An improved upper limit on the neutrino mass from a direct kinematic method by KATRIN

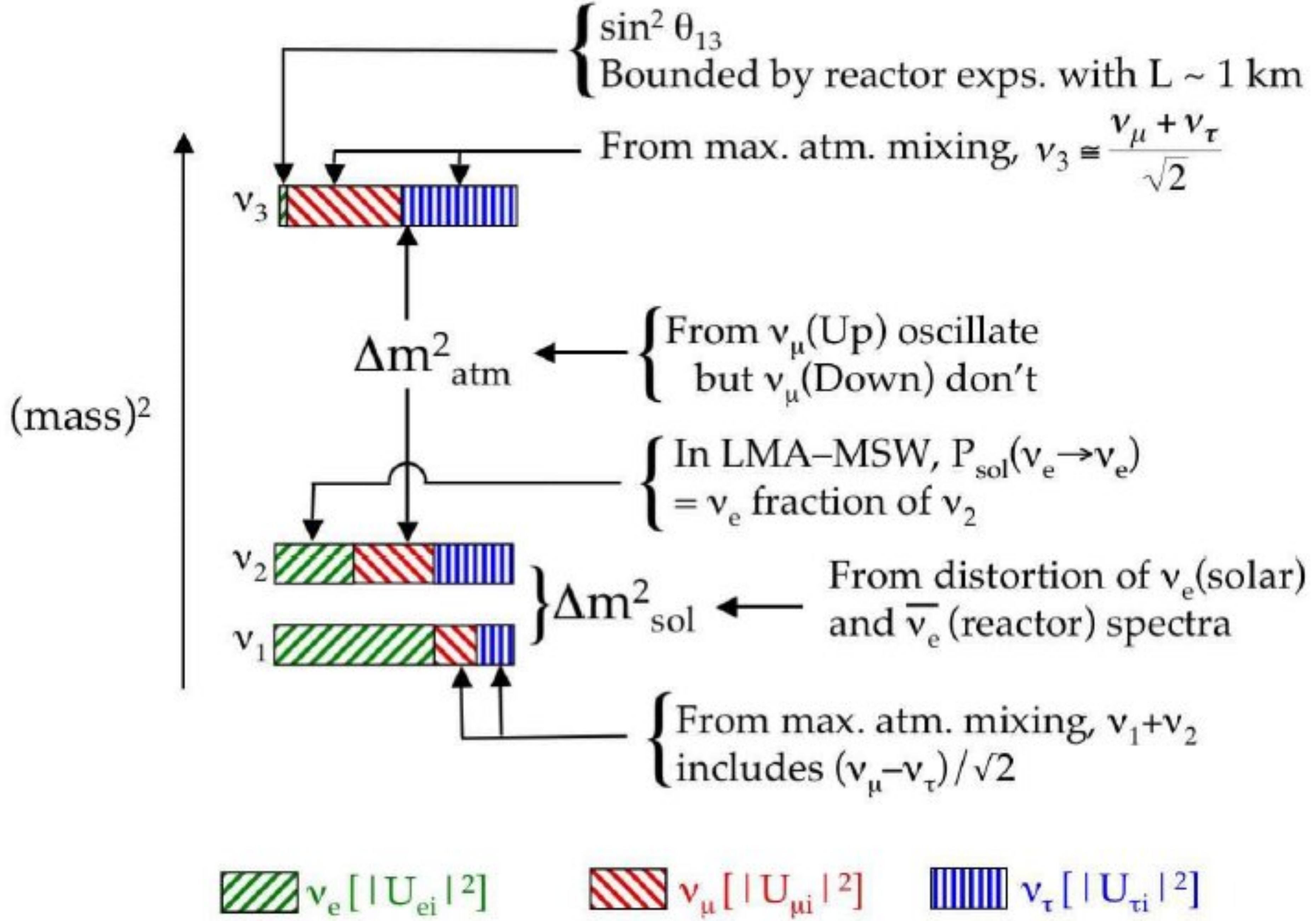
3 flavor eigenstates ν_e, ν_μ, ν_τ

3 mass eigenstates ν_1, ν_2, ν_3
Ordering 1-2-3 or 3-1-2 unknown

