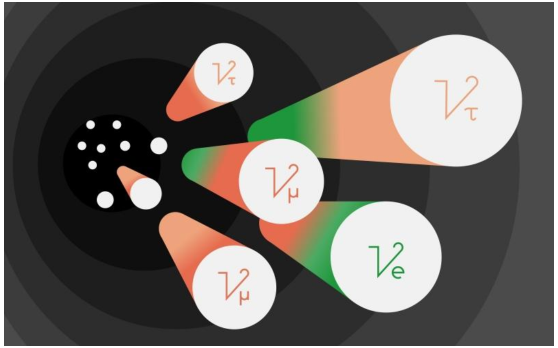
KATRIN Neutrino Experiment

Based on the report by: M. Aker, et al.

Neutrino Background

- Most abundant particle
- Lightest subatomic particle to have mass (very small though)
- Fundamental particle
- 3 flavors: Tau neutrinos, electron neutrinos and mu neutrinos

ν_τ ν_e ν_μ



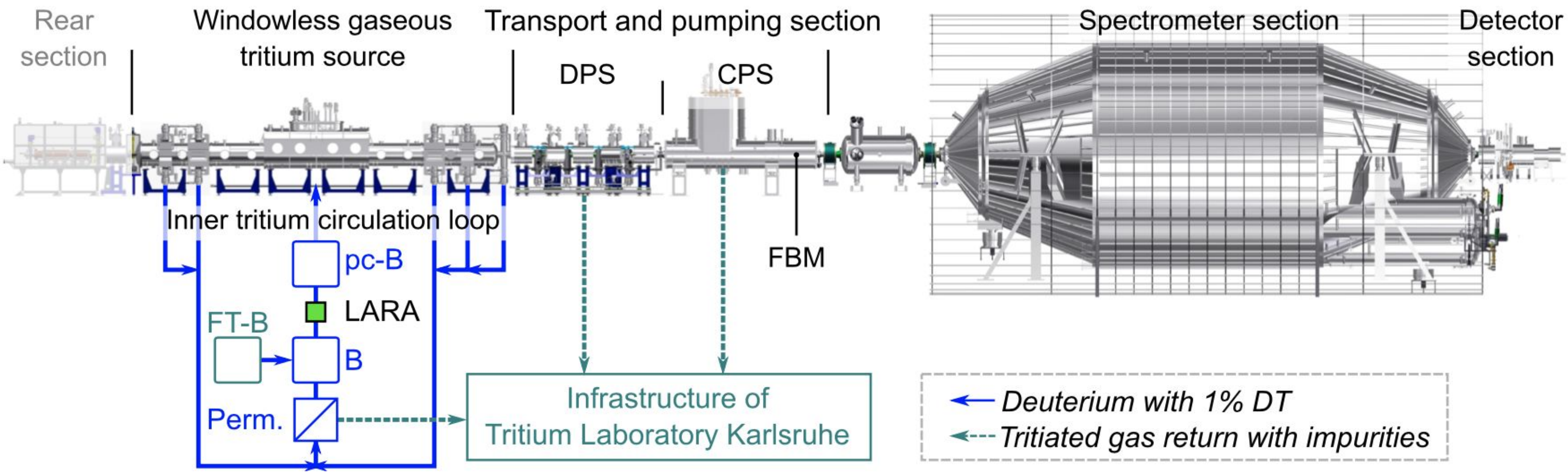
What is KATRIN?

