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STUDY OF THE $K^- \to \pi^0 e^- \nu$ DECAY

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Abstract

Ajinenko I.V., Akimenko S.A., Belous K.S. et al. Study of the $K^- \to \pi^0 e^- \nu$ decay: IHEP Preprint 2003-18. – Protvino, 2003. – p. 8, figs. 7, tables 1, refs.: 13.

The decay $K^- \to \pi^0 e^- \nu$ has been studied using in-flight decays detected with ISTRA+ setup working at the 25 GeV negative secondary beam of the U-70 PS. About 560K events were used for the analysis. The λ_+ parameter of the vector form-factor has been measured: $\lambda_+ = 0.0286 \pm 0.0008(stat) \pm 0.0006(syst)$. The limits on a possible tensor and scalar couplings have been derived: $|f_T|/f_+(0) = 0.021^{+0.064}_{-0.075}(stat) \pm 0.026(syst)$; $|f_S|/f_+(0) = 0.002^{+0.020}_{-0.022}(stat) \pm 0.003(syst)$

Аннотация

Ажиненко И.В., Акименко С.А., Белоус К.С. и др. Исследование распада $K^- \to \pi^0 e^- \nu$. : Препринт ИФВЭ 2003-18. – Протвино, 2003. – 8 с., 7 рис., 1 табл., библиогр.: 13.

Представлены результаты исследования распада $K^- \to \pi^0 e^- \nu$ на установке ИСТРА+, работающей на пучке отрицательно заряженных частиц с импульсом 25 ГэВ/с на ускорителе У-70. В результате анализа 560K распадов определен параметр наклона векторного формфактора λ_+: $\lambda_+ = 0.0286 \pm 0.0008(.) \pm 0.0006(.)$. Получены пределы на эффективные константы тензорного и скалярного взаимодействий: $|f_T|/f_+(0) = 0.021^{+0.064}_{-0.075}(.) \pm 0.026(.)$; $|f_S|/f_+(0) = 0.002^{+0.020}_{-0.022}(.) \pm 0.003(.)$

1. Introduction

The decay $K \to e\nu\pi^0$(K$_{e3}$) is known to be a promising one to search for an admixture of scalar (S) or tensor (T) interactions to the Standard Model (SM) V-A . This topic has been attracting significant interest during resent years and moreover some previous experiments with charged and neutral kaon beams have reported indications for some anomalous S and T signals [1], [2]. On the other hand, recent KEK [3,4] experiment with stopped K^+ and our preliminary studies [5] have reported negative results of the searches. Another goal of our study is a precise measurement of the V-A $f_+(t)$ form-factor of the K_{e3} decay which is interesting in view of new calculations in Chiral Perturbation Theory(CPT) to order p^6 [6].

In our analysis, which is a full statistics update of our preliminary result [5] we present a new study of K^-_{e3} decay based on the statistics of about 560K events.

2. Experimental setup

The experiment has been performed at the IHEP 70 GeV proton synchrotron U-70. The experimental setup ISTRA+ (Fig. 1) has been described in some details in our paper [5].

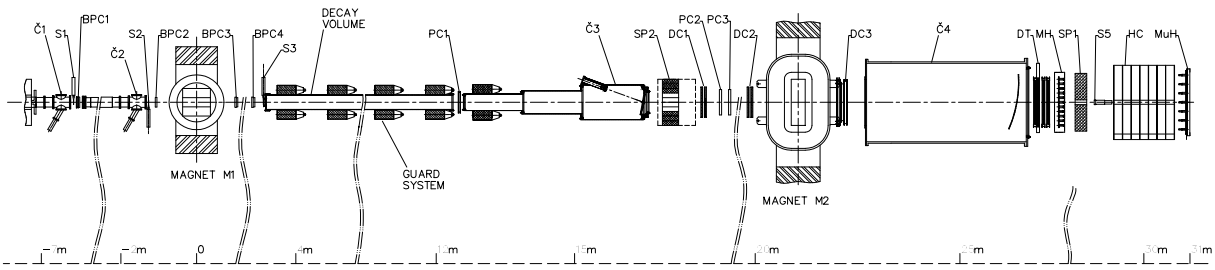

Figure 1. Elevation view of the ISTRA+ detector.

