Fitting strategies for the KATRIN neutrino mass analysis using KaFit

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The KATRIN experiment

The KATRIN collaboration aims to determine the effective electron antineutrino mass with a sensitivity of $0.2\,\text{eV}/c^2$ (90 % CL)

The endpoint region of the tritium β-electron spectrum is measured and fit to obtain the fit parameters:

- Neutrino mass squared, m_ν^2
- Tritium endpoint energy, E_0
- Signal amplitude, Sig
- Background rate, Bg

Measured data from the tritium β-spectrum is fit by minimising the negative log likelihood, $-\log\mathcal{L}\left(m_\nu^2, E_0, \text{Sig}, \text{Bg}\right)$

Multi-fitting

Tritium β-electron spectra are collected with high statistics:

- **Spatially:** over 148 detector pixels
- **Time-wise:** iteratively over many runs and measurement phases

To obtain one final result on the effective electron antineutrino mass data from all pixels and measurement phases must be combined

The multi-fitting strategy
Spectra: No averaging of data, all information is in resulting spectra
Parameters: Fit parameter can be radially and time-wise evolving

$$-\log\mathcal{L} = \sum_{i=1} -\log\mathcal{L}_i\left(m_\nu^2, E_{0i}, \text{Sig}_i, \text{Bg}_i\right)$$

The model spectra are calculated for every set of inputs, the negative log likelihoods are summed and minimised to obtain the fit parameters

Monte Carlo

Asimov data sets were simulated using realistic run conditions from four example measurement phases:

- Parameters (column density, tritium purity) are from measurement data
- Pixel-wise magnetic/electric fields are from measurements data
- Monte Carlo truth is inserted for the fit parameters: m_ν^2, E_0, Sig, Bg

	m_ν^2 (eV^2)	E_0 (eV)	Sig	Bg (cps)
Measurement phase *a*	0.0	18 573.700	1.186	0.369
Measurement phase *b*	0.0	18 573.572	1.186	0.271
Measurement phase *c*	0.0	18 573.613	1.182	0.275
Measurement phase *d*	0.0	18 573.507	1.187	0.287

The neutrino mass bias arising from data combination can be quantified by fitting the Monte Carlo data sets

Pixel combination

Pixels can be combined in any desired pattern, summing negative log likelihoods over rings, pixels, or segments
Examples include uniform, multi-ring, and multi-pixel (using "stacked" run combination):

Uniform fit

Multi-ring fit

Multi-pixel fit

- 1 spectrum
- $1 -\log\mathcal{L}$
- $1\times E_0$, Sig, Bg
- $1\times m_\nu^2$
- m_ν^2 bias $<5\times 10^{-3}\,\text{eV}^2$

- 12 spectra
- 12 summed $-\log\mathcal{L}$
- $12\times E_0$, Sig, Bg
- $1\times m_\nu^2$
- m_ν^2 bias $<3\times 10^{-3}\,\text{eV}^2$