- Karlsruhe Tritium Neutrino experiment
- Designed to directly measure effective $m_{\bar{\nu}_e}$
- Uses kinematics of Beta-decay to measure $m_{\bar{\nu}_e}$

Tritium Beta-Decay Formula

$$(T \rightarrow {}^{3}He^{+} + e^{-} + \bar{\nu}_e)$$

- Why Tritium?
- Relatively short half-life of 12.3 years
- Well-known theoretical representation
- Low endpoint of 18.6 keV


Rear section
Windowless gaseous tritium source
Transport and pumping section
Spectrometer section
Detector section
DPS
CPS
FBM
Inner tritium circulation loop
pc-B
LARA
FT-B
B
Perm.
Infrastructure of Tritium Laboratory Karlsruhe
Deuterium with 1% DT
Tritiated gas return with impurities

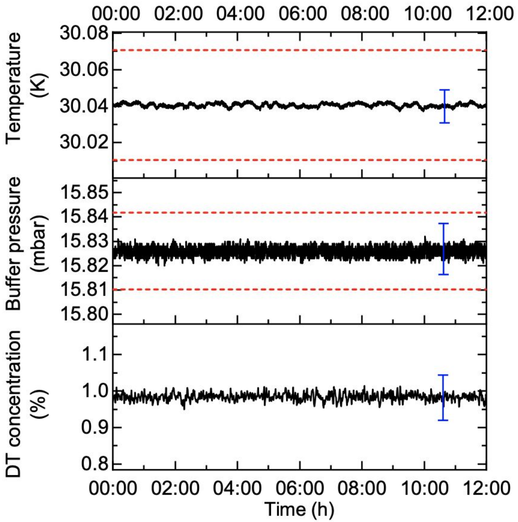
First Tritium Campaign

- To control rate of source stability, these parameters were closely monitored

    1. Beam tube temperature

    2. Buffer vessel pressure

    3. Isotopic purity

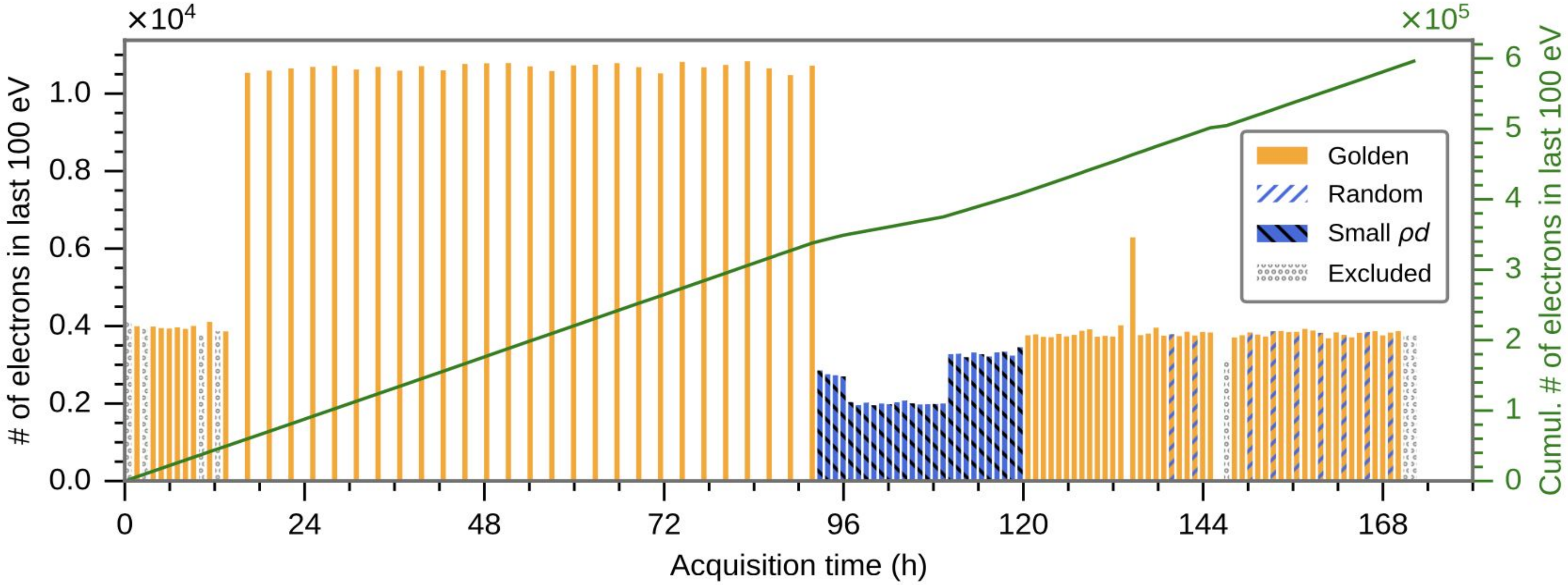


Spectral Measurement

- Obtained by applying different retarding energies to spectrometer
- Then counting the number of transmitted Beta-electrons with focal plane detector
- Applied in an increasing, decreasing, and random voltages
- Scans last from 1-3 hours
- Total of 122 scans and 168 hours, resulting in about 0.6 million electrons

$$t_{scan} = \Sigma t(qU_i)$$

Spectral Measurement (continued)



Beta-Decay Tritium Spectrum

$$R_{\mathrm{calc}}(qU_i) = A_{\mathrm{s}} N_{\mathrm{T}} \int_{qU_i}^{E_0} R_{\beta}(E) f_{\mathrm{calc}}(E, qU_i)\,\mathrm{d}E + R_{\mathrm{bg}}$$

- Derived in “Analysis of KATRIN Neutrino Experiment”