The setup is located in the negative unseparated secondary beam. The beam momentum in the measurements is ~ 25 GeV with $\Delta p/p \sim 1.5\%$. The admixture of K^- in the beam is $\sim 3\%$. The beam intensity is $\sim 3 \cdot 10^6$ per 1.9 sec. U-70 spill. The beam particle deflected by M$_1$ is measured by $BPC_1 \div BPC_4$ PC's with 1mm wire step, the kaon identification is done by $\check{C}_0 \div \check{C}_2$ threshold $\check{C}$-counters. The 9 meter long vacuumed decay volume is surrounded by 8 lead glass

rings $LG_1 \div LG_8$ used to veto low energy photons. SP_2 is a lead glass calorimeter to detect/veto large angle photons. The decay products deflected in M2 with 1Tm field integral are measured with $PC_1 \div PC_3$- 2 mm step proportional chambers; $DC_1 \div DC_3$- 1 cm cell drift chambers and finally with 2 cm diameter drift tubes $DT_1 \div DT_4$. Wide aperture threshold Cerenkov counters $\check{C}_3$, $\check{C}_4$ are filled with He and are not used in the present measurements. SP_1 is a 576-cell lead glass calorimeter, followed by HC- a scintillator-iron sampling hadron calorimeter, subdivided into 7 longitudinal sections 7×7 cells each. MH is a 11×11 cell scintillating hodoscope, used to improve the time resolution of the tracking system, MuH is a 7×7 cell muon hodoscope.
The trigger is provided by $S_1 \div S_5$ scintillation counters, $\check{C}_0 \div \check{C}_2$ Cerenkov counters, analog sum of amplitudes from the last dinodes of the SP_1 : $T = S_1 \cdot S_2 \cdot S_3 \cdot \bar{S}_4 \cdot \check{C}_0 \cdot \bar{\check{C}}_1 \cdot \bar{\check{C}}_2 \cdot \bar{S}_5 \cdot \Sigma(SP_1)$, here S_4 is a scintillator counter with a hole to suppress beam halo ; S_5 is a counter downstream the setup at the beam focus; $\Sigma(SP_1)$- a requirement for the analog sum of amplitudes from SP_1 to be larger than ∼700 MeV – a MIP signal. The last requirement serves to suppress the $K \to \mu\nu$ decay.

3. Event selection

During physics runs in Spring (run 1) and Winter (run 2) 2001, 363M and 332M events were logged on tapes. This information is supported by about 260M MC events generated with Geant3 [7] Monte Carlo program. MC generation includes a realistic description of the setup including decay volume entrance windows, track chambers windows, gas, sense wires and cathode structure, Cerenkov counters mirrors and gas, shower generation in EM calorimeters, etc.

The data processing starts with the beam particle reconstruction in $BPC_1 \div BPC_4$, then the secondary tracks are looked for in $PC_1 \div PC_3$; $DC_1 \div DC_3$; $DT_1 \div DT_4$ and events with one good negative track are selected. The decay vertex is searched for, and a cut is introduced on the matching of incoming and decay track. The next step is to look for showers in SP_1 calorimeter. The matching of the charged track and a shower in SP_1 is done on the basis of the distance r between the track extrapolation to the ECAL and the shower coordinates ($r \leq 3$ cm). The electron identification is done using the ratio of the energy of the shower to the momentum of the associated track. The E/p distribution is shown in Fig. 2. The particles with $0.8 < \mathrm{E/p} < 1.3$ were accepted as electrons.

The events with one charged track identified as electron and two additional showers in ECAL are selected for further processing. The mass spectrum of $\gamma\gamma$ is shown in Fig. 3.

The π^0 peak is situated at $M_{\pi 0} = 134.8$ MeV with a resolution of 8.6 MeV.

Further selection is done by the requirement that the event passes 2C $K \to e\nu\pi^0$ fit. To minimize effects of a beam associated background and systematics a cut on the difference between the fitted P_K value and the nominal beam energy (25.2 GeV for the first run and 26.3 GeV for the second run) is applied: $|P_K - P_{beam}| < 1$ GeV, see Fig. 4.

The missing energy $E_\nu = E_K - E_e - E_{\pi^0}$ after this step is shown in Fig. 5. The peak at low E_ν corresponds to the remaining $K^- \to \pi^-\pi^0$ background. The cut is $E_\nu > 0.3$ GeV. To further suppress the $K^- \to \pi^-\pi^0$ contamination it is required that 5C $K \to \pi^-\pi^0$ fit should fail.

The surviving background is estimated from MC to be less than 1.5%.

