and lowest magnetic field downstream
- Reduction of background by factor 2
- Calibration via simulations and $^{83\mathrm{m}}\mathrm{Kr}$ conversion electrons
  arXiv:2408.07022
- **Field inhomogeneities require segmentation of data**
  → 14 patches with 9 pixels each



EPJ C **82**, 258 (2022)



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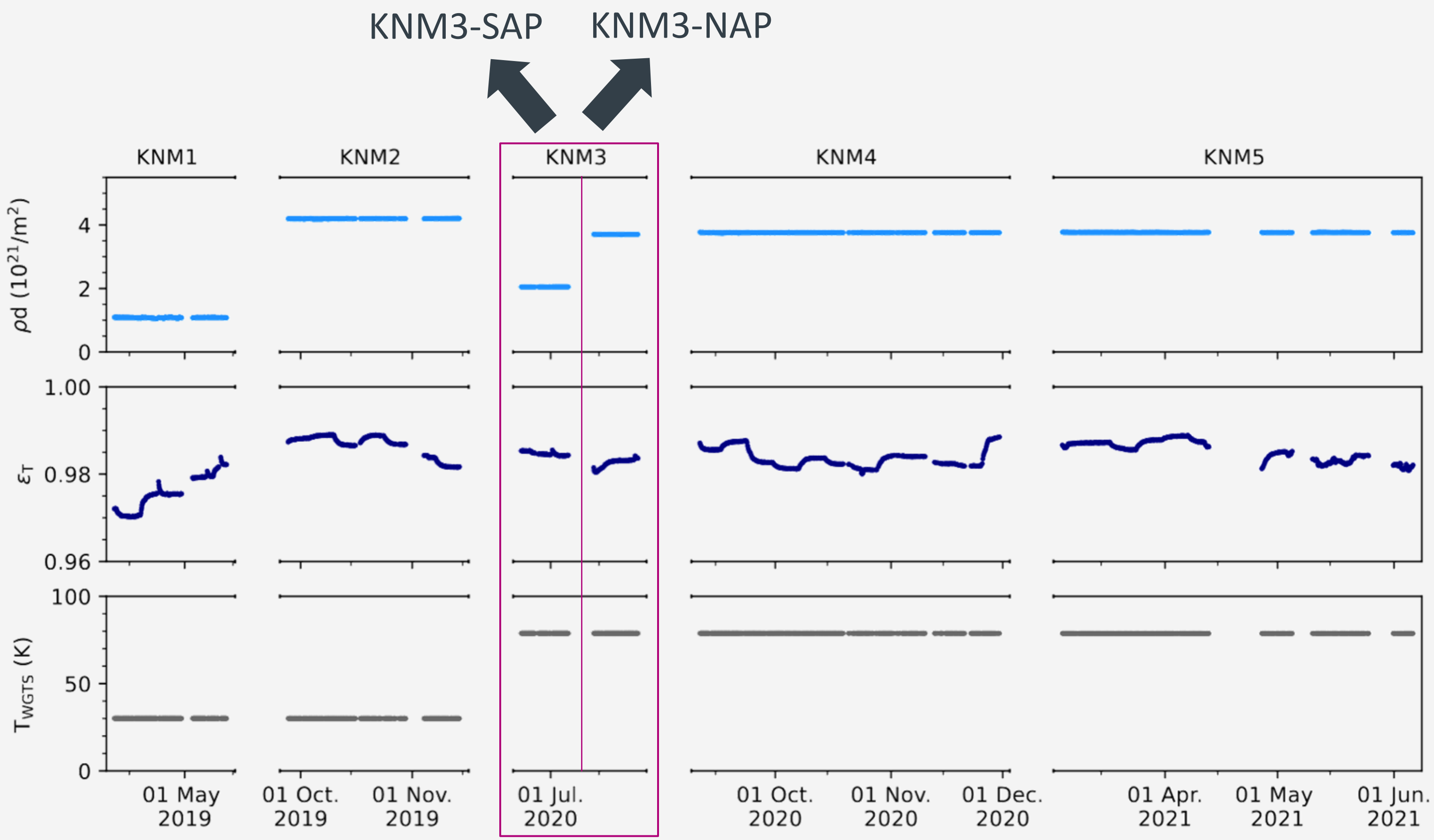