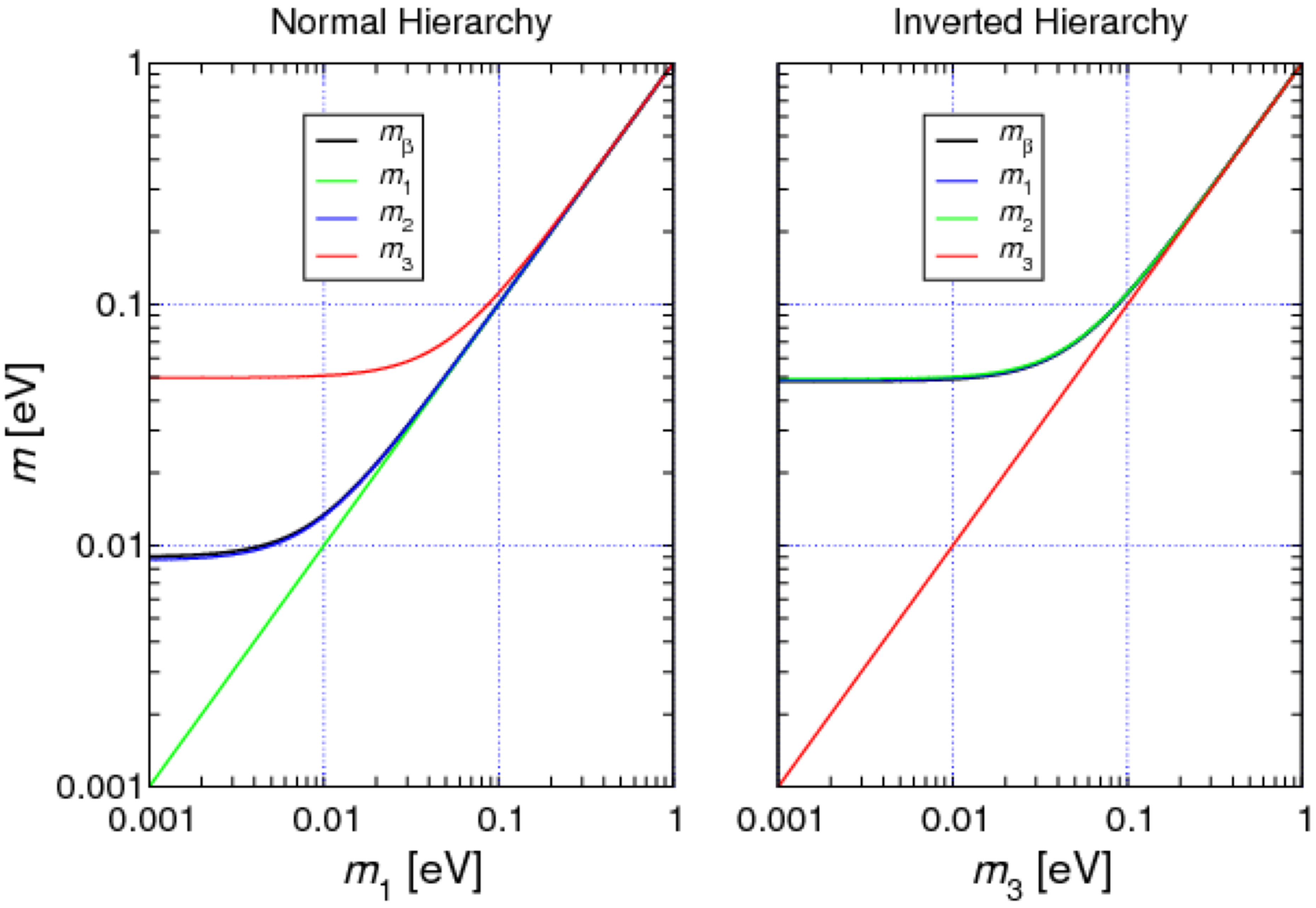
Constraints from cosmology on $\sum_i m(\nu_i)$ (i=1,2,3), but assume ΛCDM, and depend on data set

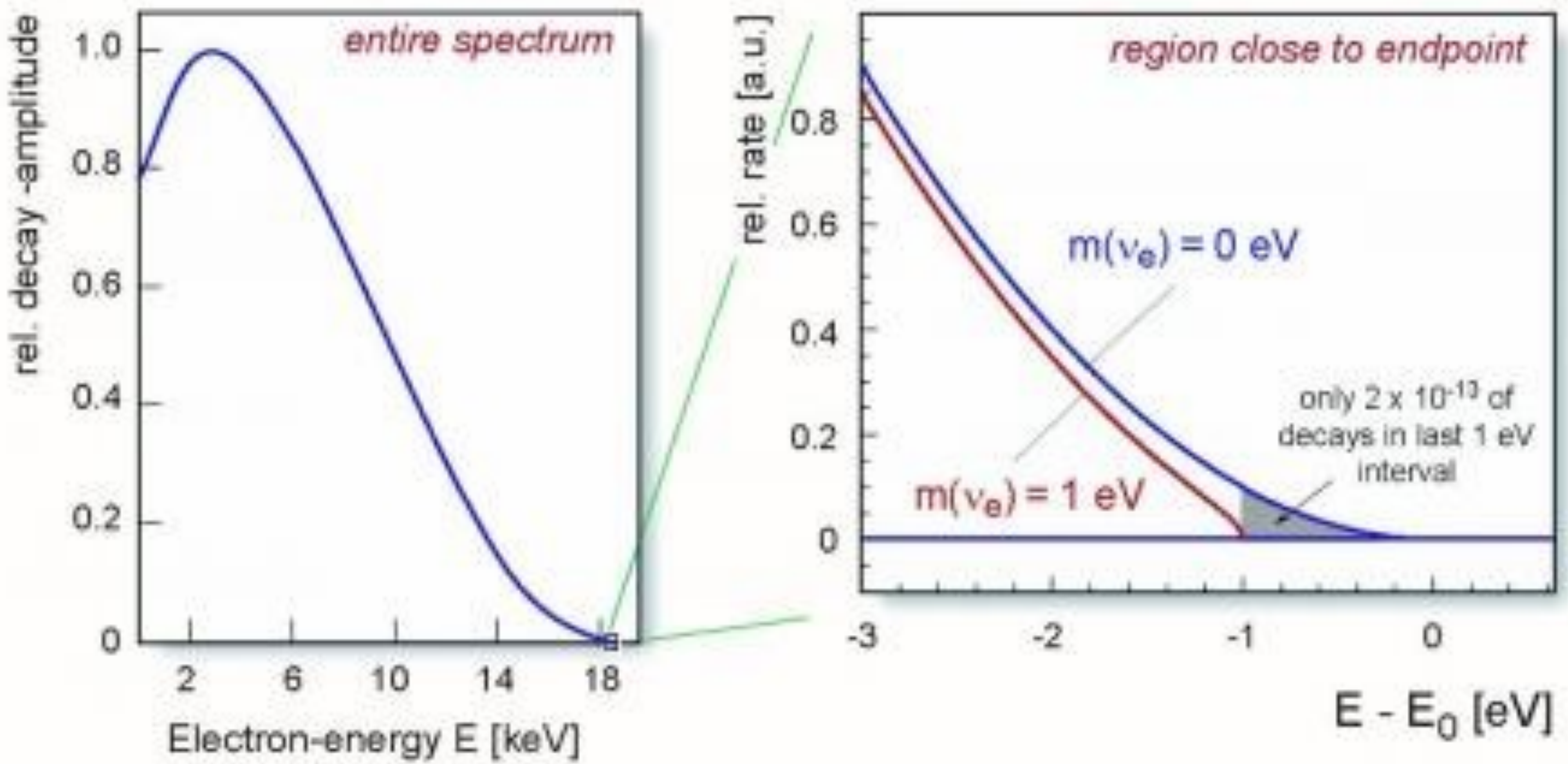
Model independent: beta decay: $m_\beta^2 = \sum_i |U_{ei}|^2 \, m(\nu_i)^2$

