Analysis of KATRIN Data Using Monte Carlo Propagation

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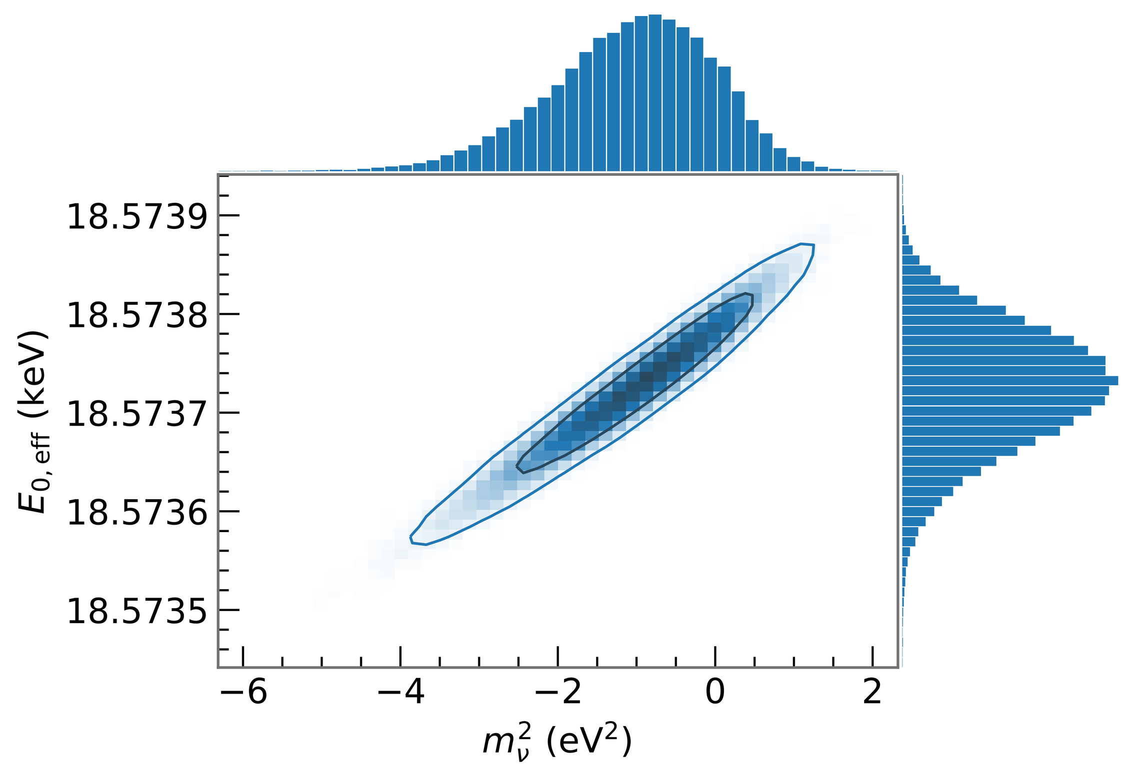
First Neutrino Mass Measurement [1]

- KATRIN is designed to determine the effective electron anti-neutrino mass $m_\nu = \left(\sum_i |U_{ei}|^2 \cdot m_i^2\right)^{\frac{1}{2}}$ by investigating the energy spectrum of tritium β-decay electrons near the endpoint of ≈ 18.574 keV
- First neutrino mass data was taken between April 10 and May 13 2019
- Around 2 million counts in the analysed dataset
- We present one of our analysis methods: Monte Carlo propagation (MC prop.)
- Our fit to this data including all dominant systematic effects leads to a best-fit value of $m_\nu^2 = -1.0^{+0.9}_{-1.1}\,\mathrm{eV}^2$
- From this result we derive an upper limit of $m_\nu < 1.1\,\mathrm{eV}$ (90 % C.L.) which coincides with our sensitivity



m_ν^2-$E_{0,\mathrm{eff}}$ distribution with 1- and 2-σ ellipses from MC prop.