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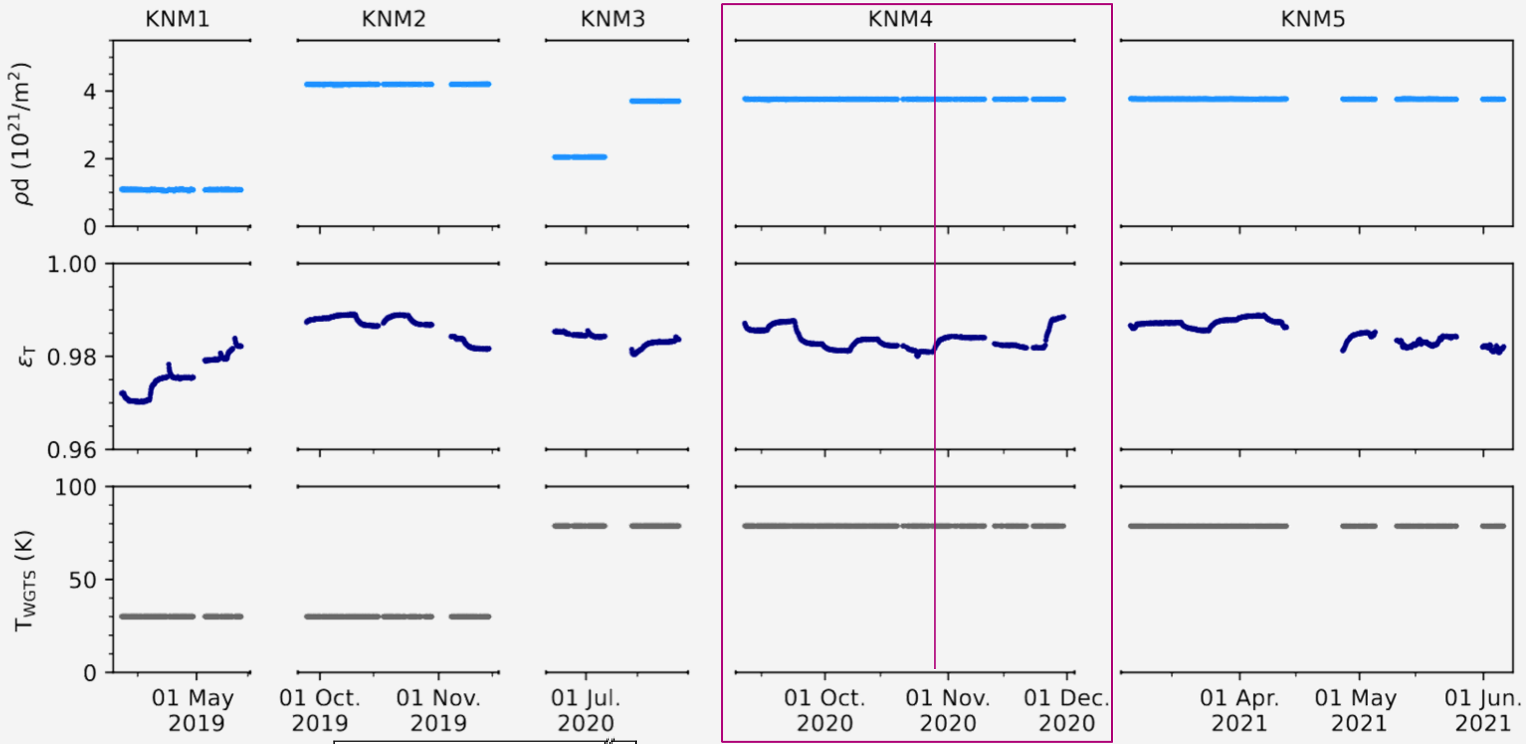
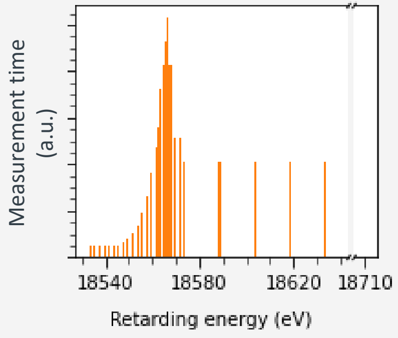
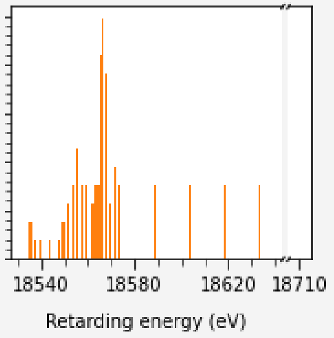
KNM3-SAP KNM3-NAP