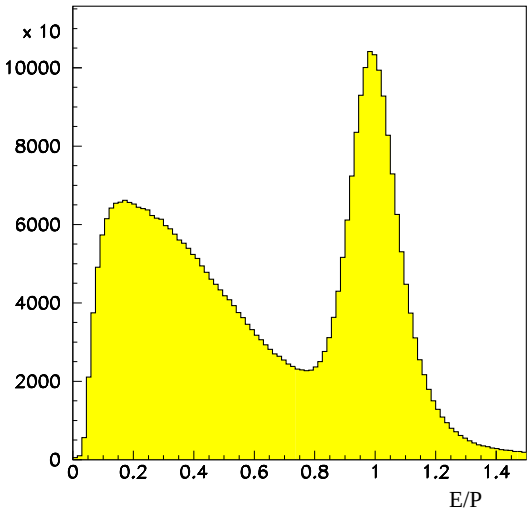

Figure 2: The ratio of the energy of the associated ECAL cluster to the momentum of the charged track(E/P plot).

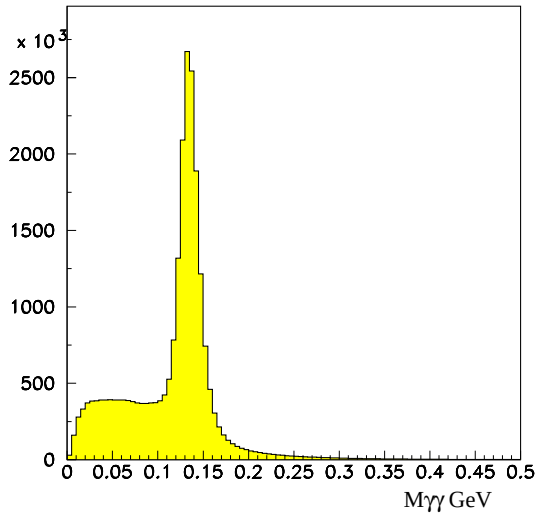

Figure 3: The $\gamma\gamma$ mass spectrum for the events with the identified electron and two extra showers.

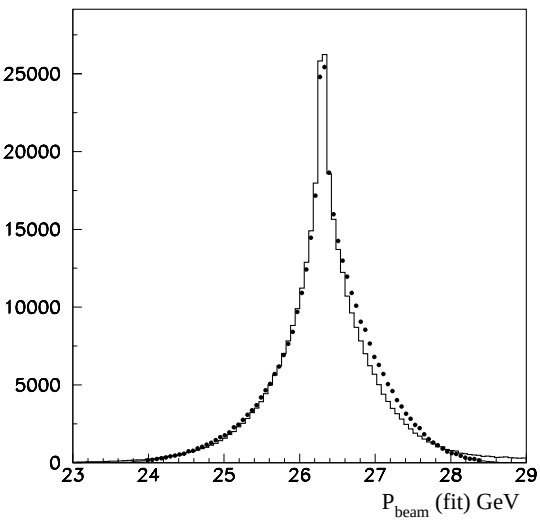

Figure 4: The beam kaon momentum after 2C K_{e3} fit. The points with errors is the run 2 data, the histogram- MC.

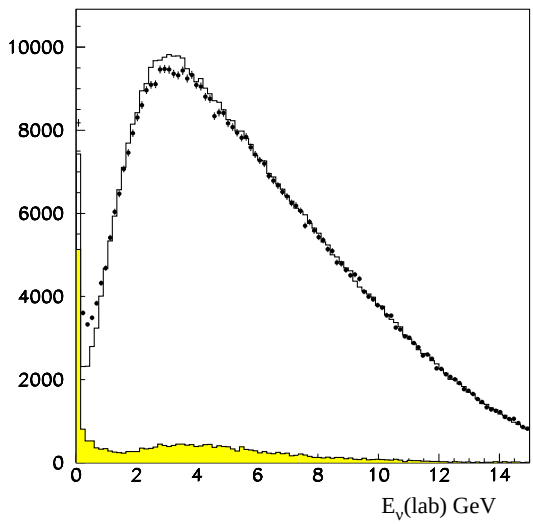

Figure 5: The missing energy for the $e\pi^0$ events. The points with errors is the run 2 data, the dark histogram- $K^- \to \pi^-\pi^0$ background, the light histogram- total MC signal plus background.

