Search for Lorentz-Invariance Violation with the first KATRIN data

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Some extensions of the Standard Model of Particle Physics allow for Lorentz invariance and Charge-Parity-Time (CPT)-invariance violations. In the neutrino sector strong constraints have been set by neutrino-oscillation and time-of-flight experiments. However, some Lorentz-invariance-violating parameters are not accessible via these probes. In this work, we focus on the parameters (a(3)(0))_{100} and (a(3)(0))_{11}, which would manifest themselves in a non-isotropic β-decaying source as a sidereal oscillation and an overall shift of the spectral endpoint. Based on the data of the first scientific run of the KATRIN experiment, we set the first limit on |(a(3)(0))_{11}| of < 3.7 × 10^{-6} GeV at 90% confidence level. Moreover, we derive new constraints on (a(3)(e))_{100} and (a(3)(e))_{11}.
I. INTRODUCTION

CPT and Lorentz invariance are central ingredients of modern physics and of the Standard Model (SM) of particle physics. However, some extensions of the SM such as string theories [1], loop quantum gravity [2], and non-commutative quantum field theories [3] suggest that Charge-Parity-Time (CPT) and Lorentz invariance may be violated at high energies. Yet, so far, no experimental evidence for CPT or Lorentz invariance violation was ever observed and the parameter space is strongly constrained.

Deviations from Lorentz symmetry are typically described in a relativistic effective field theory, the so-called Standard Model Extension (SME) [3-7]. In particular, the SME specifies all possible Lorentz-invariance-violating operators for neutrino propagation, many of which have been constrained with neutrino-oscillation experiments [8]. The so-called “oscillation-free” modes, which cannot be assessed via oscillation experiments, are usually constrained by time-of-flight experiments, which probe the neutrinos’ group velocity compared to that of photons. However, there are four oscillation-free parameters, \((a^{(d=3)}_{\text{ref}})_{jm}\), where \(j\) and \(m\) denote the angular momentum quantum numbers with \(j = 0, 1\) and \(d\) stands for the mass dimension. These parameters can only be accessed by interaction processes, such as the \(\beta\)-decay of tritium [9, 10].

The operators arise from the introduction of the Lorentz-invariance-violating four-vector \(a^\mu\), which can be illustrated as an external vector field, as shown in fig. [1]. Lorentz invariance violation of type \(a^\mu\) in tritium beta decay, is governed by Lagrangian contributions for each of the fermions

\[
L_{\text{SME}}^a = -\bar{\psi}_w a^\mu \gamma_\mu \psi_w, \tag{1}
\]

where the species subscript \(w \in \{T, H, e, n\}\) labels the tritium, helium, electron, and neutrino, respectively. In the calculation of the \(\beta\)-decay spectrum, the momenta of the external particles are modified by \(a^\mu\) and, at first order, terms \(a^\mu p_\mu = a^0 p_0 - \vec{a} \cdot \vec{p}\) appear, where \(p^\mu\) denotes the momentum of the emitted electron. This term causes both a time-dependent and time-independent shift of the spectral endpoint \(E_0\). The former only occurs for non-isotropic \(\beta\)-sources, where \(\vec{a} \cdot \vec{p}\) does not vanish. The time-dependence is caused by the rotation of the Earth in the vector field \(a^\mu\), which leads to a temporal change of the relative direction between the electron’s momentum and the vector field and hence results in a periodic change of the endpoint frequency

\[
\omega_{\text{rot}} = \frac{2 \pi}{\text{sidereal month}}. \tag{2}
\]

The latter is caused by the isotropic part \(a^0\) as well as the component \(a^z\) along the rotation axis. Usually the operator \(a^\mu\) is expressed in spherical decomposition, where the isotropic part is represented by \((a^{(3)}_{\text{ref}})_{00}\), the part along the rotation axis by \((a^{(3)}_{\text{ref}})_{10}\) and the periodically time-dependent part by \((a^{(3)}_{\text{ref}})_{11}\) and \((a^{(3)}_{\text{ref}})_{1-1} = -(a^{(3)}_{\text{ref}})_{11}\) [9, 10].