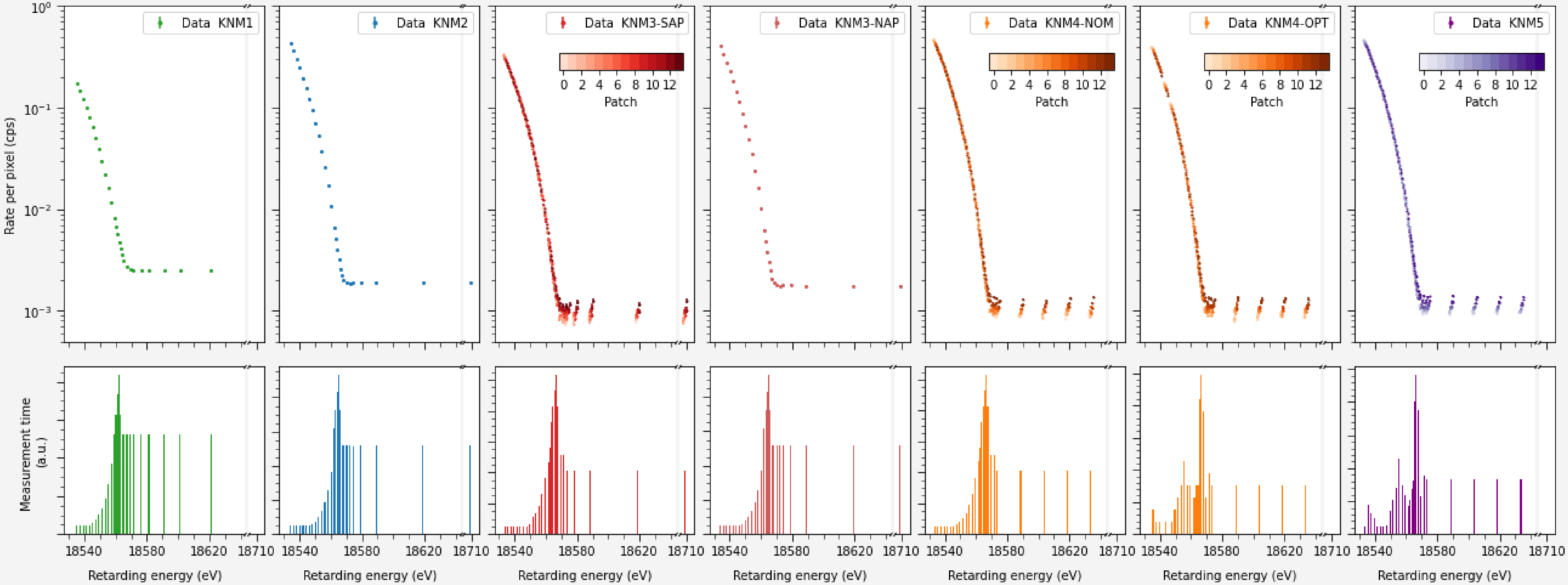


KNM4-NOM KNM4-OPT

This was a post-unblinding modification



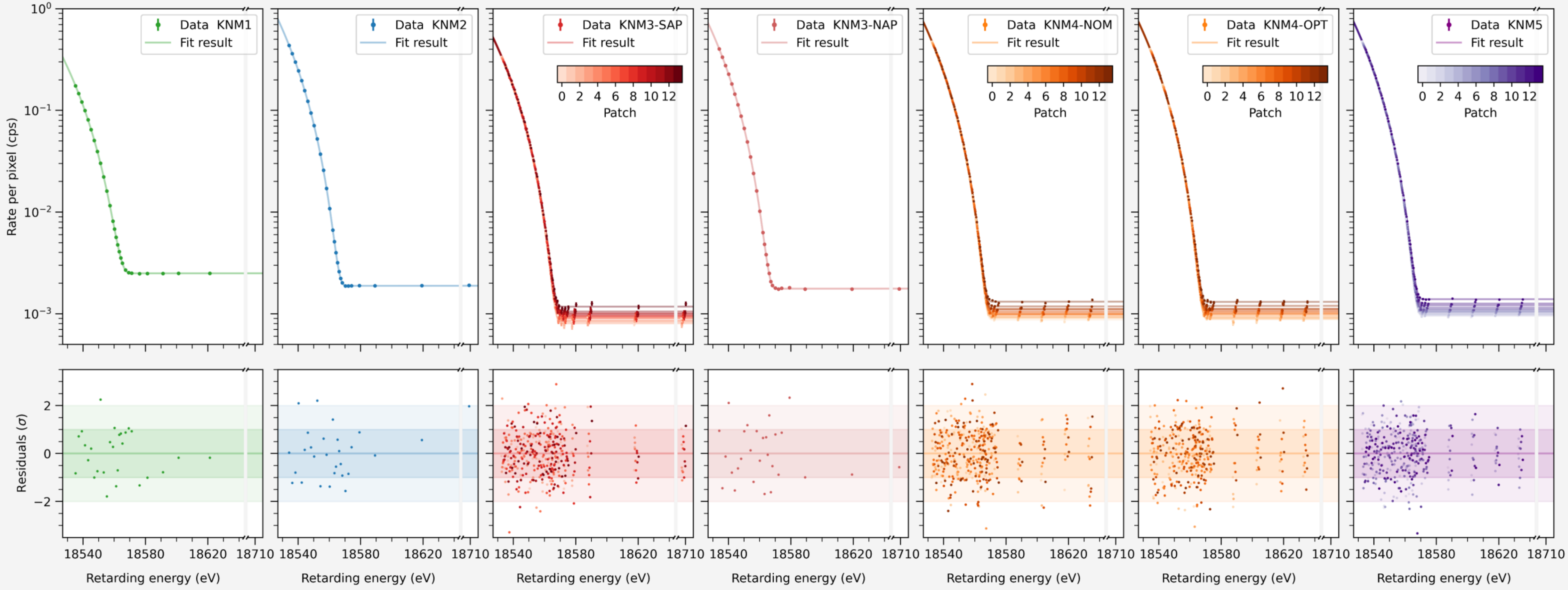
Spectra KNM1-5



27	+	28	+	14x28	+	28	+	14x28	+	14x25	+	14x28

In total **1609 data points**
from **59 stacked spectra**

Spectra KNM1-5



27	+	28	+	14x28	+	28	+	14x28	+	14x25	+	14x28

In total **1609 data points** from **59 stacked spectra**

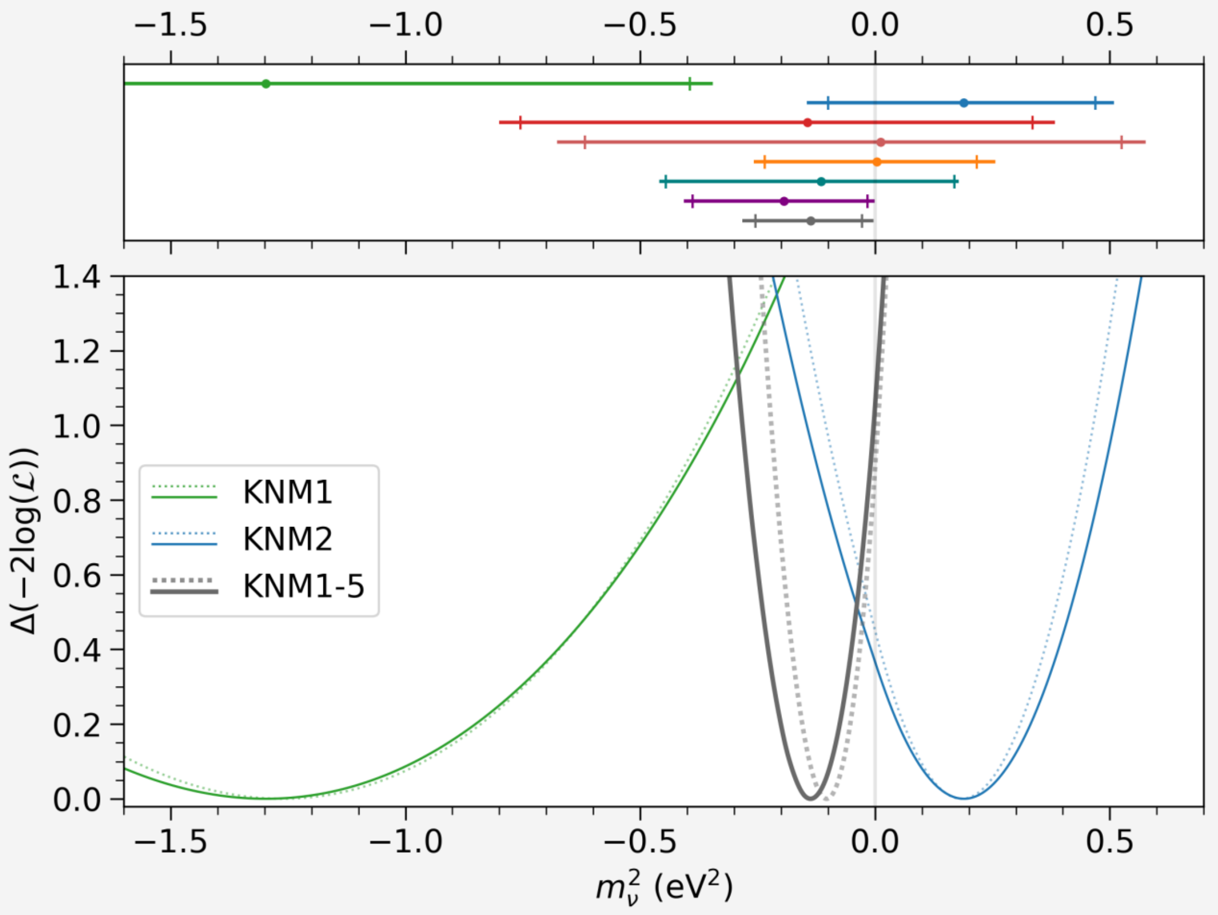
& **178 free fit parameters:** $1m_\nu^2 + 59A_s + 59E_0 + 59R_{bg}$