PMNS matrix

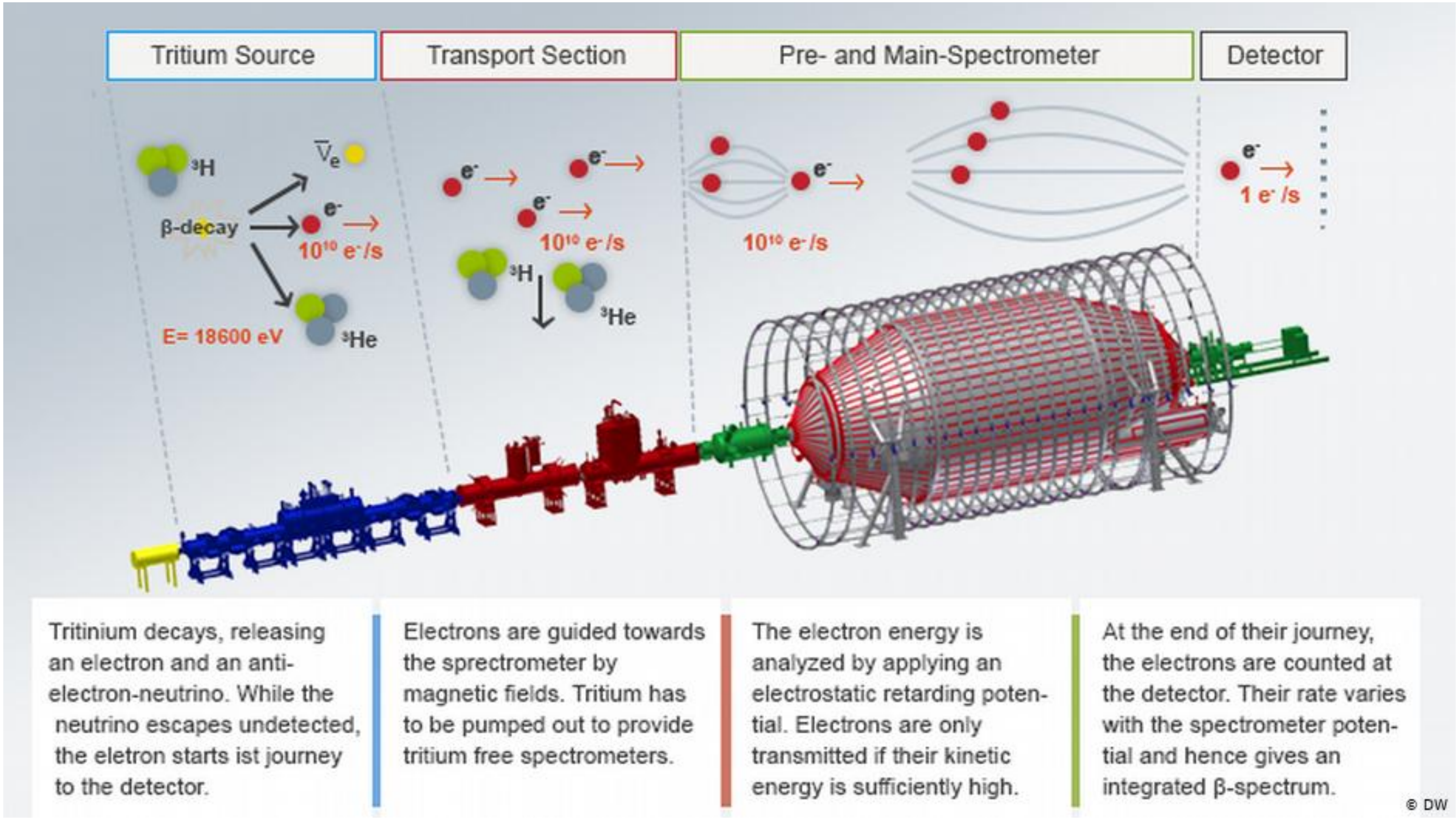


sin² θ13
Bounded by reactor exps. with L ~ 1 km
From max. atm. mixing, ν3 ≅ (νμ + ντ)/√2
ν3
Δm²atm
From νμ(Up) oscillate
but νμ(Down) don't
(mass)²
In LMA–MSW, Psol(νe→νe)
= νe fraction of ν2
ν2
ν1
Δm²sol
From distortion of νe(solar)
and ν̄e (reactor) spectra
From max. atm. mixing, ν1+ν2
includes (νμ–ντ)/√2
νe [|Uei|²]
νμ [|Uμi|²]
ντ [|Uτi|²]