In this work, we assume an isotropic tritium \(\beta\)-decay source and introduce anisotropy by considering a sub-set of \(\beta\)-electrons, which are emitted under a conical solid angle, defined by the experimental acceptance angle \(\theta_0\), as illustrated in figure [1]. The endpoint \(E_0\) of their energy spectrum is modified by \(a^\mu\) in the following way:

\[
\Delta E_0 = (\gamma - \beta_{\text{rot}} B \sin \xi) \frac{1}{\sqrt{4\pi}} a^{(3)}_{00} + \sqrt{\frac{3}{4\pi}} B \sin \chi \cos \xi a^{(3)}_{10} \nonumber \\
+ \sqrt{\frac{3}{2\pi}} \cos (\omega_{\text{rot}} T_{\text{Earth}}) \left[ (\beta_{\text{rot}} - B \sin \xi) \Im(a^{(3)}_{11}) \right] \nonumber \\
- B \cos \xi \cos \chi \Re(a^{(3)}_{11}) \nonumber \\
+ \sqrt{\frac{3}{2\pi}} \sin (\omega_{\text{rot}} T_{\text{Earth}}) \left[ (\beta_{\text{rot}} - B \sin \xi) \Re(a^{(3)}_{11}) \right] \nonumber \\
+ B \cos \xi \cos \chi \Im(a^{(3)}_{11}), \tag{3}
\]

where \(\gamma\) is the Lorentz factor, \(\beta_{\text{rot}}\) is the rotation velocity of Earth at the location of the experiment, \(\chi\) is the colatitude of the experiment, and \(\xi\) the orientation of the experimental beam-axis with respect to the local north, as shown in fig. [2]. The factor \(B = M_T^{-1}(2\pi(1-\cos \theta_0))^{-1} \pi \sqrt{E^2_0 - m_e^2 \sin^2 \theta_0}\) depends on the mass of the tritium atom \(M_T\), the mass of the electron \(m_e\), the endpoint without Lorentz invariance violation \(E_0\), and the acceptance angle \(\theta_0\). From this it becomes clear that an acceptance angle of less than 90°, and thus an anisotropy, is necessary to cause a temporal oscillation in addition to a time-independent shift.

In this work we use data from the first scientific run of the Karlsruhe Tritium Neutrino (KATRIN) experiment, which took place in spring 2019 and lasted about one month. The data was acquired in 361 two-hour-long scans, from each of which the spectral endpoint \(E_0\) is inferred individually. This time series of \(E_0\) measurements is used to search for a temporal oscillation, expressed by \(\Delta E_0 = A \cos(\omega_{\text{rot}} t - \phi)\), where the oscillation is described by an amplitude \(A\) and phase \(\phi\). The amplitude can directly be used to limit the Lorentz-invariance-violating parameter \((a^{(3)}_{\text{ref}})_{11}\) via the relation

\[
A = \sqrt{\frac{3}{2\pi}} \left| (a^{(3)}_{\text{ref}})_{11} \right| \sqrt{B^2 \cos^2 \chi \cos^2 \xi + (\beta_{\text{rot}} - B \sin \xi)^2}. \tag{4}
\]

II. KATRIN EXPERIMENT

The goal of KATRIN is to measure the effective electron antineutrino mass \(m_\nu\) with a sensitivity of 0.2 eV.
at 90% confidence level (C.L.) after about 1000 days of taking data [11, 12]. Recently, KATRIN has published the first direct sub-eV upper limit on the neutrino mass of \( m_\nu < 0.8 \text{ eV} \) (90% CL) based on the first two data-taking campaigns [13]. This work uses data from the first high-luminosity (2.45 \( \times \) 10\(^{10} \) Bq) tritium campaign, which ran from April 10 to May 13, 2019 [21, 22]. The integral spectrum was recorded by repeatedly scanning the energy interval from \( E_0 - 90 \text{ eV} \) to \( E_0 + 50 \text{ eV} \). In each so-called scan a series of 39 non-equidistant high-voltage (HV) set points is applied to the main spectrometer. The HV set points \( U \) are applied in alternating upward (up-scan) and downward (down-scan) directions to compensate for possible time-dependent drifts of the system to first order. The measurement time at each HV set point lasts between 17 and 576 s, as shown in fig. 3. The net scan time is about 2 hours.