- 148 spectra
- 148 summed $-\log\mathcal{L}$
- $148\times E_0$, Sig, Bg
- $1\times m_\nu^2$
- m_ν^2 bias $<1\times 10^{-3}\,\text{eV}^2$
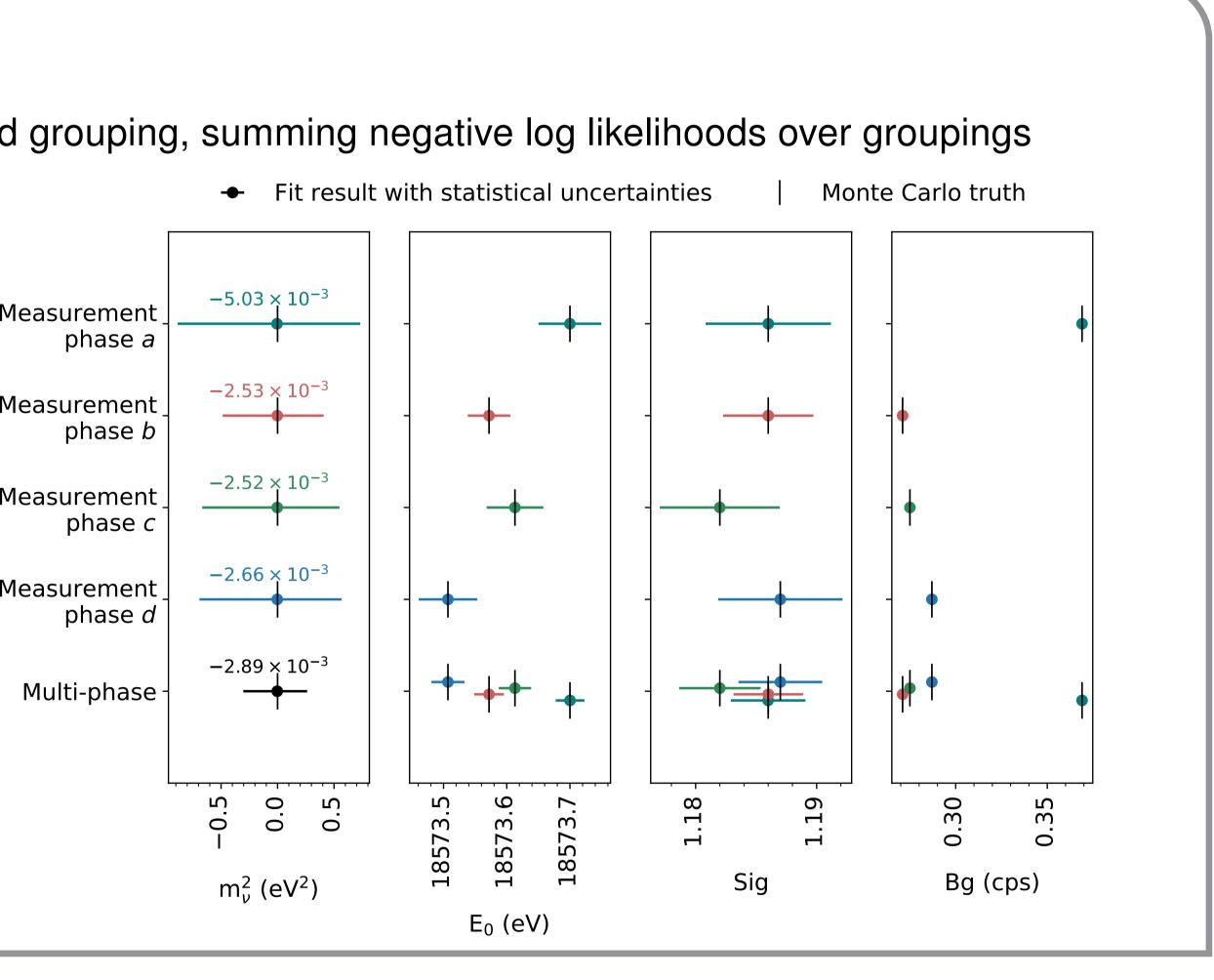
Run combination

Runs can be combined in any desired grouping, summing negative log likelihoods over groupings
Examples include combining N runs or N measurement phases:

- N spectra
- N summed $-\log\mathcal{L}$
- $N\times E_0$, Sig, Bg
- $1\times m_\nu^2$

Within a measurement phase runs can be "stacked" where HV set points and input parameters are averaged

Neutrino mass bias on Monte Carlo measurement phases *a*, *b*, *c*, and *d* (using uniform pixel combination):

$$m_\nu^2 \text{ bias} <3\times 10^{-3}\,\text{eV}^2$$

$\Longrightarrow$ On the same order as that from the individual measurement phases

Future fit strategies using multi-fitting

Systematics
- Can be included via pull term or Markov Chain Monte Carlo (MCMC)

Multi-fitting is fully flexible and versatile
- Data can be fit with any pixel combination and run combination together to further reduce bias on the neutrino mass result
- Every fit parameter can be either free or held constant to study spatial and time patterns (e.g. radial B-fields, Bg evolution)
- Relationships between any input or fit parameters can be fit (e.g. the linear relation, $\text{Bg} = \text{Bg}_{\text{slope}} \times \text{ring} + \text{Bg}_{\text{base}}$)

Multi-fitting enables the combined analysis of multiple β-electron spectra measured with KATRIN to obtain a final result on the effective electron antineutrino mass