Differential Beta-Electron Spectrum and Experimental Response Function

$$R_\beta(E) = C \cdot F(E, Z') \cdot p \cdot (E + m_e) \cdot (E_0 - E)\sqrt{(E_0 - E)^2 - m_\nu^2}$$

Where $C = \frac{G_F^2}{2\pi^3}\cos^2\Theta_C|M_{\mathrm{nucl}}|^2$ and $m_\nu^2 = \sum_{i=1}^{3}|U_{ei}|^2 m_i^2$

$$f_{\mathrm{calc}}(E, qU_i) = \int_0^E T(E - \varepsilon, qU_i)\left(P_0\,\delta(\varepsilon) + P_1\,f(\varepsilon) + P_2\,(f \otimes f)(\varepsilon) + \ldots\right)\mathrm{d}\varepsilon$$

Observed Endpoint

- Setting the beginning of the spectra at 0, we need to find the cut-off energy of our fit:

$$E_0^{\mathrm{fit}} = E_0 + \Phi_{\mathrm{WGTS}} - \Phi_{\mathrm{MS}}$$

Data Selection

- Scan Selection: 40 scans were excluded due to parameter testing, 82 usable
- Pixel Selection: Some pixels were excluded (past detector range)
- Fit Range Selection: Data past $qU^{\mathrm{min}} = E_0 - 100\,\mathrm{eV}$ were irrelevant

Fitting Procedure

- Single-scan fit: to observe time-dependence of fit parameters
- Stacking: counts in sub-scans added to construct high statistics single spectrum but relies on high reproducibility of individual electron retarding energy settings
- Appending: eliminates the need for high producibility of individual electron retarding energy settings
- Single-pixel fit: to observe spatial dependence of fit parameters
- Uniform fit: detector pixels can be averaged because of transmission function to make calculations easier (but worsens energy resolution)
- Multi-pixel fit: all pixel dependent spectra are fitted simultaneously