4. Analysis

The event selection described in the previous section results in selected 112K events in run 1 and 440K events in run 2. The difference in the events output is explained by a higher SP_1 analog sum threshold for the second run. The distribution of the events over the Dalitz plot for the run 2 is shown in Fig.6. The variables $y = 2E_e/M_K$ and $z = 2E_\pi/M_K$, where E_e, E_π are the energies of the electron and π^0 in the kaon c.m.s are used. The background events, as MC shows, occupy the peripheral part of the plot.

The most general Lorentz invariant form of the matrix element for the decay $K^- \to l^-\nu\pi^0$ is [8]:

$$M = \frac{G_F V_{us}}{2}\bar{u}(p_\nu)(1+\gamma^5)[2m_K f_S - [(P_K+P_\pi)_\alpha f_+ + (P_K-P_\pi)_\alpha f_-]\gamma^\alpha + i\frac{2f_T}{m_K}\sigma_{\alpha\beta}P_K^\alpha P_\pi^\beta]v(p_l) \quad (1)$$

It consists of scalar, vector and tensor terms. $f_\pm$ are the functions of $t = (P_K - P_\pi)^2$. In the Standard Model (SM) the W-boson exchange leads to the pure vector term. The "induced" scalar and/or tensor terms due to EW radiative corrections are negligibly small, i.e the nonzero scalar/tensor form factors indicate physics beyond the SM.

The term in the vector part, proportional to f_- is reduced (using the Dirac equation) to a scalar form-factor. In the same way, the tensor term is reduced to a mixture of scalar and vector form-factors. The redefined V, S and the corresponding Dalitz plot density in the kaon rest frame ($\rho(E_\pi, E_l)$) are [9]:

$$\begin{aligned}
\rho(E_\pi, E_l) &\sim A\cdot|V|^2 + B\cdot Re(V^*S) + C\cdot|S|^2 \qquad (2)\\
V &= f_+ + (m_l/m_K)f_T,\\
S &= f_S + (m_l/2m_K)f_- + \left(1 + \frac{m_l^2}{2m_K^2} - \frac{2E_l}{m_K} - \frac{E_\pi}{m_K}\right)f_T,\\
A &= m_K(2E_lE_\nu - m_K\Delta E_\pi) - m_l^2(E_\nu - \frac{1}{4}\Delta E_\pi),\\
B &= m_l m_K(2E_\nu - \Delta E_\pi);\ E_\nu = m_K - E_l - E_\pi,\\
C &= m_K^2\Delta E_\pi;\ \Delta E_\pi = E_\pi^{max} - E_\pi;\ E_\pi^{max} = \frac{m_K^2 - m_l^2 + m_\pi^2}{2m_K}.
\end{aligned}$$

In case of K_{e3} decay one can neglect the terms proportional to m_l and m_l^2. Then, assuming linear dependence of f_+ on t: $f_+(t) = f_+(0)(1 + \lambda_+ t/m_\pi^2)$ and real constants f_S, f_T we get:

$$\begin{aligned}
\rho(E_\pi, E_l) &\sim m_K(2E_lE_\nu - m_K\Delta E_\pi)\cdot(1+\lambda_+ t/m_\pi^2)^2\\
&+ m_K^2\Delta E_\pi\cdot\left(\frac{f_S}{f_+(0)} + \left(1 - \frac{2E_l}{m_K} - \frac{E_\pi}{m_K}\right)\frac{f_T}{f_+(0)}\right)^2. \qquad (3)
\end{aligned}$$

The procedure for the experimental extraction of the parameters λ_+, f_S, f_T starts from the Dalitz plot region $y = 0.12 \div 0.92; z = 0.55 \div 1.075$ subdivision into 40×40 cells. The distribution of the numbers of events in the cells (i,j) over Dalitz plots in the case of simultaneous extraction of λ_+ and $\frac{f_S}{f_+(0)}$, for example, is fitted with the function:

$$W^{MC}(i,j) \sim W_1(i,j) + W_2(i,j)\cdot\lambda_+ + W_3(i,j)\cdot\lambda_+^2 + W_4(i,j)\cdot\left(\frac{f_S}{f_+(0)}\right)^2. \qquad (4)$$

Here W_l are MC-generated functions, which are build up as follows: the MC events are generated with constant density over the Dalitz plot and reconstructed with the same program as for the real events. Each event carries the weight w determined by the corresponding term in formula (3), calculated using the MC-generated values for y and z. The radiative corrections according to [10] is taken into account. Then W_l is calculated by summing up the weights of the reconstructed events in the corresponding Dalitz plot cell. This procedure allows to avoid the systematic errors due to the "migration" of the events over the Dalitz plot because of the finite experimental resolution.