Results

- Combined best-fit value:

$$m_\nu^2 = -0.14^{+0.13}_{-0.15}\ \mathrm{eV}^2$$

- Compatible with 0 within $\sim 1\sigma$
- Good agreement between both analysis methods (KaFit and Netrium)
- Negative mass values allowed to obtain continuous likelihood in case of statistical fluctuations



Limit Setting

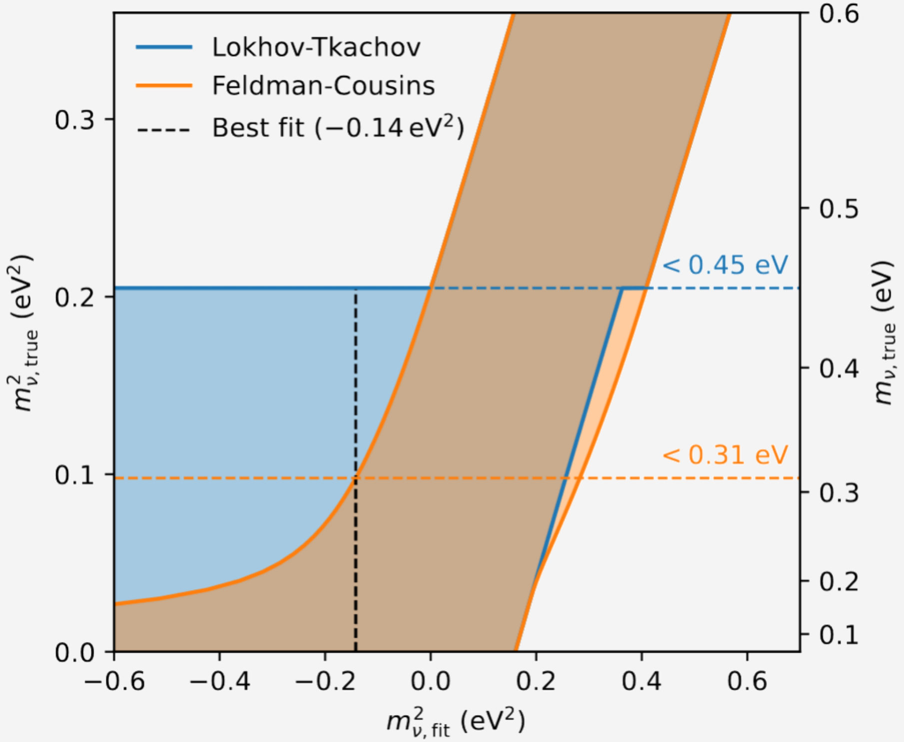
- Upper limit from Lokhov-Tkachov construction

$$m_\nu < 0.45 \text{ eV } (90\% \text{ C.L.})$$

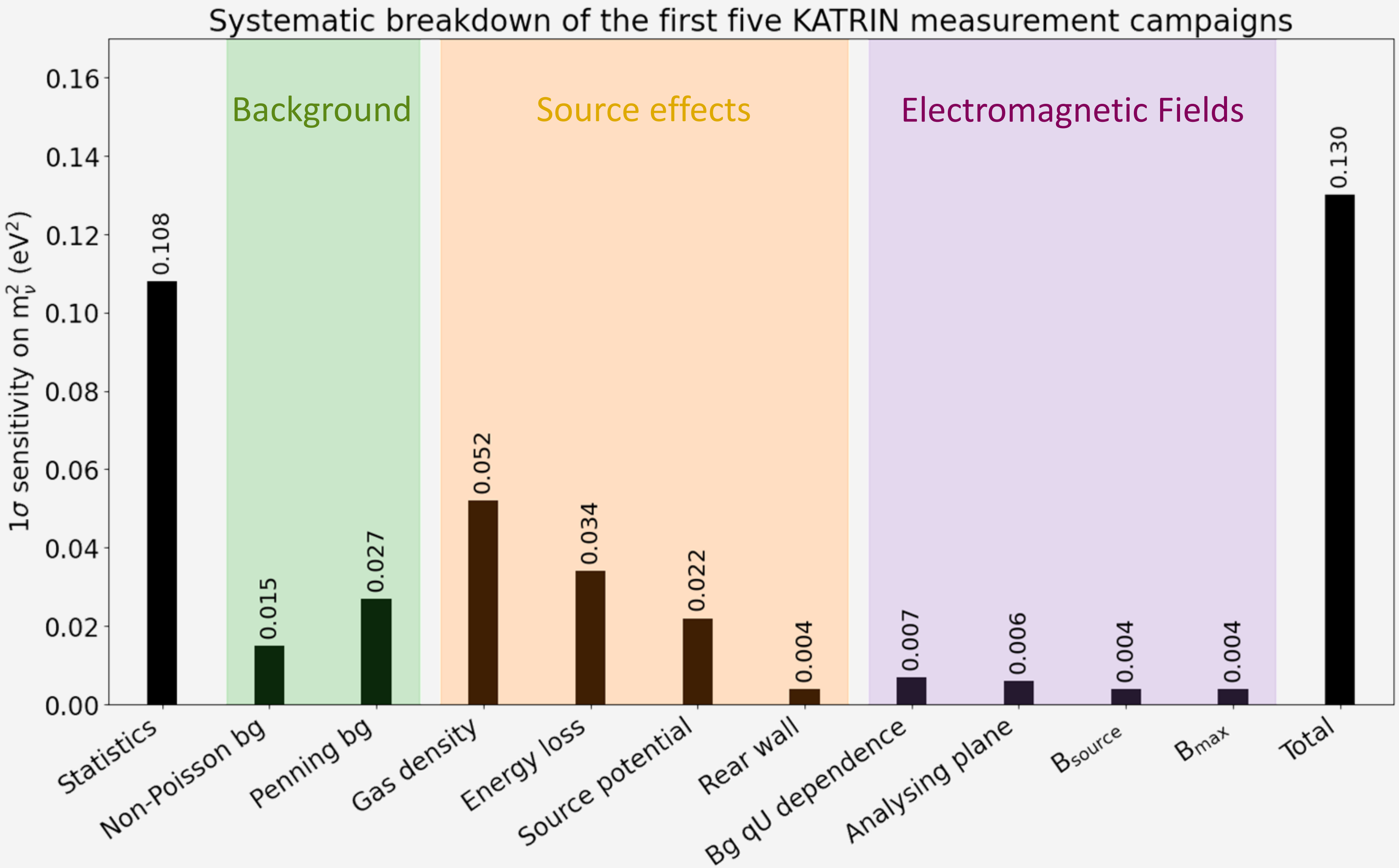
→ Returns sensitivity for negative m_ν^2 best fits
→ Statistical underfluctuations do not produce stricter limit
→ More conservative approach than Feldman-Cousins