The presented search for Lorentz invariance violation follows the same initial protocol as the neutrino mass analysis. To this end, we choose an analysis interval covering a region from \( 40 \text{ eV} \) below \( E_0 \) (22 HV set points) to \( 50 \text{ eV} \) above \( E_0 \) (5 HV set points). In the same manner as for the neutrino-mass analysis, we apply quality cuts to each scan and select 274 stable scans which corresponds to a total scan time of 521.7 h. The 117 selected pixels (79% of the detector area) are combined to one effective pixel (so-called uniform fit), which leads to 274 integral spectra \( R(qU_i) \) with about 7400 events each. For the presented analysis it is important that the KATRIN experiment accepts only electrons that are emitted at an an angle of less than 50.4° relative to the magnetic field lines in the source. The acceptance angle \( \theta_0 = \arcsin \left( \sqrt{B_s/B_{\text{max}}} \right) \) is determined by the source magnetic field \( B_s = 2.52 \text{T} \) and the maximal magnetic field in the beamline \( B_{\text{max}} = 4.24 \text{T} \). These values are chosen to exclude electrons with a long path through the source and hence increased scattering probability. It is this selection of direction which makes KATRIN sensitive to the anisotropic Lorentz-invariance-violating operator \( (a^{(3)}_{\text{eff}})_{11} \).

In addition, a slowly decreasing magnetic field (from \( B_{\text{max}} = 4.24 \text{T} \) to \( B_{\text{min}} = 0.63 \text{ mT} \) in the center of the main spectrometer) aligns the momenta of the isotropically created electrons. This magnetic adiabatic collimation provides a large angular acceptance (\( \theta_0 = 50.4° \)) with a sharp cut-off energy (\( \Delta E(18.6 \text{ keV}) = 2.8 \text{ eV} \)) at the same time. By measuring the rate of transmitted electrons (charge \( q = -e \)) as a function of the retarding energy \( qU \) the integral \( \beta \)-decay spectrum is obtained, as illustrated in fig. 3. The electrons are detected by a 148-pixel silicon PIN focal-plane detector (d), installed at the exit of the spectrometer [20].
Figure 2. Main components of the KATRIN experiment: a) tritium source, b) transport and pumping sections, c) main spectrometer, d) focal plane detector. The dashed line below illustrates the KATRIN beamline. The experiment has an orientation of $\xi \approx 16^\circ$ east to the local north N. The acceptance angle $\theta_0 = 50.4^\circ$ defines the acceptance cone of the $\beta$-electrons. The black arrows below the spectrometer indicate the electron momentum (without electric field). When propagating from $B_s$ to $B_{\text{min}}$ the pitch angle $\theta$ (angle between the electron momentum and the magnetic field lines) is reduced, while when moving from $B_s$ to $B_{\text{max}}$ the pitch angle is increased. An electron starting with $\theta > \theta_0$ will be reflected at $B_{\text{max}}$.

Figure 3. a) Electron spectrum $R(qU)$ of a single scan where all pixels are combined (uniform fit). The spectrum of the best fit $R_{\text{calc}}(qU)$ extends to the endpoint $E_0$ and lies on top of an energy-independent background $R_{\text{bg}}$. b) Residuals of $R(qU)$ relative to the 1σ-uncertainty band of the best fit model. c) Measurement-time distribution.

III. ENDPOINT FIT OF INTEGRAL SPECTRUM

The theoretical spectrum $R_{\text{calc}}(qU)$ consists of the differential $\beta$ spectrum $R_\beta$, the experimental response function $f(E,qU)$, and a retarding-energy-independent background $R_{\text{bg}}$:

$$R_{\text{calc}}(qU) = A_s \cdot N_T \cdot \int R_\beta(E; m_\nu^2, E_0) \cdot f(E-qU)dE + R_{\text{bg}}$$

(4)

where $A_s$ is the amplitude of the signal and $N_T$ is the effective number of tritium atoms in the source. $E$ denotes the energy of the electron. The differential spectrum, described in detail for example in [22, 23], depends on the endpoint of the tritium spectrum $E_0$ as well as the effective electron antineutrino mass $m_\nu = \sum_{i=1}^3 |U_{ei}|^2 m_i$, where $U$ is the PNMS matrix and $m_i$ the masses of the neutrino-mass eigenstates. In addition, it is considered that the tritium molecule can be in rotational, vibrational, and electronic excited states, which are described by means of a final-states distribution. The response function $f(E,qU)$ describes the transmission probability of an electron as a function of its energy. It includes the spectrometer resolution and energy losses due to scattering in the gaseous source.