The parameters of the amplitude of the decay is extracted by minimizing the extended log-likelihood function:

$$\mathcal{L} = \sum_{i,j} \left\{ \left(A \cdot W_{i,j}^{MC} + N_{ij}^{\mathrm{bgr}} - N_{i,j}^{\mathrm{exp}} \right) + N_{i,j}^{\mathrm{exp}} \cdot \ln \frac{N_{i,j}^{\mathrm{exp}}}{A \cdot W_{i,j}^{MC} + N_{ij}^{\mathrm{bgr}}} \right\}, \tag{5}$$

where the sum runs over all populated cells of the Dalitz plot. Here "A" is the data/MC normalization parameter; N_{ij}^{bgr}- the MC estimated background. The background normalization is determined by the ratio of the real and generated $K^- \to \pi^-\pi^0$ events. The minimization is performed by means of the MINUIT program [11].

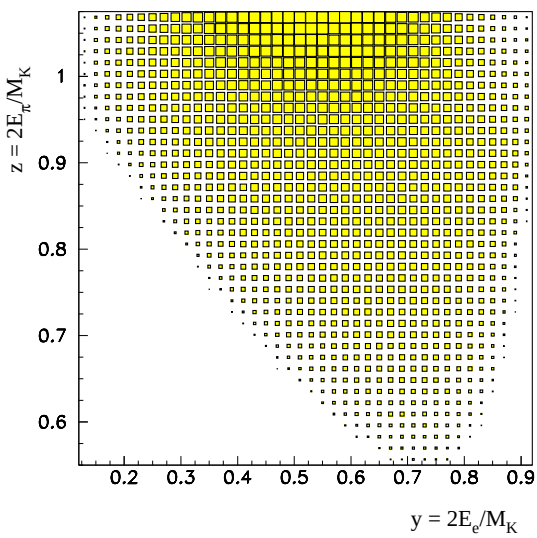

Figure 6: Dalitz plot for the selected $K \to e\nu\pi^0$ events. Run 2 data.

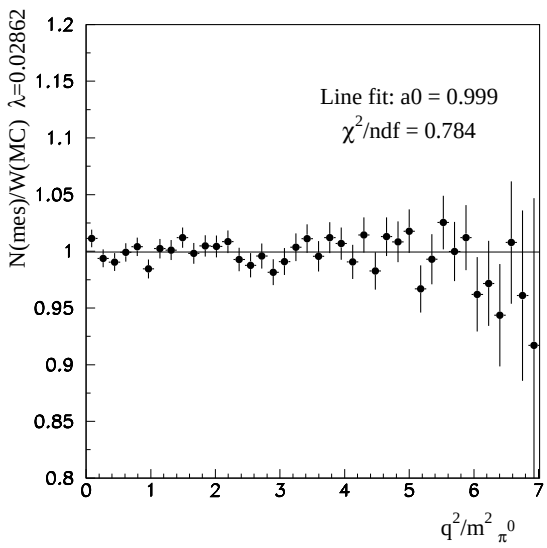

Figure 7: The ratio of the real data minus background over W_{MC}(see (4)) for the run 1+run 2 data;
W_{MC} is calculated with $\lambda_+ = 0.0286$ and $f_T = f_S = 0$.

5. Results

The results of the fit are summarized in Table.1.

Table 1. Results of the fit.

	run 1	run 2	run 1 + run 2
λ_+	0.0291 ± 0.0018	0.0285 ± 0.0009	0.0286 ± 0.0008
$f_T/f_+(0)$	$0.018^{+0.087}_{-0.099}$	$0.024^{+0.081}_{-0.107}$	$0.021^{+0.064}_{-0.075}$
$f_S/f_+(0)$	$0.003^{+0.024}_{-0.029}$	$0.002^{+0.019}_{-0.032}$	$0.002^{+0.020}_{-0.022}$
χ^2/ndf	1.13	1.14	1.14
N_{bins}	1120	1119	2239

The combination of the two runs is done by the simultaneous fit. The first line corresponds to pure V-A SM fit. In the second line the tensor and in the third the scalar terms are added into the fit.