- Upper limit from Feldman-Cousins construction

$$m_\nu < 0.31 \text{ eV } (90\% \text{ C.L.})$$

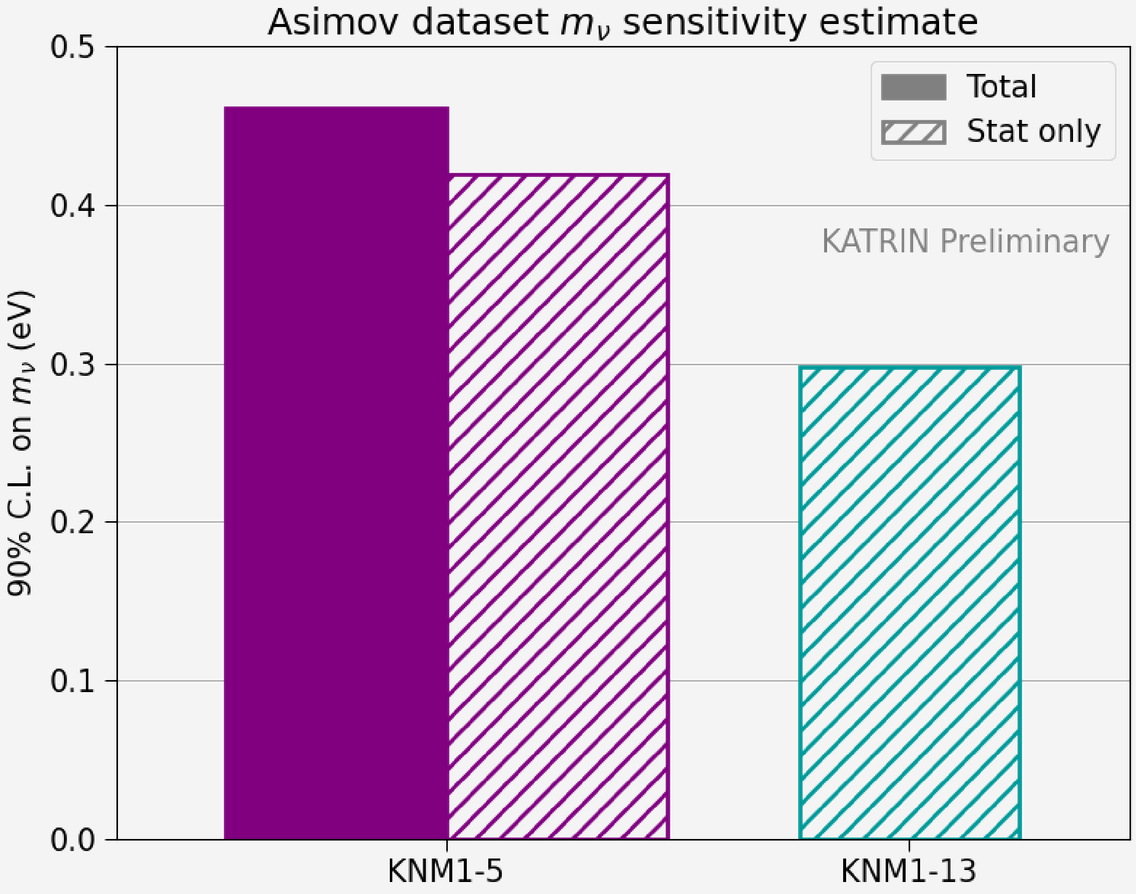


Uncertainty Breakdown



Statistical uncertainty outlook

- Collected data until summer 2024 improves statistical sensitivity to 0.3 eV
- Computational challenge grows
  → 6313 data points and 682 free fit parameters (KATRIN Final)
  → Additional analysis steps on Asimov data
- KATRIN final sensitivity after 1000 measurement days expected to be below 0.3 eV



Summary & Outlook

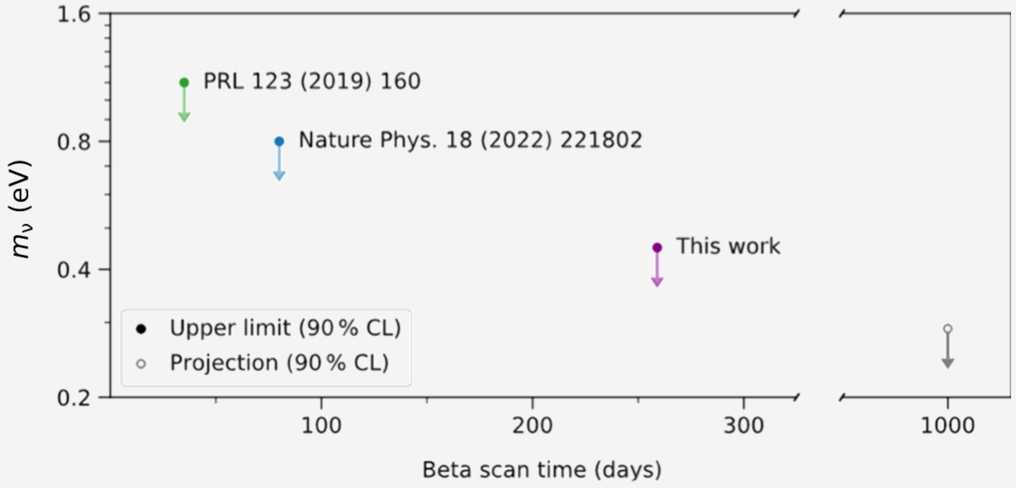
- KATRIN improved upper limit with data from only first 5 science runs