Normal Hierarchy
Inverted Hierarchy
m_β
m_1
m_2
m_3
m_β
m_1
m_2
m_3
1
0.1
0.01
0.001
m [eV]
0.001
0.01
0.1
1
m_1 [eV]
0.001
0.01
0.1
1
m_3 [eV]



Due to its low endpoint energy ($E_0 = 18.57$ keV) and favorable half-life ($t_{1/2} = 12.32$ yr), the decay of tritium $^3H \rightarrow {}^3He^+ + e^- + \bar{\nu}_e$ has been investigated by a large


Tritium Source
Transport Section
Pre- and Main-Spectrometer
Detector
³H
$\overline{\nu}_e$
β-decay
e⁻
10¹⁰ e⁻/s
E= 18600 eV
³He
e⁻
e⁻
e⁻
10¹⁰ e⁻/s
³H
³He
e⁻
10¹⁰ e⁻/s
e⁻
1 e⁻/s
Tritinium decays, releasing an electron and an anti-electron-neutrino. While the neutrino escapes undetected, the eletron starts ist journey to the detector.
Electrons are guided towards the sprectrometer by magnetic fields. Tritium has to be pumped out to provide tritium free spectrometers.
The electron energy is analyzed by applying an electrostatic retarding poten-tial. Electrons are only transmitted if their kinetic energy is sufficiently high.
At the end of their journey, the electrons are counted at the detector. Their rate varies with the spectrometer poten-tial and hence gives an integrated β-spectrum.
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UNITED KINGDOM
NETHERLANDS
POLAND
BELARUS
Rhine River
BELGIUM
GERMANY
0 200
Km
Deggendorf
UKRAINE
Atlantic Ocean
Karlsruhe
Danube River
Munich
HUNGARY
FRANCE
ROMANIA
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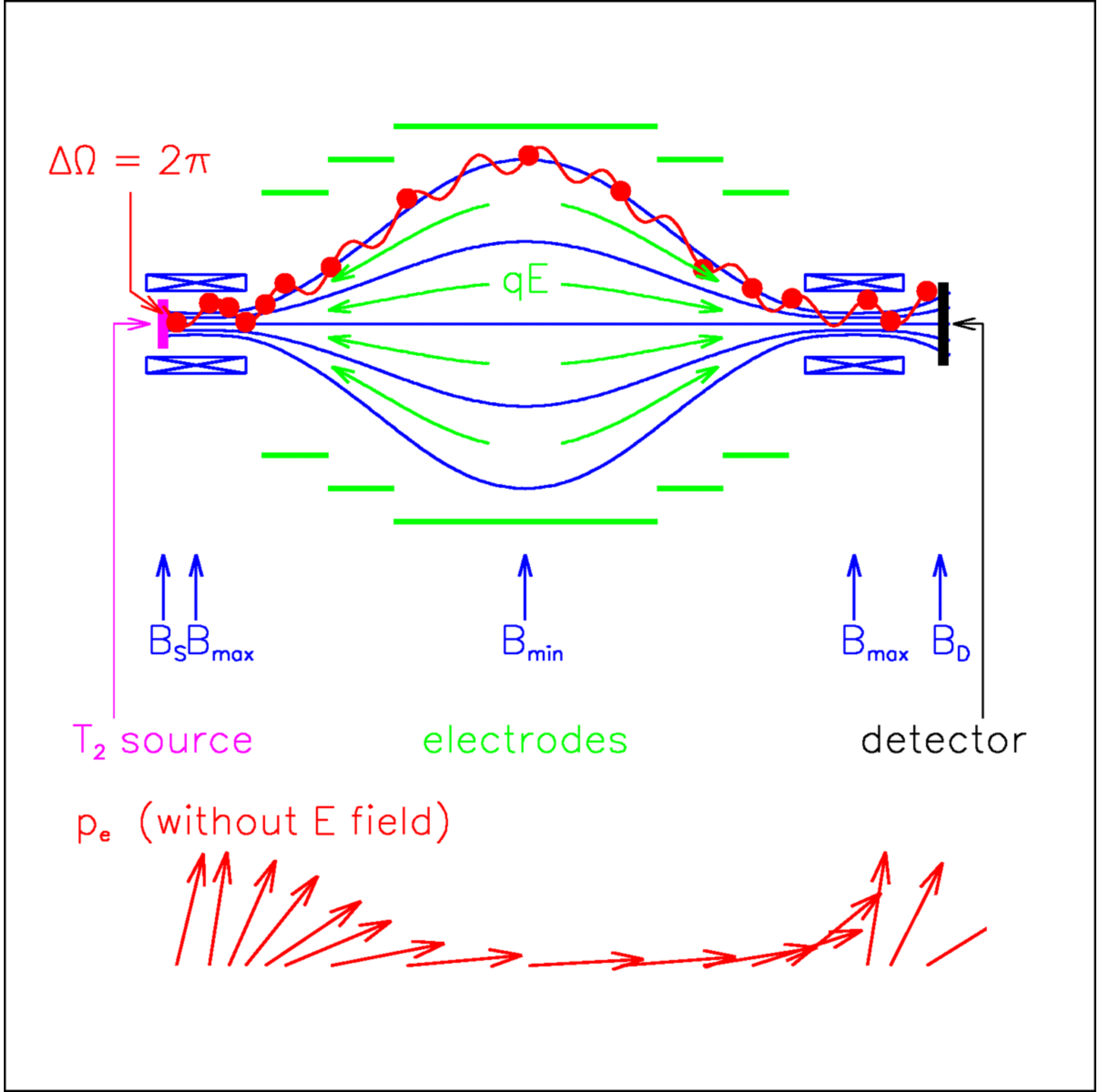
TURKEY
ALGERIA
Mediterranean Sea



based on the principle of magnetic adiabatic collimation with electrostatic filtering (MAC-E-filter) [22, 23], devel-