Basis: Fit Function and Likelihood

KATRIN measures an integrated tritium β-spectrum:

$$N(qU;\boldsymbol{\theta}) = A \cdot \int_{qU}^{E_{0,\mathrm{eff}}} D(E;m_\nu^2,E_{0,\mathrm{eff}}) \cdot R(qU,E)\,\mathrm{d}E + N_\mathrm{bkg}$$

Free parameters $\boldsymbol{\theta}$

m_ν^2	Effective electron anti-neutrino mass
$E_{0,\mathrm{eff}}$	Effective endpoint of the β-spectrum
A	Signal amplitude
N_bkg	Constant background

Poisson likelihood:

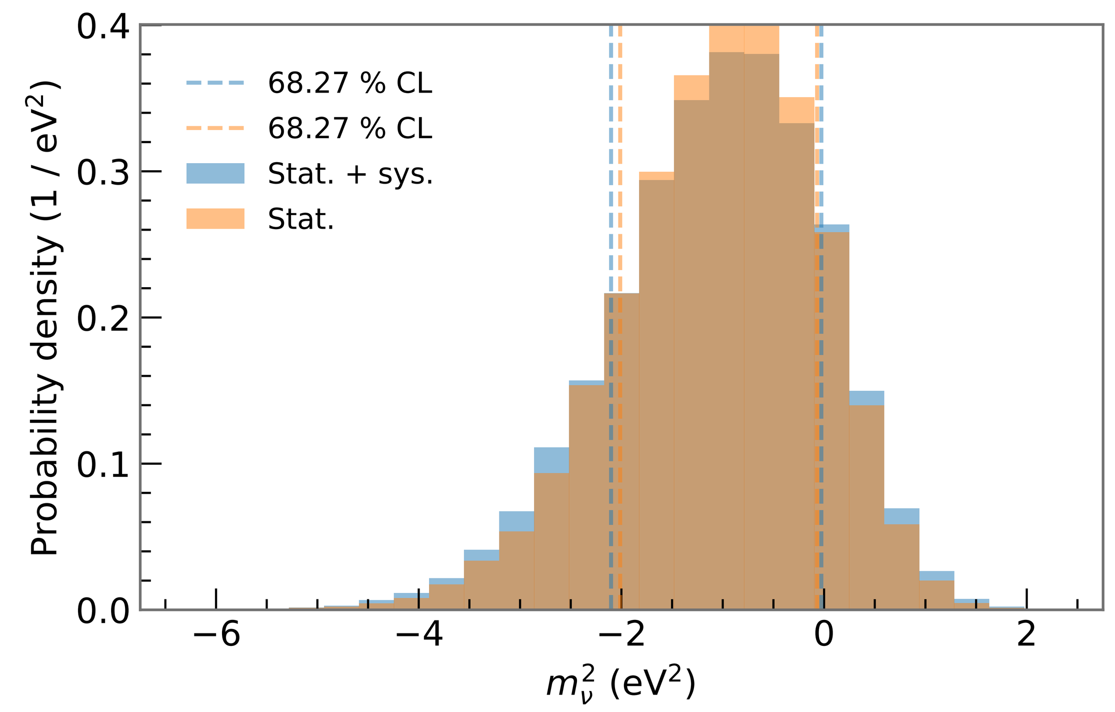
- Likelihood $\mathcal{L}(\text{data}|\text{model}) = \prod_i \mathcal{P}_i(d_i|N_i)$
- Poisson distribution assumed for $\mathcal{P}$
- Maximize likelihood with respect to the free parameters $\boldsymbol{\theta}$

At this step any nuisance parameters are fixed to their best-estimate.

Systematics Treatment: Monte Carlo Propagation of Uncertainty [2, 3]