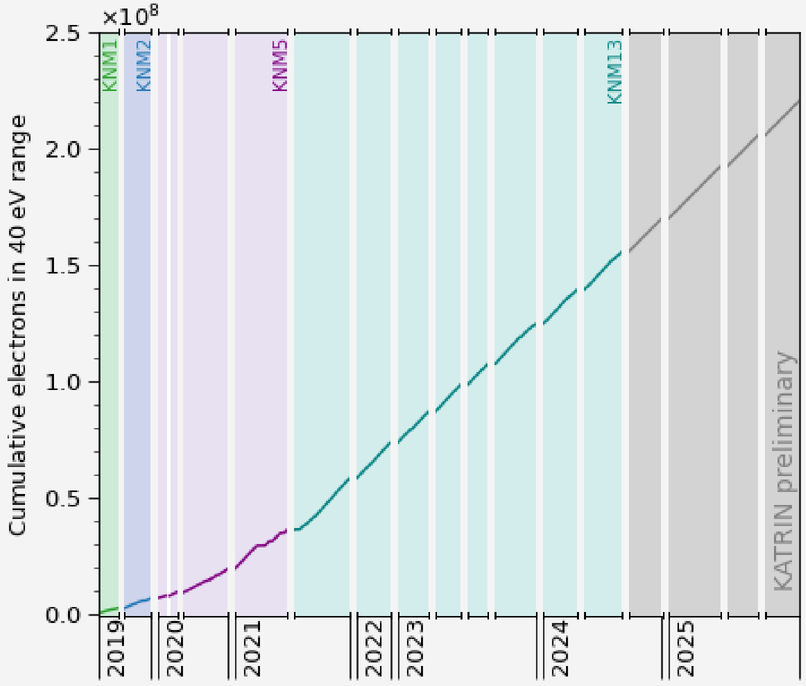
$$m_\nu < 0.45 \text{ eV } (90\% \text{ C.L.})$$

- Preprint available here: arXiv:2406.13516

- Bayesian analysis and BSM searches in preparation

Data taking ongoing until end of 2025
→ Expected sensitivity $m_\nu < 0.3$ eV (90% C.L.)





SUPPLEMENT

Post-Unblinding Changes

Data Combination:

- Split KNM4 into two separate periods: **KNM4-NOM** and **KNM4-OPT**

Re-Evaluation of systematic parameters:

- Column density:
  Take into account new measurements that suggest energy-dependency of electron angle from mono-energetic photoelectron source.
- Energy-loss function:
  Upscaled uncertainty to cover tension between different measurement modes
  (integral and time-of-flight)
- Penning-trap-related background:
  Model changed from linear to quadratic to be consistent with simulations and dedicated measurements
- Rear-wall residual tritium:
  Resolved small discrepancies