A defining property of a MAC-E-filter is $\Delta E/E$, the filter width at energy E, which is given by the ratio $B_{\min}/B_{\max}$ of the minimum to maximum magnetic field in non-relativistic approximation. The present ratio (0.63 mT/4.24 T) is equivalent to $\Delta E = 2.8$ eV at E_0. This value constrains the size V_{ft} of the flux-tube

Source: Windowless Gaseous Tritium Source: high purity T_2

90 mm, 10 m long cylinder, nominal column density 5×10^{17} molecules/cm^2

Electrons are absorbed and scattered in the source gas: source needs to be stable.
In the first run, some issues with stability, so column density = nominal/5
Still 2.45×10^{10} Bq, 4 g tritium/day

Otherwise nominal performance obtained, except for background:

- Rydberg atoms sputtered off surface from ^{206}Pb from ^{210}Po: “Poisson” component
- ^{219}Rn from the NEG pumps, “non-Poissonian” component (major systematic)

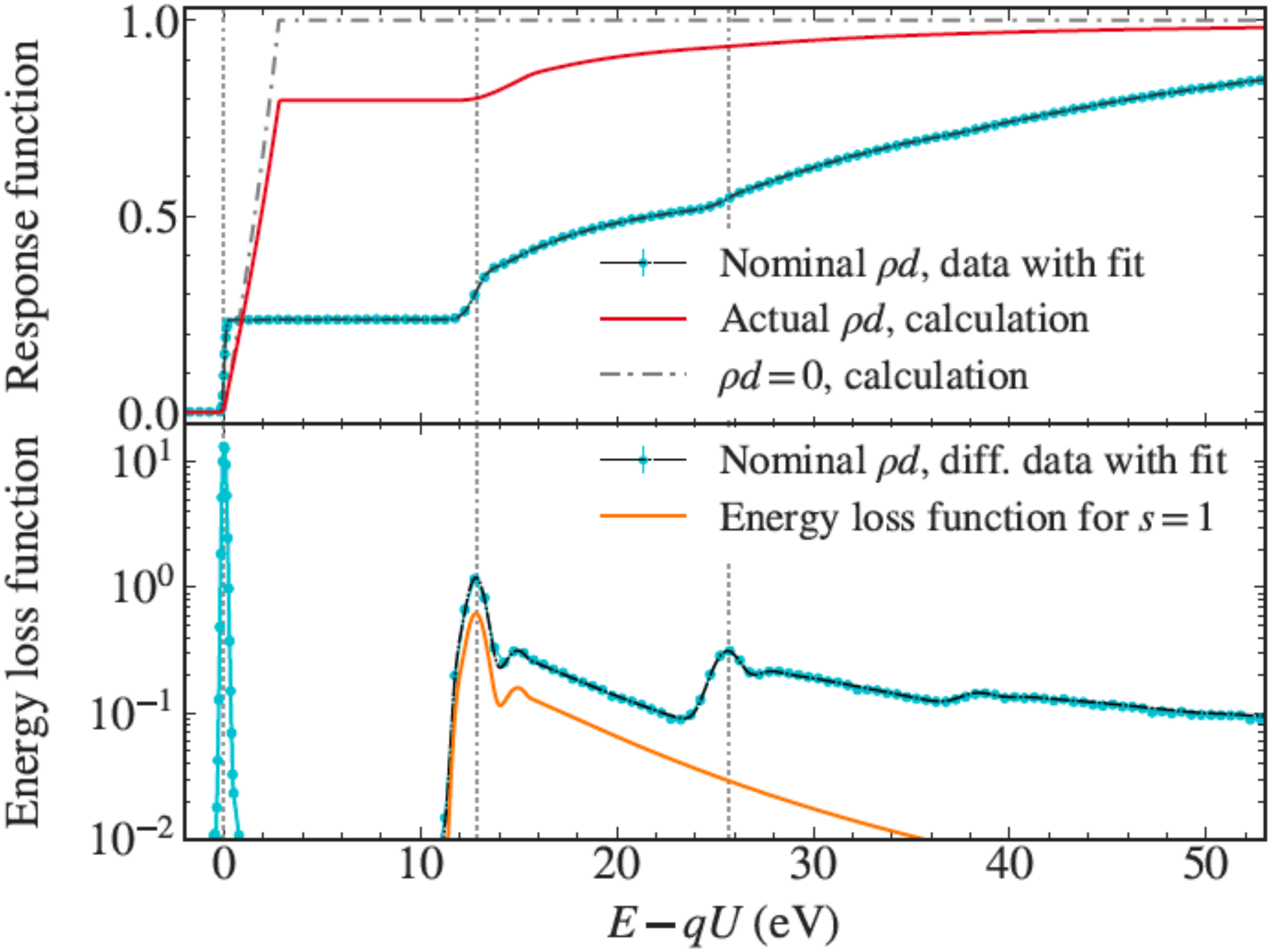


FIG. 2. (top) Measured and calculated response functions $f(E - qU)$ for electron surplus energies $E - qU$ at different ρd values of T_2. Measured $f(E - qU)$ for a narrow-angle photo-electron source close to ρd_{nom} and fit (cyan); and calculated $f_{\mathrm{calc}}(E - qU)$ for isotropically emitted β-decay electrons up to θ_{max} at ρd_{exp} ($1.11 \cdot 10^{17}$ cm^{-2}), the set point of our scans (red line), and in the limit of vanishing $\rho d = 0$ (grey, dash-dotted). (bottom) Differential distributions of energy losses δE from the