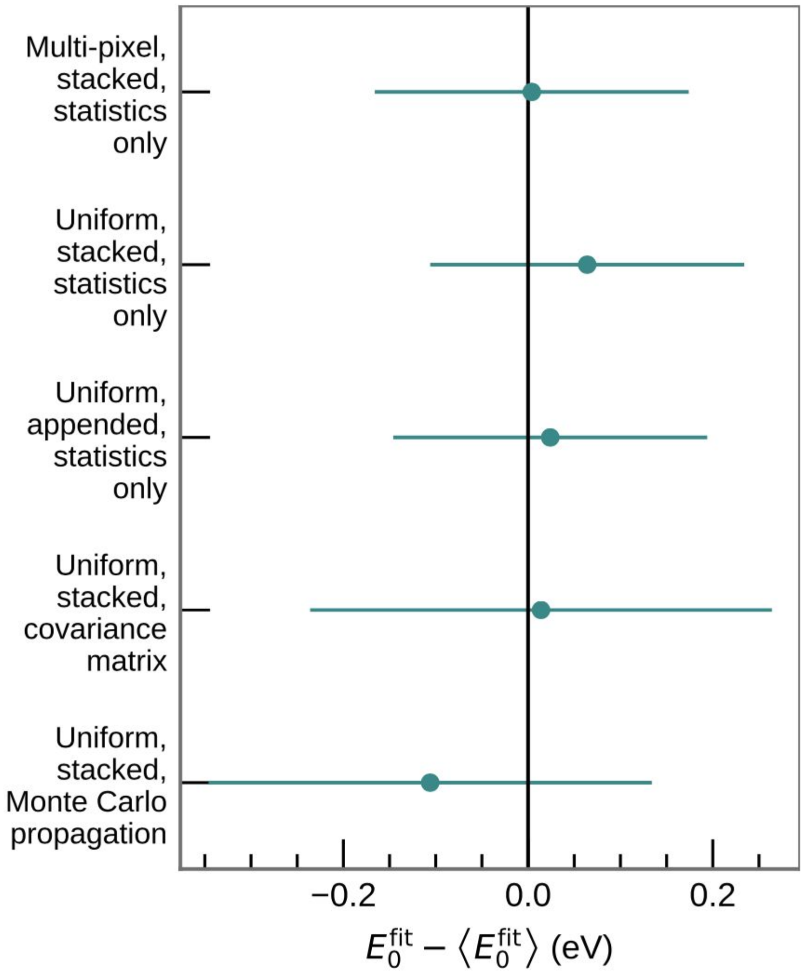
Treatment of Systematics

- Nuisance Parameters: can treat uncertainties as systematic parameters

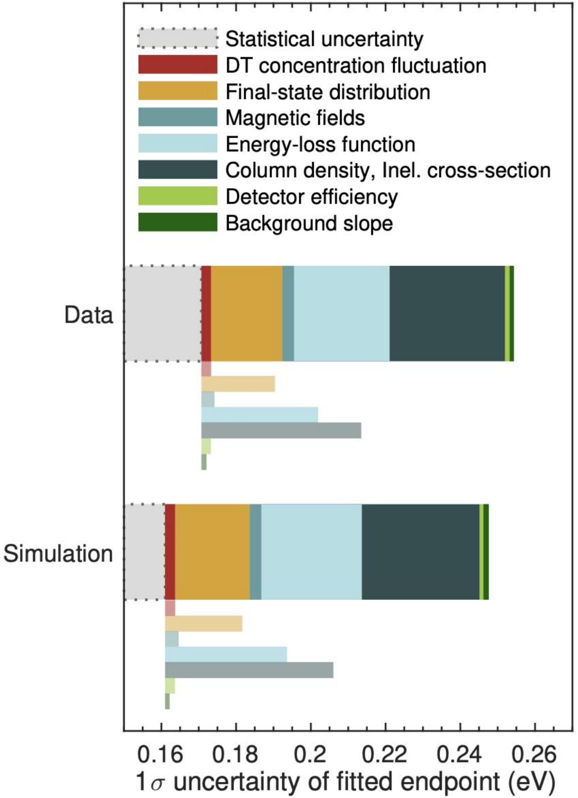
- Covariance Matrix: spectrum prediction is run thousands of times while changing system parameters each time to extract variances

- Monte Carlo Propagation: fit is varied instead to extract variances

- Maximum Error Estimation: shift method


Multi-pixel, stacked, statistics only
Uniform, stacked, statistics only
Uniform, appended, statistics only
Uniform, stacked, covariance matrix
Uniform, stacked, Monte Carlo propagation
−0.2
0.0
0.2
$E_0^{fit} - \langle E_0^{fit} \rangle$ (eV)

Systematic Uncertainties



- Systematic Budget
- Column Density
- Tritium Concentration
- Energy-loss Function
- Magnetic Fields
- Electric Potentials
- Final-State Distributions
- Detector Efficiency
- Background