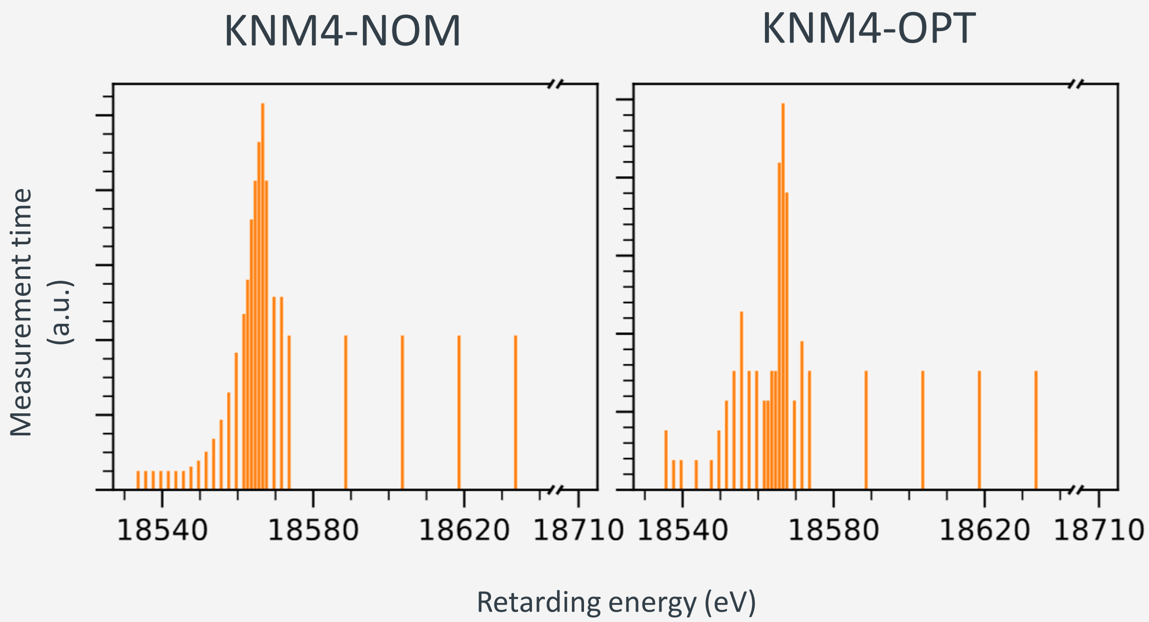
KNM4 Data Combination

Split KNM4 into KNM4-NOM and KNM4-OPT
→ nominal and optimized time distribution

- Source potential drift of 60 mV during KNM4 was not taken into account

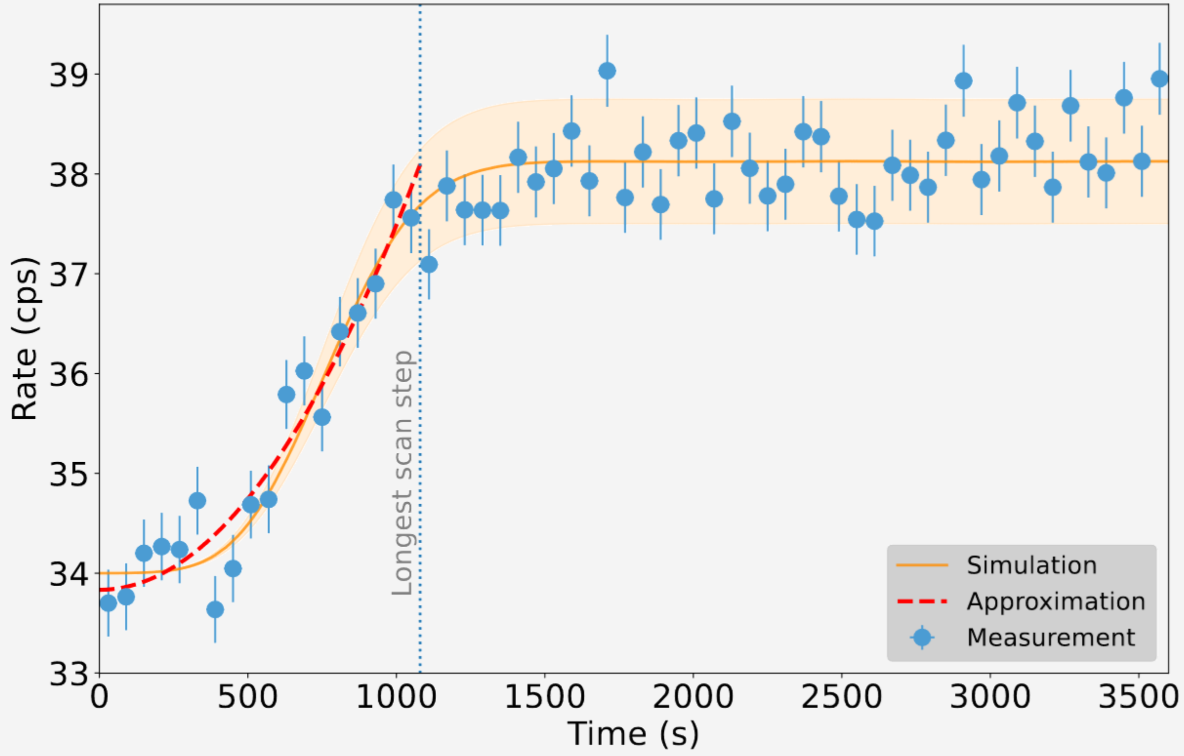
→ Modification causes shift of m_ν^2 by -0.1 eV^2

→ Additional analysis steps before unblinding in the future



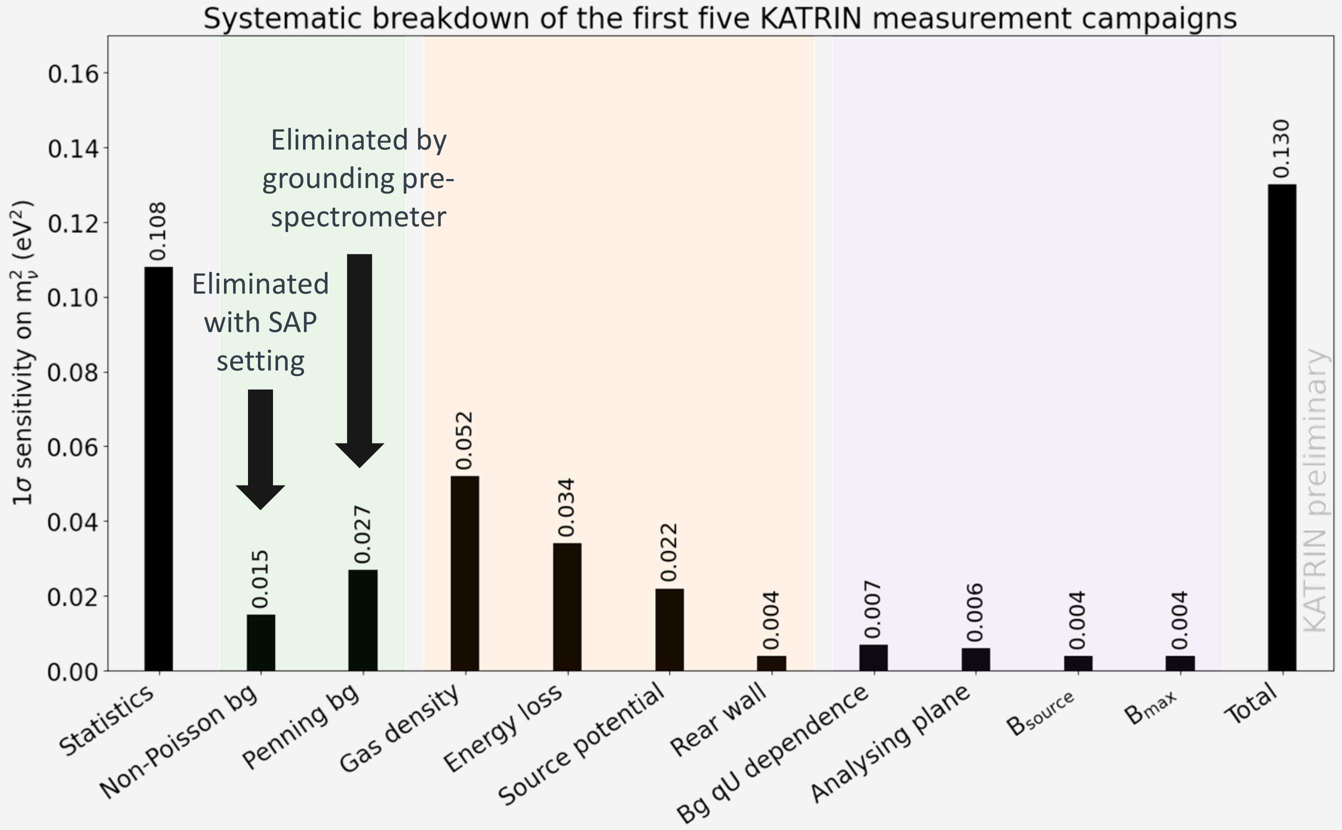
Penning-Trap-Related Background

- Inter-spectrometer Penning trap where electrons accumulate over time
- Production of positive ions that travel into main spectrometer
  → Creation of low-energy background electrons
- Scan-step-duration-dependent background rate
- Effect mitigated by grounding pre-spectrometer



Uncertainty Breakdown

- 3 categories of systematic uncertainties
  - Background
    → Fully mitigated through spectrometer configuration
  - Source effects
    → Dominant effects from gas density and energy loss will be reduced through hardware and analysis improvements in the future
  - Electromagnetic Fields