The computed spectrum $\tilde{R}_{\text{calc}}$ is fit to the data $\tilde{R}_{\text{data}}$ by minimizing

$$\chi^2(\theta) = (\tilde{R}_{\text{calc}}(\vec{\eta}) - \tilde{R}_{\text{data}})^T C^{-1} (\tilde{R}_{\text{calc}}(\vec{\eta}) - \tilde{R}_{\text{data}}),$$

(5)

with respect to the free parameters $\vec{\eta}$ including the covariance matrix $C$. For the neutrino-mass analysis [22] the combined data of all scans are analyzed with the four free fit parameters $A_s$, $E_0$, $R_{\text{bg}}$, and $m_\nu^2$. An excellent agreement of the model with the data was demonstrated in [21, 22]. In this work, in contrast, we analyze the scans separately, which leads to an individual endpoint for each scan. Moreover, we set $m_\nu^2$ to zero in the fits, since we assume it to be a time-independent parameter, which has no effect on the oscillation signal due to Lorentz invariance violation. An example fit can be seen in fig. [24].

Every fitted endpoint has an uncertainty, which is composed of a statistical and a systematic part. As we are
interested in a temporal variation of the endpoint, only the statistical uncertainties and those systematic uncertainties, which can vary with time are of concern for this analysis. For example, the time-independent uncertainty on the theoretical description of the final states would have the same effect on the endpoints of all scans, and thus would not affect the oscillation signal. In contrast, the magnetic field may vary slightly from scan to scan and therefore influences the uncertainty of the fitted oscillation of the endpoint.

Uncertainties of a statistical nature, such as the Poisson uncertainty of each data point and additional source activity and background fluctuations, are included via the covariance matrix $C$ of equation [5]. To determine the influence of systematic uncertainties we employ the Monte Carlo propagation technique [22]. Here, the data are fitted about $10^5$ times while varying the relevant systematic parameters (e.g. the magnetic fields and source properties) in each fit. The distribution of fitted endpoints is used to determine the best-fit value and uncertainty of the endpoint.

The statistical uncertainty of the endpoint in a single scan is $\sigma_{E_0}^{\text{stat}} = 247 \text{ meV}$, which dominates over the total systematic uncertainty of $\sigma_{E_0}^{\text{syst}} = 70 \text{ meV}$. The largest effect beyond the statistical uncertainty arises from the background. Certain background sources lead to time-correlated background events and hence do not follow a Poissonian distribution [24] but instead a broader distribution. This over-dispersion of the background-rate distribution increases the statistical uncertainty and contributes $69 \text{ meV}$ to the uncertainty budget of the endpoint in each scan. Uncertainties of the column density $\rho d$ (the integral of the gas density $\rho$ over the length of the source $d$), activity fluctuations during a scan, the concentration of different tritium isotopologues in the source, the source electric potential, as well as the magnetic field stability contribute with less than $10 \text{ meV}$ each to the endpoint uncertainty per scan. All uncertainties are summarized in table I.

Since we are interested in a temporal oscillation of the endpoint, we verified the absence of any oscillatory behaviour of the individual slow-control and nuisance parameters. We exclude any statistically significant sinusoidal time evolution of the background rate, the source activity, and any of the systematic parameters mentioned above.

The spectral model $R_{\text{calc}}(qU)$ assumes a constant endpoint, and thus neglects the fact that, in the case of Lorentz invariance violation, the endpoint would slightly change during the course of a 2 hour scan. We justify this approximation, by simulating several up- and down-scans, including a continuously changing endpoint, according to various assumed values of Lorentz invariance violation. We fit these simulated scans using $R_{\text{calc}}(qU)$ and demonstrate that the inferred endpoint agrees within < 1% with the theoretical true endpoint at a fixed time $t_e$ relative to the start of the 2-hour scan. As the spectral data points have different sensitivity to the endpoint, $t_e$ depends on the measurement-time distribution and the scan direction. We find $t_e = t_0 + 87 \text{ min}$ (for up scans) and $t_e = t_0 + 52 \text{ min}$ (for down scans), where $t_0$ is the start time of the scan.