MAC-E-ToF mode after a selection $35\ \mu s \leq ToF \leq 50\ \mu s$ at $\rho d \approx \rho d_{\mathrm{nom}}$ and fit (cyan). The "no loss" peak at $\delta E = E - qU = 0$ is followed by peaks with $s = 2$ ($s = 3$) scattering at twice (triple) the δE-value of $s = 1$. The energy loss function $\varepsilon(\delta E)$ for $s = 1$ is obtained by deconvolution (orange).

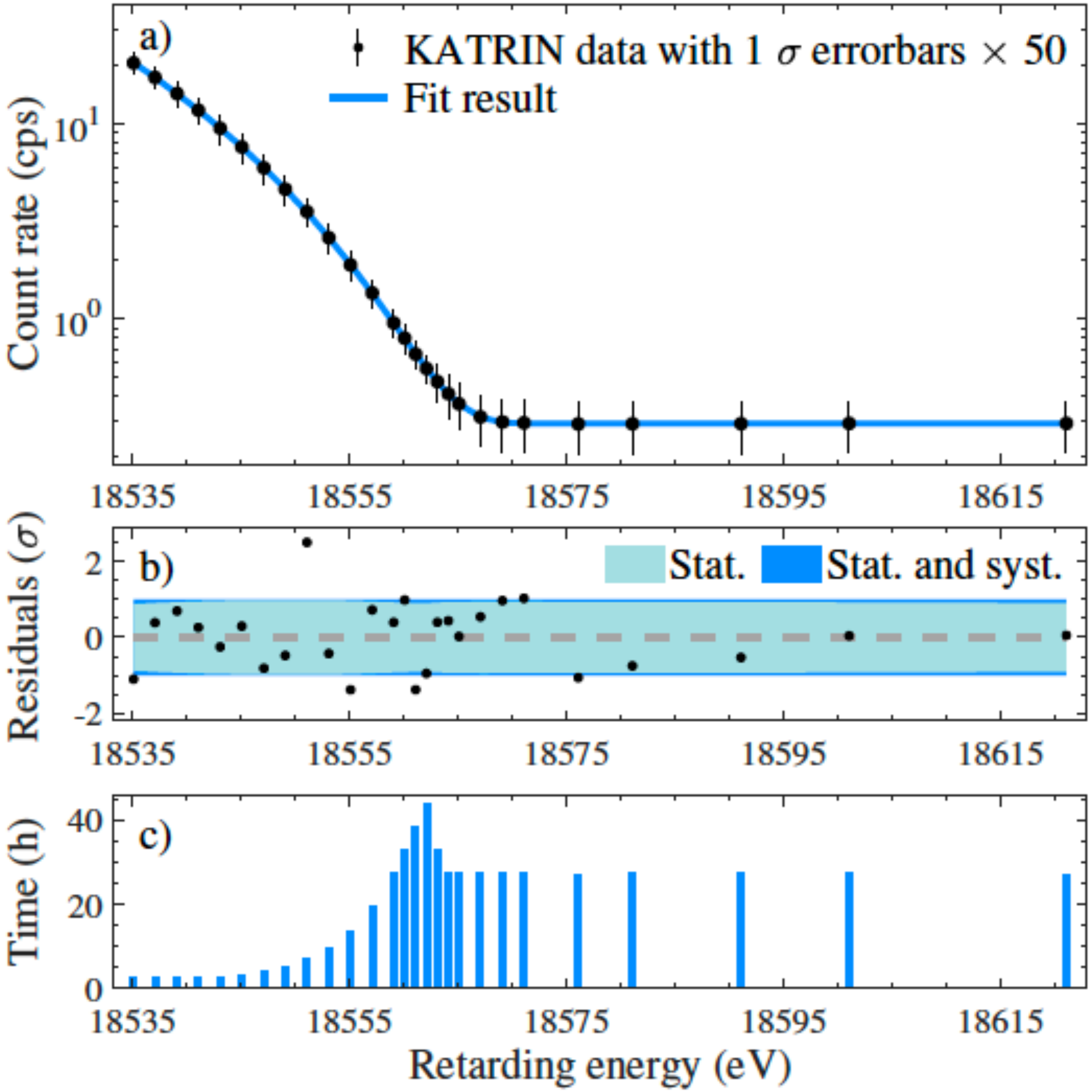


FIG. 3. a) Spectrum of electrons $R(\langle qU \rangle)$ over a 90 eV-wide interval from all 274 tritium scans and best-fit model $R_{\mathrm{calc}}(\langle qU \rangle)$ (line). The integral β-decay spectrum extends up to E_0 on top of a flat background R_{bg}. Experimental data are stacked at the average value $\langle qU \rangle_l$ of each HV set point and are displayed with 1-σ statistical uncertainties enlarged by a factor 50. b) Residuals of $R(\langle qU \rangle)$ relative to the 1-σ uncertainty band of the best fit model. c) Integral measurement time distribution of all 27 HV set points.

The experimental spectrum is well described by our detailed model of the KATRIN response to β-decay electrons and background. It contains four free parameters: the signal amplitude A_s, the effective β-decay endpoint E_0, the background rate R_{bg} and the neutrino mass square m_ν^2. We leave E_0 and A_s unconstrained, which is equivalent to a "shape-only" fit. The goodness-of-fit is illustrated in Fig. 3 b) from the scatter of residuals around the error band of the model.