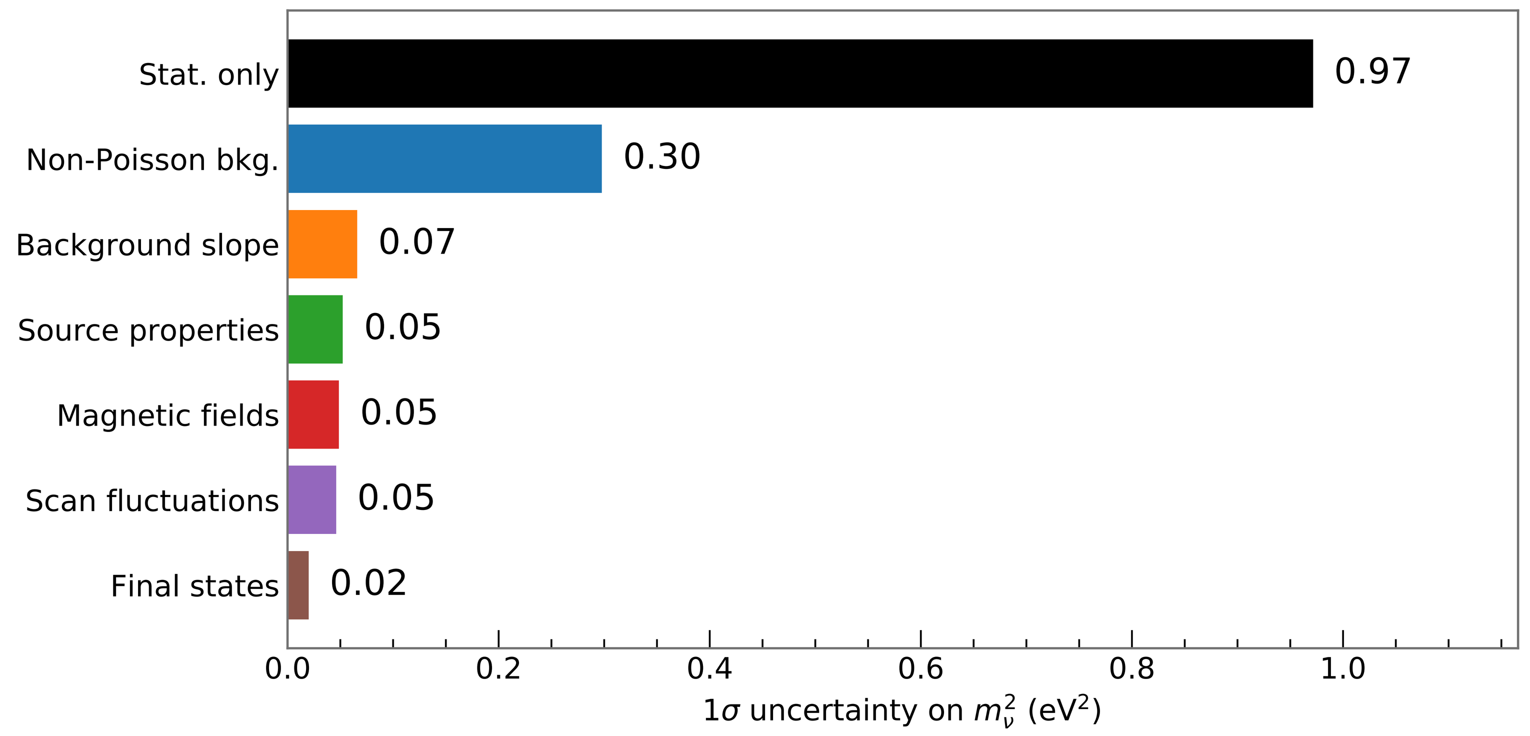
1. Retrieve initial model from a stat. only fit to the data as described in "Basis"
2. Vary nuisance parameters according to 1-σ systematic uncertainties
3. Fit varied model to statistically fluctuated MC spectrum assuming the initial model to get parameter values
4. Fit varied model to data to determine the likelihood value used as "weight"
5. Repeat often (≈ 10^4-times) to retrieve the distribution of model parameters using the values from 3 and the weights from 4
6. Infer best-fit (mode) and uncertainties (central confidence interval) from the weighted parameter distributions

Option to perform analysis with statistical uncertainty, systematic uncertainty or both to retrieve an uncertainty breakdown as well as the final confidence interval.