### IV. SEARCH FOR SIDEREAL ENDPOINT OSCILLATION

The fitted endpoints with corresponding uncertainties of the individual scans, illustrated in fig. 3, can be used to search for oscillations with sidereal frequency $\omega \approx 2\pi / (23 \text{h}56 \text{min})$ caused by the Lorentz-invariance-violating parameter ($\alpha_{11}^{(3)}$). The oscillation is described by $E_0^{\text{fit}}(t_e) = D + A \cos(\omega t_e - \phi)$ with baseline $D$, amplitude $A$ and phase $\phi$, which are treated as free parameters.

To set a limit on the amplitude and phase, we used a two-dimensional $\chi^2$-grid search in $(A, \phi)$. Thereby an exclusion contour is extracted from the $\chi^2$ map using a likelihood ratio as test statistic $\Lambda(A, \phi) = -2 \ln L(A, \phi) - \ln L_{\text{best}}^2$. Applying Wilks’ theorem, $\Delta \chi^2(\Lambda) = -2 \ln \Lambda(A, \phi) = \chi^2(A, \phi) - \chi^2_{\text{best}}$ behaves according to a $\chi^2$ distribution with two degrees of freedom [25]. This means that for a confidence level of 90%, one excludes all grid points for which $\Delta \chi^2 > \chi^2_{\text{best}} \approx 4.61$ holds. We confirmed the correct coverage of this approach by means of Monte-Carlo simulations. For about 5000 simulations of the experiment assuming the null hypothesis $H_0$ ($A = 0 \text{ eV}$) and several alternative hypotheses $H_1$ ($A \neq 0 \text{ eV}$) we show that the $\Delta \chi^2$ distribution follows the theoretical $\chi^2$ curve and gives a critical $\chi^2$ of $\chi^2_{\text{crit}} = 4.55 \pm 0.06$, which is in good agreement with Wilks’ theorem. Finally, according to eq. 5, we translate the limit on the amplitude $A$ into a limit on $(\alpha_{11}^{(3)})$.

### V. RESULTS

In order to prevent human-induced bias in the analysis and to determine a sensitivity of the considered data set to possible Lorentz invariance violation, the $\chi^2$ grid scan

| effect                                      | $\sigma(E_0)$ |
|---------------------------------------------|---------------|
| Non-Poissonian background                   | 0.069         |
| Subrun activity fluctuation                 | 0.006         |
| Source electric potential                   | 0.005         |
| Column density $\rho d$                     | 0.004         |
| Magnetic fields                             | 0.004         |
| Isotopologue concentration                 | $< 0.001$     |
| **Total syst. uncertainties**               | 0.070         |
| **Stat. uncertainty**                       | 0.247         |
| **Total uncertainty**                       | 0.257         |
is first performed on simulated data, assuming no Lorentz invariance violation. The sensitivity to the amplitude of the sidereal oscillation is found to be $A < 0.05 \, \text{eV}$ (90% CL). This translates into a sensitivity of $\left| (a_{\text{of}})^{(3)} \right|_{11} < 2.0 \cdot 10^{-6} \, \text{GeV}$ (90% CL).

After the investigation with simulated data, the grid search is performed with the real data, as shown in fig. 4. The best fit is found at $A_{\text{best}} = 0.03 \, \text{eV}$ and $\phi_{\text{best}} = 0.78\pi$. The difference of the $\chi^2$ of the null hypothesis and the best fit is $\Delta \chi^2 = 1.86$ for two degrees of freedom, which corresponds to a p-value of 0.39 and is thus not significant at 90% confidence level. The resulting exclusion curve, illustrated in fig. 5, shows that amplitudes between $A < 0.08 \, \text{eV}$ (at $\phi \approx 0.78\pi$) and $A < 0.02 \, \text{eV}$ (at $\phi \approx 0$) can be excluded. This null result can be transformed into the first constraint of $\left| (a_{\text{of}})^{(3)} \right|_{11} < 3.7 \cdot 10^{-6} \, \text{GeV}$ (corresponding to $A = 0.08 \, \text{eV}$) by means of eq. (3).