The 4-parameter fit procedure over the averaged HV set points $\langle qU \rangle_l$ compares the experimental spectrum $R(\langle qU \rangle)$ to the model $R_{calc}(\langle qU \rangle)$. The latter is the convolution of the differential β-electron spectrum $R_\beta(E)$ with the calculated response function $f_{calc}(E - \langle qU \rangle)$, with an added energy-independent background rate R_{bg}:

$$R_{calc}(\langle qU \rangle) = A_s \cdot N_T \int R_\beta(E) \cdot f_{calc}(E - \langle qU \rangle)\, dE + R_{bg} \,. \tag{1}$$

Here, N_T denotes the number of tritium atoms in the source multiplied with the accepted solid angle of the setup $\Delta\Omega/4\pi = (1 - \cos\theta_{max})/2$ and the detector efficiency ($\theta_{max} = \arcsin\sqrt{(B_{WGTS}/B_{max})} = 50.4°$).

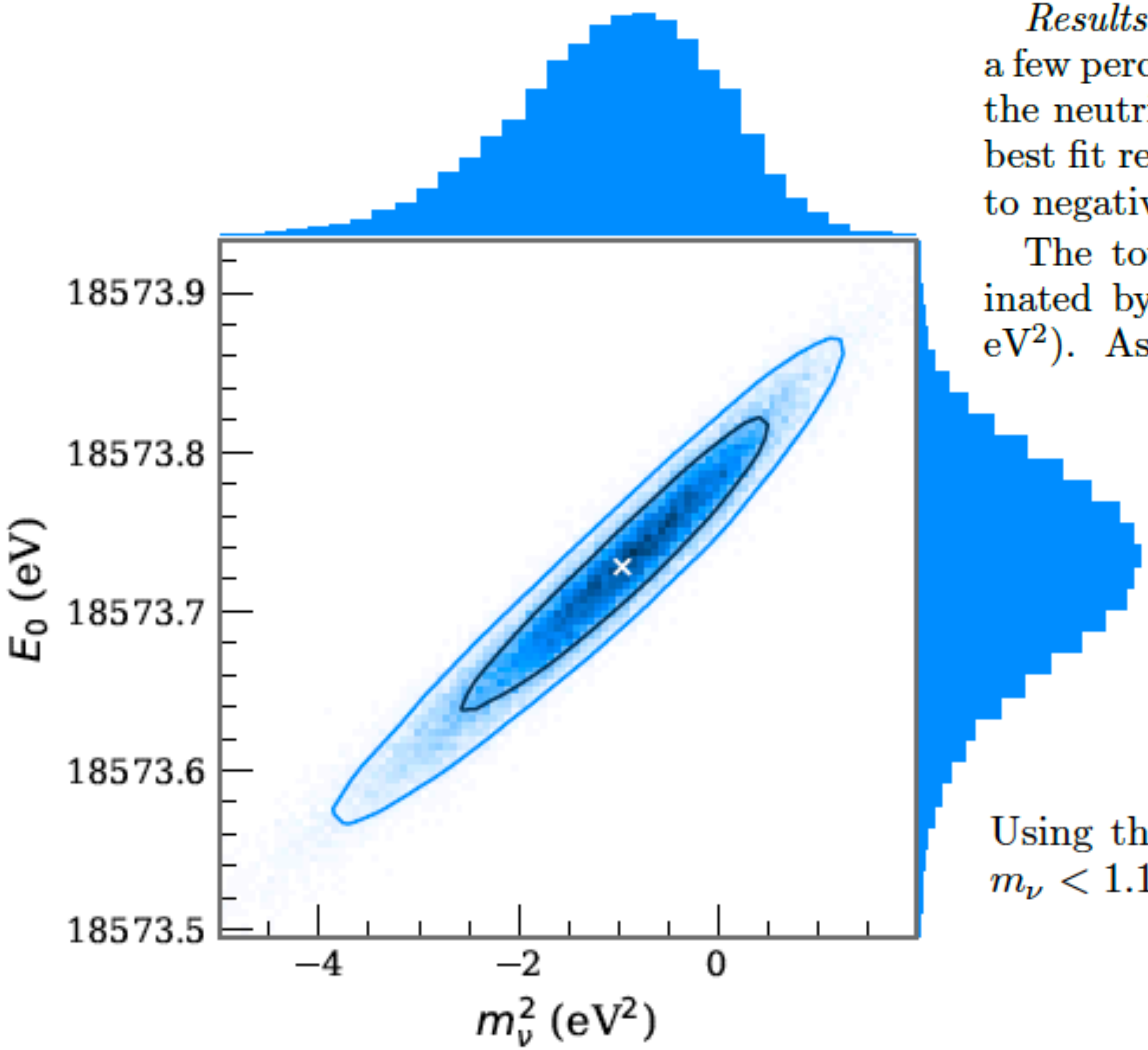
The electron spectrum $R_\beta(E)$ from the superallowed β-decay of molecular tritium is calculated using Fermi's Golden Rule:

$$\begin{aligned} R_\beta(E) = \; & \frac{G_F^2 \cdot \cos^2\Theta_C}{2\pi^3} \cdot |M_{nucl}^2| \cdot F(E, Z') \\ & \cdot (E + m_e) \cdot \sqrt{(E + m_e)^2 - {m_e}^2} \\ & \cdot \sum_j \zeta_j \cdot \varepsilon_j \cdot \sqrt{\varepsilon_j^2 - m_\nu^2} \cdot \Theta(\varepsilon_j - m_\nu) \,, \end{aligned} \tag{2}$$

with the square of the energy-independent nuclear matrix element $|M_{nucl}^2|$, the neutrino energy $\varepsilon_j = E_0 - E - V_j$, the Fermi constant G_F, the Cabibbo angle Θ_C, the electron mass m_e, and the Fermi function $F(E, Z' = 2)$. In addition, our calculations incorporate radiative corrections (for details see [12, 20]) and we account for thermal Doppler broadening at 30 K.