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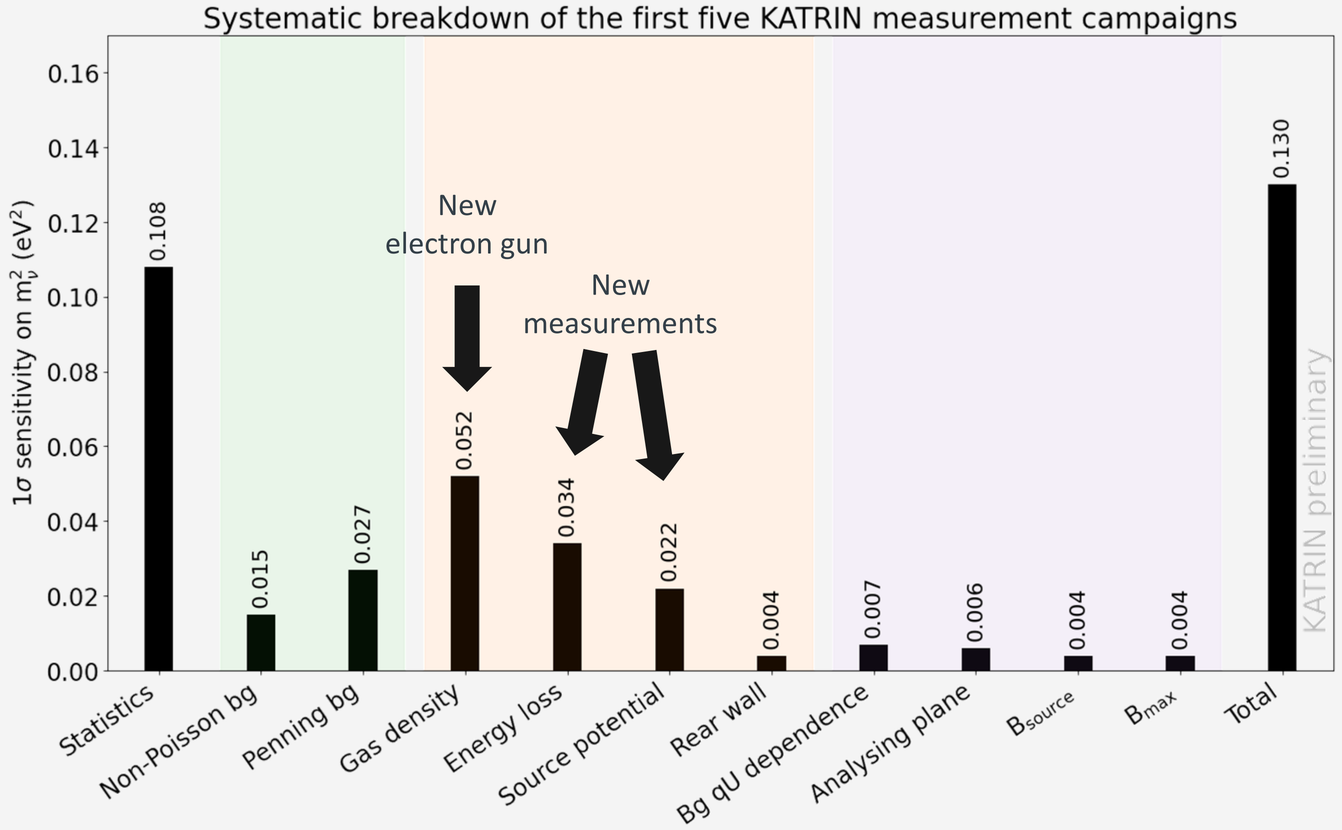
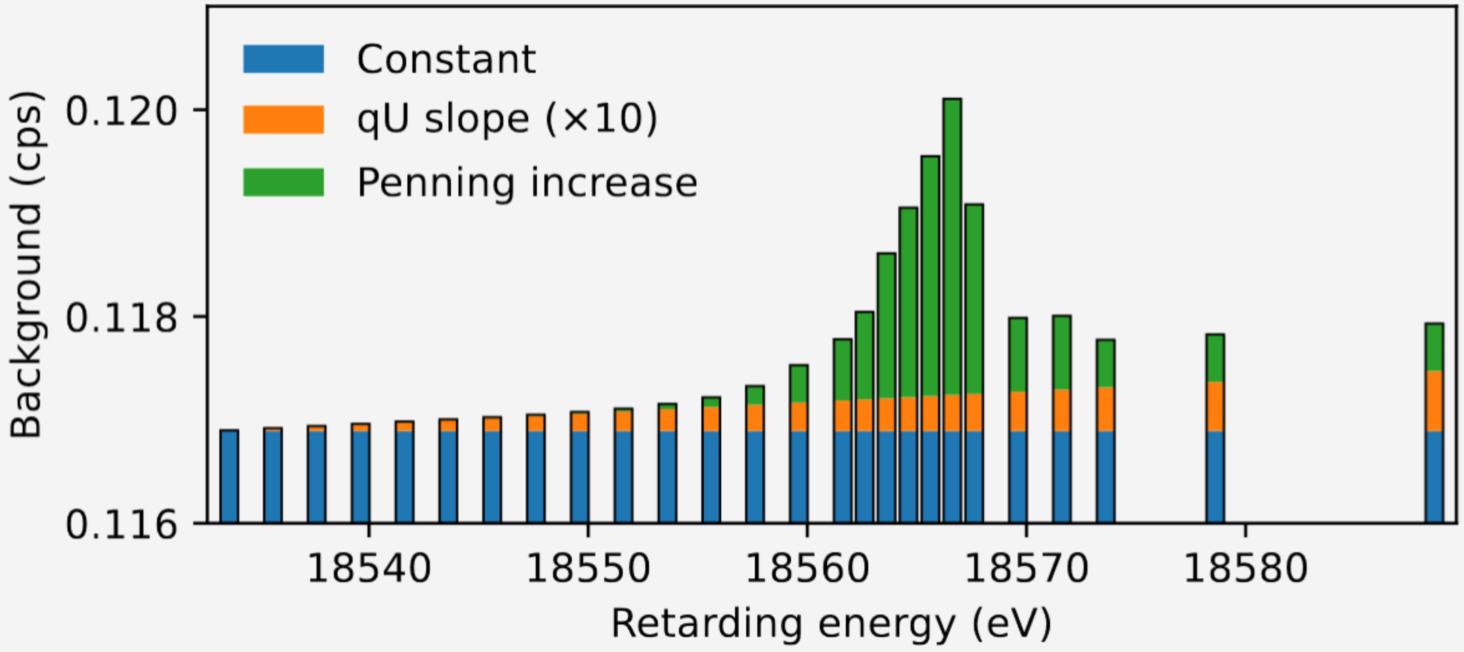


Backgrounds



Model Blinding

- Unknown broadening of molecular final state distribution
- Creates unknown shift of m_ν^2