Systematic Uncertainties (continued)

Effect	Description	1 σ uncertainty	1 σ uncertainty of fitted endpoint (eV)
Source scattering	Column density	3 %	0.13
	Inel. scat. cross-section	2 %	
DT concentration fluctuation	For single sub-scan (60 s)	1.5 %	
	For all scans combined (40 000 s)	0.08 %	0.03
Energy-loss function	Excitation peak position P_1	0.017 eV	0.11
	Ionization peak position P_2	0.18 eV	
	Excitation peak width W_1	0.05 eV	
	Ionization peak width W_2	0.13 eV	
	Normalization A	0.15 eV^{-1}	
Final-state distribution	Normalization	1 %	0.08
	Ground-state variance	1 %	
	Excited-states variance	3 %	
Magnetic fields	Source	2.5 %	0.03
	Analyzing plane	1 %	
	Maximum field at pinch	0.2 %	
Detector efficiency	Retarding potential dependence	0.1 %	0.03
Background	slope	5 mcps/keV	0.02
Gas density profile	on/off		< 0.01
Theoretical correction	on/off		< 0.01
Stacking	on/off		< 0.01
Total systematic uncertainty			0.19
Statistical uncertainty			0.17
Total uncertainty (stat. and syst.)			0.25

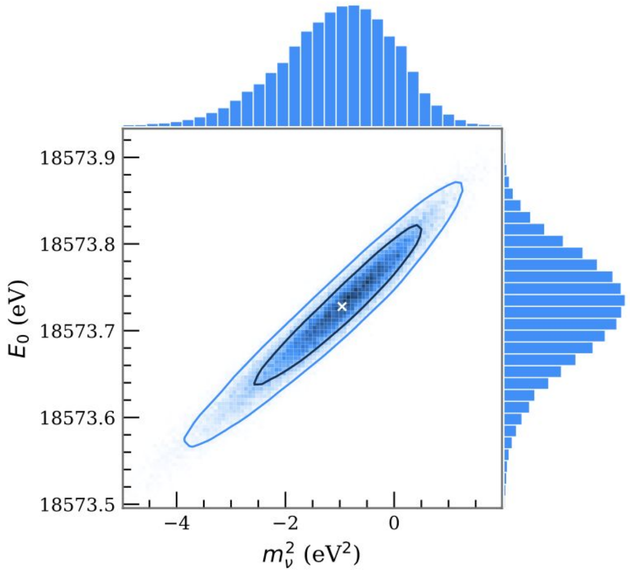
Results

- Combining all data of golden scans, treating golden pixels as single effective pixel, and performing a fit at $qU^{\min} = E_0 - 100\,\mathrm{eV}$ we get

$$E_0^{\mathrm{fit}}(\mathrm{DT}) = 18574.39 \pm 0.17(\mathrm{stat}) \pm 0.19(\mathrm{sys})\ \mathrm{eV}$$
$$= 18574.39 \pm 0.25(\mathrm{tot})\ \mathrm{eV},$$

Results (continued)

- Now that the ends of our spectra have been measured our best fit value is



$$m_\nu^2 = (-1.0 \, {}^{+\,0.9}_{-\,1.1}) \text{ eV}^2$$

$$\sigma_{stat} = 0.97eV^2$$

$$\sigma_{sys} = 0.32eV^2$$

Works Cited

M. Aker, et al. “First Operation of the KATRIN experiment with Tritium.” Karlsruhe Institute of Technology. 13 Sept. 2019. Research Publication. 7 Feb. 2022.

M. Aker, et al. “An Improved Upper Limit on the Neutrino Mass from a direct Kinematic Method by KATRIN.” Karlsruhe Institute of Technology. 13 Sept. 2019. Research Publicaiton. 7 Feb. 2022.

M. Aker, et al. “The KATRIN Neutrino Mass Results: An alternative Interpretation.” Karlsruhe Institute of Technology. 21 Nov. 2021. Research Publication. 7 Feb. 2022.