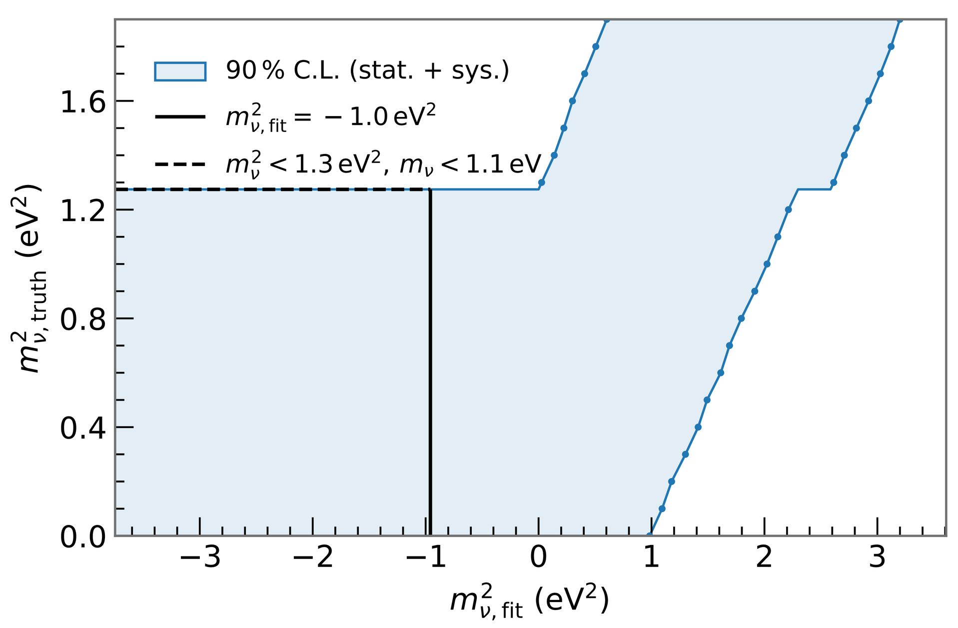
m_ν^2-distribution with 1-σ intervals from MC prop. The parameter values come from step 3 and are weighted by the likelihood retrieved in step 4.

Application: Uncertainty Breakdown

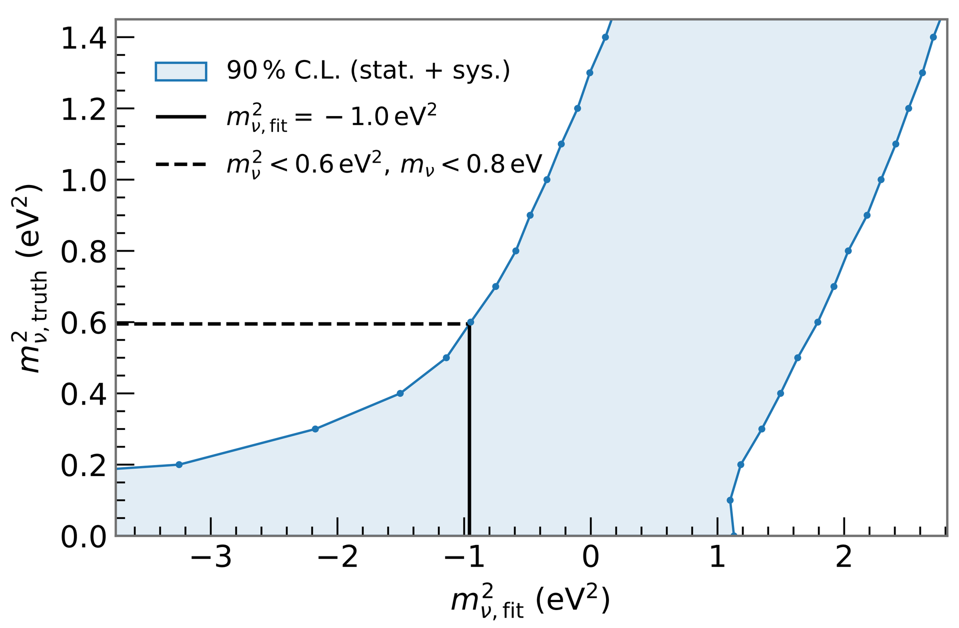


Uncertainty breakdown for the first neutrino mass measurement. To retrieve the individual contributions the Monte Carlo propagation was performed with only the corresponding source of uncertainty activated.