TABLE I. 1-σ systematic uncertainties (σ_{syst}) for m_ν^2 in eV^2, averaged over positive and negative errors, using the method of MC propagation.

Effect	relative uncertainty	$\sigma(m_\nu^2)$ in eV^2
Source properties		
$\rho d \cdot \sigma$	0.85%	0.05
energy loss $\varepsilon(\delta E)$	$\mathcal{O}(1\%)$	negligible
Beamline		0.05
B_{WGTS}	2.5 %	
B_{min}	1 %	
B_{max}	0.2 %	
Final state distribution	$\mathcal{O}(1\%)$	0.02
Fluctuations in scan *k*		0.05
HV stacking	2 ppm	
ρd variation	0.8%	
isotopologue fractions	0.2%	
Background		
background slope	1.7%/keV	0.07
non-Poisson background	6.4%	0.30
Total syst. uncertainty		**0.32**



Results.- The two independent methods agree to within a few percent of the total uncertainty. As best fit value for the neutrino mass we find $m_\nu^2 = (-1.0\,^{+\,0.9}_{-\,1.1})\ \mathrm{eV}^2$. This best fit result corresponds to a 1-σ statistical fluctuation to negative values of m_ν^2 possessing a p-value of 0.16.

The total uncertainty budget of m_ν^2 is largely dominated by σ_{stat} (0.97 eV^2) as compared to σ_{syst} (0.32 eV^2). As displayed in Table I, the dominant contribu-

Using the LT construction we derive an upper limit of $m_\nu < 1.1$ eV (90% CL) as the central result of this work.

Particle Data Book:

$\overline{\nu}$ MASS SQUARED (electron based)

Given troubling systematics which result in improbably negative estimators of $m_{\nu_e}^{2(\mathrm{eff})} \equiv \sum_i |U_{ei}|^2 \, m_{\nu_i}^2$, in many experiments, we use only KRAUS 05 and LOBASHEV 99 for our average.

VALUE (eV^2)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
− 0.6 ± 1.9 OUR AVERAGE					
− 0.67 ± 2.53		[1] ASEEV	11	SPEC	^3H β decay
− 0.6 ± 2.2 ± 2.1		[2] KRAUS	05	SPEC	^3H β decay

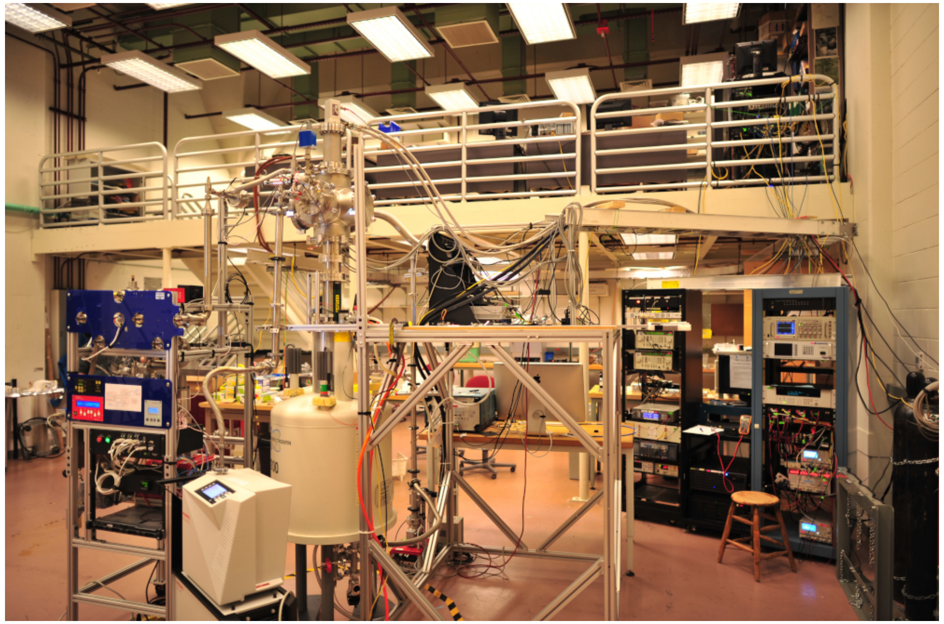
Why are all (?) measurements negative?

Future

KATRIN → 0.2 eV

Project 8:

“The goal of the Project 8 experiment is to measure the absolute neutrino mass using tritium beta decays. This technique, which involves precisely measuring the energies of the beta-decay electrons in the high-energy tail of the spectrum, has a history spanning more than 40 years. The approach to making that measurement taken by the Project 8 collaboration is to use a new method of electron spectroscopy, Cyclotron Radiation Emission Spectroscopy (CRES), which was first demonstrated by the collaboration in 2014.
In Project 8, we adopt the dictum of Arthur Schawlow: "Never measure anything but frequency!." In this case, we take advantage of the motion of charged particles in magnetic fields to make a measurement of their energies.”



Goal: 40 meV