The final errors presented are calculated by the MINOS procedure of the MINUIT program [11]. The errors are estimated at the $2\Delta\mathcal{L}$ level of 2.3 that corresponds to the coverage probability of 68.27% for joint estimation of 2 parameters [13].

To illustrate the quality of the fit, Fig.7 shows the ratio of the real data minus MC-predicted background $(N_{RD} - N_{BG})$ over W_{MC}, calculated using expression 4, with $\lambda_+ = 0.0286$ and $f_T = f_S = 0$, versus $t/m^2_{\pi^0}$.

Different sources of systematics were investigated:

- Dalitz plot bining:
  $\Delta\lambda_+ = \pm 0.00006$; $\Delta f_T = \pm 0.003$; $\Delta f_S = \pm 0.0006$. This kind of systematics is very small in our case because of the fitting method used (see formula (4)).
- Selection cuts variation
  1. 5C fit $K \to \pi^-\pi^0$ probability cut :
     $\Delta\lambda_+ = \pm 0.00041$; $\Delta f_T = \pm 0.0144$; $\Delta f_S = \pm 0.0018$.
  2. 2C $K \to e\nu\pi^0$ fit probability cut:
     $\Delta\lambda_+ = \pm 0.00025$; $\Delta f_T = \pm 0.008$; $\Delta f_S = \pm 0.0012$.
  3. Missing energy (E_ν) cut:
     $\Delta\lambda_+ = \pm 0.00015$; $\Delta f_T = \pm 0.0081$; $\Delta f_S = \pm 0.0008$.
  4. $|P_K - P_{beam}|$ cut:
     $\Delta\lambda_+ = \pm 0.00026$; $\Delta f_T = \pm 0.0104$; $\Delta f_S = \pm 0.0018$.
  5. E/p electron selection cut:
     $\Delta\lambda_+ = \pm 0.00014$; $\Delta f_T = \pm 0.010$; $\Delta f_S = \pm 0.0008$.
- MC signal variation: $\Delta\lambda_+ = \pm 0.00005$; $\Delta f_T = \pm 0.001$; $\Delta f_S = \pm 0.0001$.
- MC background variation: $\Delta\lambda_+ = \pm 0.00015$; $\Delta f_T = \pm 0.011$; $\Delta f_S = \pm 0.0003$.

From that, the summary systematics is: $\Delta\lambda_+ = \pm 0.0006$; $\Delta f_T = \pm 0.026$; $\Delta f_S = \pm 0.003$.

The comparison of our results with the most recent $K^{\pm}$ data [1,4] shows very good agreement in the λ_+ parameter. We do not observe any visible contributions of scalar and tensor terms in the amplitude in agreement with the conclusions of [4,5].

Some difference (2σ) with CPT order p^4 calculations for λ_+: $\lambda_+ = 0.031$ [12] is observed.

We also test a possible contribution of the quadratic term $\lambda_+^{''} t^2/m_\pi^4$ to the f_+ form-factor. The value of $\lambda_+^{''} = -0.00042^{+0.0011}_{-0.0015}$ was obtained with a fixed $\lambda_+ = 0.0286$. If λ_+ is allowed to vary its value is shifted to $\lambda_+ = 0.02867 \pm 0.0020$ and the quadratic coefficient becomes $\lambda_+^{''} = -0.002^{+0.0031}_{-0.0066}$. In both cases we conclude that a possible quadratic contribution into the vector form-factor is compatible with zero.

6. Summary and conclusions

The K^-_{e3} decay has been studied using in-flight decays of 25 GeV K^-, detected by ISTRA+ magnetic spectrometer. Due to the high statistics, adequate resolution of the detector and good sensitivity over all the Dalitz plot space, the errors are significantly reduced as compared with the previous measurements. The λ_+ parameter of the vector form-factor has been measured to be:

$$\lambda_+ = 0.0286 \pm 0.0008(stat) \pm 0.0006(syst).$$

A limit on the quadratic nonlinearity for $f_+(t)$ is obtained:

$$\lambda_+^{''} = -0.00043^{+0.0011}_{-0.0015}(stat).$$

Limits on possible tensor and scalar couplings have been derived:

$$f_T/f_+(0) = 0.021^{+0.064}_{-0.075}(stat) \pm 0.026(syst);$$

$$f_S/f_+(0) = 0.002^{+0.020}_{-0.022}(stat) \pm 0.003(syst)$$

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