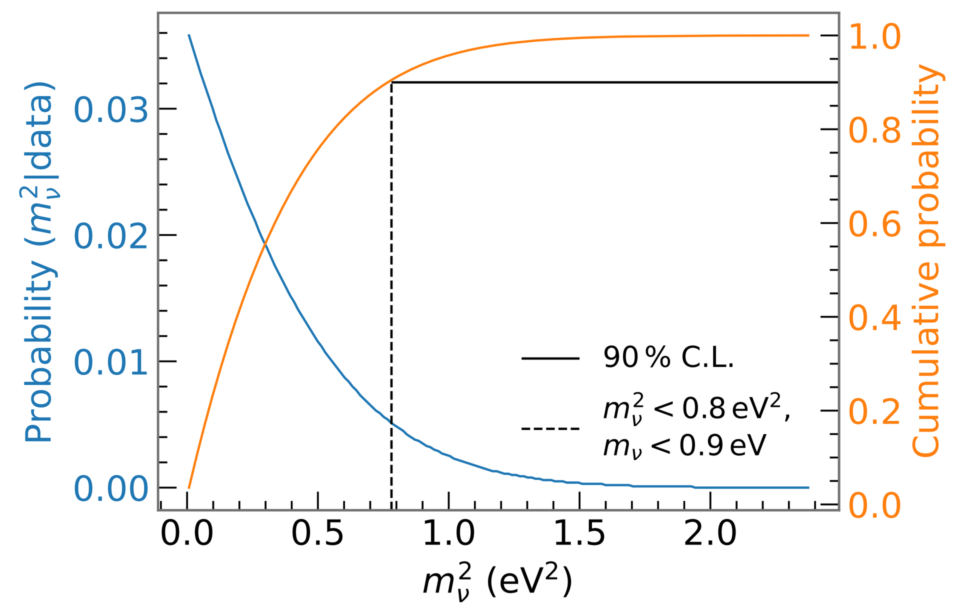
Retrieving the Confidence/Credible Interval: Frequentist Belt or Bayesian Inference



Lokhov-Tkachov belt [5]

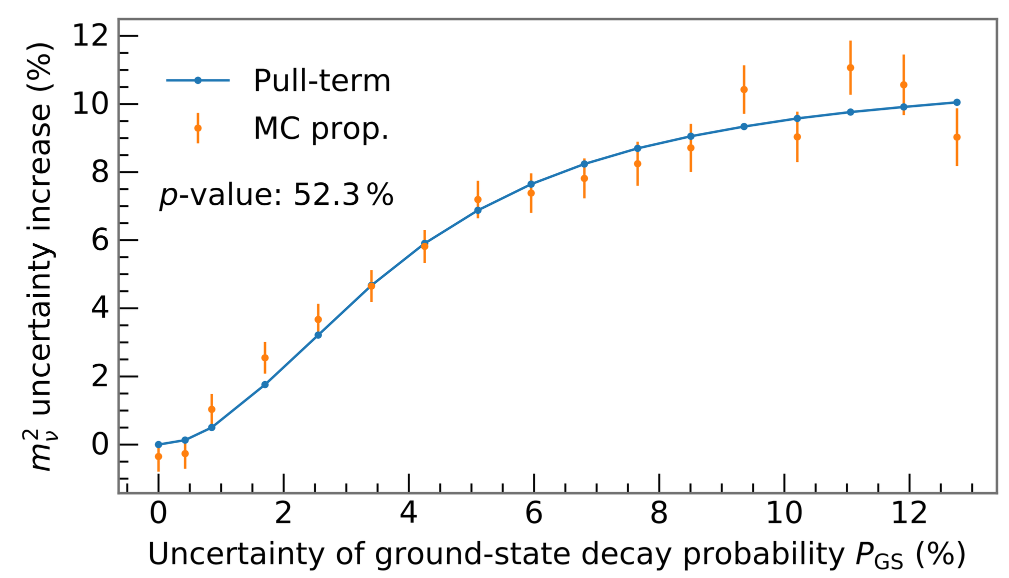


Feldman-Cousins belt [4]



Bayesian posterior with flat prior for $m_\nu^2 > 0\,\mathrm{eV}^2$

Comparison to Pull-Term Method



Comparison of pull-term method with MC prop. using the uncertainty of P_GS as proxy. The error-bars are due to the finite sample size and were estimated using resampling.

References

[1] M. Aker et al. Improved upper limit on the neutrino mass from a direct kinematic method by katrin. *Phys. Rev. Lett.*, 123:221802, Nov 2019.

[2] R. D. Cousins and V. L. Highland. Incorporating systematic uncertainties into an upper limit. *Nucl. Instrum. Meth. A*, 320(1):331 – 335, 1992.

[3] G. Cowan, K. Cranmer, E. Gross, and O. Vitells. Asymptotic formulae for likelihood-based tests of new physics. *The European Physical Journal C*, 71(2):1554, Feb 2011.

[4] G. J. Feldman and R. D. Cousins. Unified approach to the classical statistical analysis of small signals. *Phys. Rev. D*, 57:3873–3889, Apr 1998.

[5] A. V. Lokhov and F. V. Tkachov. Confidence intervals with a priori parameter bounds. *Phys. Part. Nuclei*, 46(3):347–365, May 2015.

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