In addition we can also constrain $(a_{\text{of}})^{(3)}_{00}$ and $(a_{\text{of}})^{(3)}_{10}$ as done in [9], by searching for a time-independent shift of the Q-value of the $\beta$-decay with respect to the theoretical Q-value. In order to assess the Q-value in KATRIN the measured effective endpoint $E_0$ has to be corrected for the electric potential in the source $\Phi_{\text{sp}}$, the workfunction of the spectrometer $\Phi_{\text{sp}}$, and the molecular recoil energy $E_{\text{rec}}$, which leads to $Q_{\text{KATRIN}} = E_0 + E_{\text{rec}} - (\Phi_{\text{so}} - \Phi_{\text{sp}})$, see [22] for details. The calculated Q-value $Q_{\text{calc}}$ is given by a high-precision measurement of the mass difference of $^3$He and T [26], corrected for molecular dissociation and ionization energies [27]. A significant difference between the $Q_{\text{KATRIN}}$ and $Q_{\text{calc}}$ could be interpreted as a signature of Lorentz invariance violation, caused by the parameters $(a_{\text{of}})^{(3)}_{00}$ and $(a_{\text{of}})^{(3)}_{10}$ (see eq. 2).

In order to disentangle both parameters one needs to make use of a second experiment, for example the Mainz direct neutrino mass experiment [28] which is located at a different site ($\chi = 40^{\circ}, \xi = -65^{\circ}$) from KATRIN. We infer both parameters by comparing $Q_{\text{calc}} = (18575.72 \pm 0.07) \, \text{eV}$ [26] to both $Q_{\text{KATRIN}} = (18575.2 \pm 0.5) \, \text{eV}$ [21] and $Q_{\text{Mainz}} = (18576 \pm 3) \, \text{eV}$ [29], which was obtained from a dedicated Q-value determination campaign of the Mainz experiment. Note that the analysis presented in [9] uses a different data set of the Mainz experiment. We find no significant deviation from zero for $(a_{\text{of}})^{(3)}_{00}$ and $(a_{\text{of}})^{(3)}_{10}$ and thus set an upper limit of $\left| (a_{\text{of}})^{(3)}_{00} \right| < 3.0 \cdot 10^{-8} \, \text{GeV}$ and $\left| (a_{\text{of}})^{(3)}_{10} \right| < 6.4 \cdot 10^{-4} \, \text{GeV}$ (90% CL).
Besides the anisotropic Lorentz-invariance-violating parameter, the parameters \( (a^{(3)} \phi)_{00} \) and \( (a^{(3)} \phi)_{10} \) were investigated using the absolute endpoint measurements of both the KATRIN and the Mainz experiments. We find improved limits of \( |(a^{(3)} \phi)_{00}| < 3.0 \times 10^{-8} \text{GeV} \) and \( |(a^{(3)} \phi)_{10}| < 6.4 \times 10^{-4} \text{GeV} \) (90% CL).

This initial study illustrates that the scientific potential of precision \( \beta \)-spectroscopy experiments, such as KATRIN, extends well beyond the neutrino-mass search to physics beyond the standard model.

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**VI. CONCLUSION**

KATRIN is uniquely positioned to study oscillation-free Lorentz-invariance-violating operators that cannot be accessed by time-of-flight or neutrino-oscillation experiments. Based on the first physics run of the KATRIN experiment we were able to probe the parameter \( (a^{(3)} \phi)_{11} \) by searching for a sidereal oscillation of the endpoint of the tritium \( \beta \)-decay spectrum. We find no oscillation and release the first upper limit on this parameter of \( |(a^{(3)} \phi)_{11}| < 3.7 \times 10^{-6} \text{GeV} \) (90% CL). Based on the future final KATRIN data set, a sensitivity at the level of \( 5 \times 10^{-7} \text{GeV} \) (90% CL) could be reached.

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Figure 5. 90% C.L. exclusion curves for amplitude and phase of a sidereal oscillation of the endpoint in the first physics run of KATRIN. Using a \( \chi^2 \)-grid search and Wilks' theorem the exclusion limit for the total uncertainties (blue solid line) are calculated. The green dashed-dotted line shows the exclusion limit, including only the statistical uncertainty. The orange dashed line includes an enlarged statistical uncertainty due to the non-Poissonian (NP) distribution of the background rate, as explained in the main text. The best fit is shown by the black cross.
