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Measurement of the Interference Term INT^- in the Radiative Kaon Decay $K^- \to \mu^- \bar{\nu} \gamma$

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Abstract

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Using data collected with the "ISTRA+" spectrometer during the 2001 run of the U70 proton synchrotron at IHEP, we report the first measurement of the interference term INT^- in the radiative kaon decay $K^- \to \mu^- \overline{\nu}\gamma$. We find the difference of the vector and axial form factors $F_V - F_A = 0.197 \pm 0.052(\text{stat}) \pm 0.017(\text{syst})$. The measured value is 2.6 standard deviations above the $O(p^4)$ ChPT prediction equal to 0.055.

Аннотация

Чикилёв О.Г., Акименко С.А., Бритвич Г.И. и др. Измерение интерференционного члена INT^- в радиационном распаде каона $K^- \to \mu^- \bar{\nu}\gamma$: Препринт ИФВЭ 2008-27. – Протвино, 2008. – 11 с., 7 рис., библиогр.: 11.

Использование данных установки "ИСТРА+", полученных в сеансе ускорителя У70 в 2001 г., позволило провести первое измерение интерференционного члена INT^- в радиационном распаде каона $K^- \to \mu^- \overline{\nu}\gamma$. Измерена разность векторного и аксиального форм факторов $F_V - F_A = 0.197 \pm 0.052(\text{stat}) \pm 0.017(\text{syst})$. Эта величина превышает $O(p^4)$ предсказание киральной пертурбативной теории (ChPT), равное 0.055, на 2.6 стандартных отклонения.

1. Introduction

The decay $K^- \to \mu^- \overline{\nu}\gamma$ proceeds via two distinct mechanisms: the internal Bremsstrahlung (IB) with a photon emitted by the kaon or the muon, and the structure-dependent(SD) decay involving emission of a photon from intermediate states. SD is sensitive to the electroweak structure of the kaon and allows for good test of theories describing hadron interactions and decays, like Chiral Perturbation Theory (ChPT) [1, 2]. The differential probability of the decay can be written in terms of $x = \frac{2E_\gamma}{M_K}$ and $y = \frac{2E_\mu}{M_K}$ (where M_K is the kaon mass and E_γ and E_μ are the photon and muon energies in the kaon rest frame):

$$\frac{d\Gamma}{dxdy} = A_{IB} f_{IB}(x,y) + A_{SD}[(F_V + F_A)^2 f_{SD^+}(x,y) + (F_V - F_A)^2 f_{SD^-}(x,y)] \\ -A_{INT}[(F_V + F_A) f_{INT^+}(x,y) + (F_V - F_A) f_{INT^-}(x,y)],$$

$$f_{IB}(x,y) = [\frac{1-y+r}{x^2(x+y-1-r)}][x^2 + 2(1-x)(1-r) - \frac{2xr(1-r)}{x+y-1-r}], \tag{1}$$

$$f_{SD^+}(x,y) = [x+y-1-r][(x+y-1)(1-x) - r], \tag{2}$$

$$f_{SD^-}(x,y) = [1-y+r][(1-x)(1-y) + r], \tag{3}$$

$$f_{INT^+}(x,y) = [\frac{1-y+r}{x(x+y-1-r)}][(1-x)(1-x-y) + r], \tag{4}$$

$$f_{INT^-}(x,y) = [\frac{1-y+r}{x(x+y-1-r)}][x^2 - (1-x)(1-x-y) - r], \tag{5}$$

where $r = (\frac{M_\mu}{M_K})^2$ with M_μ being the muon mass and

$$A_{IB} = \Gamma_{K_{\mu 2}} \frac{\alpha}{2\pi} \frac{1}{(1-r)^2}, \tag{6}$$

$$A_{SD} = \Gamma_{K_{\mu 2}} \frac{\alpha}{8\pi} \frac{1}{r(1-r)^2} [\frac{M_K}{F_K}]^2, \tag{7}$$

$$A_{INT} = \Gamma_{K_{\mu 2}} \frac{\alpha}{2\pi} \frac{1}{(1-r)^2} \frac{M_K}{F_K}. \tag{8}$$

In these formulas F_V and F_A are the vector and axial form factors, α is the fine structure constant, F_K is the charged kaon decay constant $(159.8 \pm 1.4 \pm 0.4)$ MeV, and $\Gamma_{K_{\mu 2}}$ is the width of the $K_{\mu 2}$ decay. We use the PDG [3] convention with dimensionless and larger by a factor $\sqrt{2}$ form factors than in many theoretical papers. As in the paper [4] a minus sign precedes the interference term, thus changing the sign of the form factors.

SD^+ and SD^- refer to different photon polarizations and do not mutually interfere. Their interference with IB leads to the terms labeled INT^+ and INT^-. The x vs y plots for different terms are illustrated in Fig. 1. The parallelogram area $1.045 < x + y < 1.15$ in this figure, with practically maximum for SD^- and INT^- terms is used in the following.

Generally form factors can depend on $q^2 = (p_K - p_\gamma)^2 = M_K^2(1-x)$. In our analysis we assume the same dependence as in [4]: $F_V(q^2) = F_V(0)/(1 - q^2/M_V^2)$ and $F_A(q^2) = F_A(0)/(1 - q^2/M_A^2)$ with $M_V = 0.870$ GeV and $M_A = 1.270$ GeV.

The absolute value of the sum of the form factors is known with high precision: $|F_V + F_A| = (0.155 \pm 0.008)$ [4], whereas the difference is still poorly known. The latest measurent [4] gives for $F_V - F_A$ only the 90% confidence level: $-0.04 < F_V - F_A < 0.24$, whereas the $O(p^4)$ ChPT prediction is equal to 0.05 [1].

2. Experimental setup and event selection

The experiment is performed at the IHEP 70 GeV proton synchrotron U70. The ISTRA+ spectrometer has been described in detail in recent papers on K_{e3} [5, 6], $K_{\mu 3}$ [7, 8] and $\pi^-\pi^\circ\pi^\circ$ decays [9]. Here we recall briefly the characteristics relevant to our analysis. The ISTRA+ setup is located in the negative unseparated secondary beam line 4A of the U70. The beam momentum is $\sim$25 GeV/c 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 U70 spill.

During the physics run in November–December 2001 350 million trigger events were collected with high beam intensity. This information is complemented by 124 M Monte Carlo (MC) events generated using Geant3 [10] for the dominant K^- decay modes, 100 M of them are the mixture of the dominant decay modes with the branchings exceeding 1% and 24 M MC events are the radiative $K_{\mu 2}$ decays.

Some information on the data processing and reconstruction procedures is given in [5, 7, 9, 6, 8], here we briefly mention the details relevant for present analysis.

The muon identification (see [7, 8]) is based on the information from the electromagnetic calorimeter SP_1 and hadron calorimeter HC. The energy deposition in the SP_1 is required to be compatible with the MIP signal in order to suppress charged pions and electrons. The sum of the signals in the HC cells associated with charged track is required to be compatible with the MIP signal. The muon selection is further enhanced by the requirement that the ratio r_3 of the HC energy in last three layers to the total HC energy exceeds 5%. The used cut values are the same as in [8].

Events with one reconstructed charged track and one reconstructed shower in the calorimeter SP_1 are selected.

A set of cuts is developed to suppress various backgrounds and/or to do data cleaning:

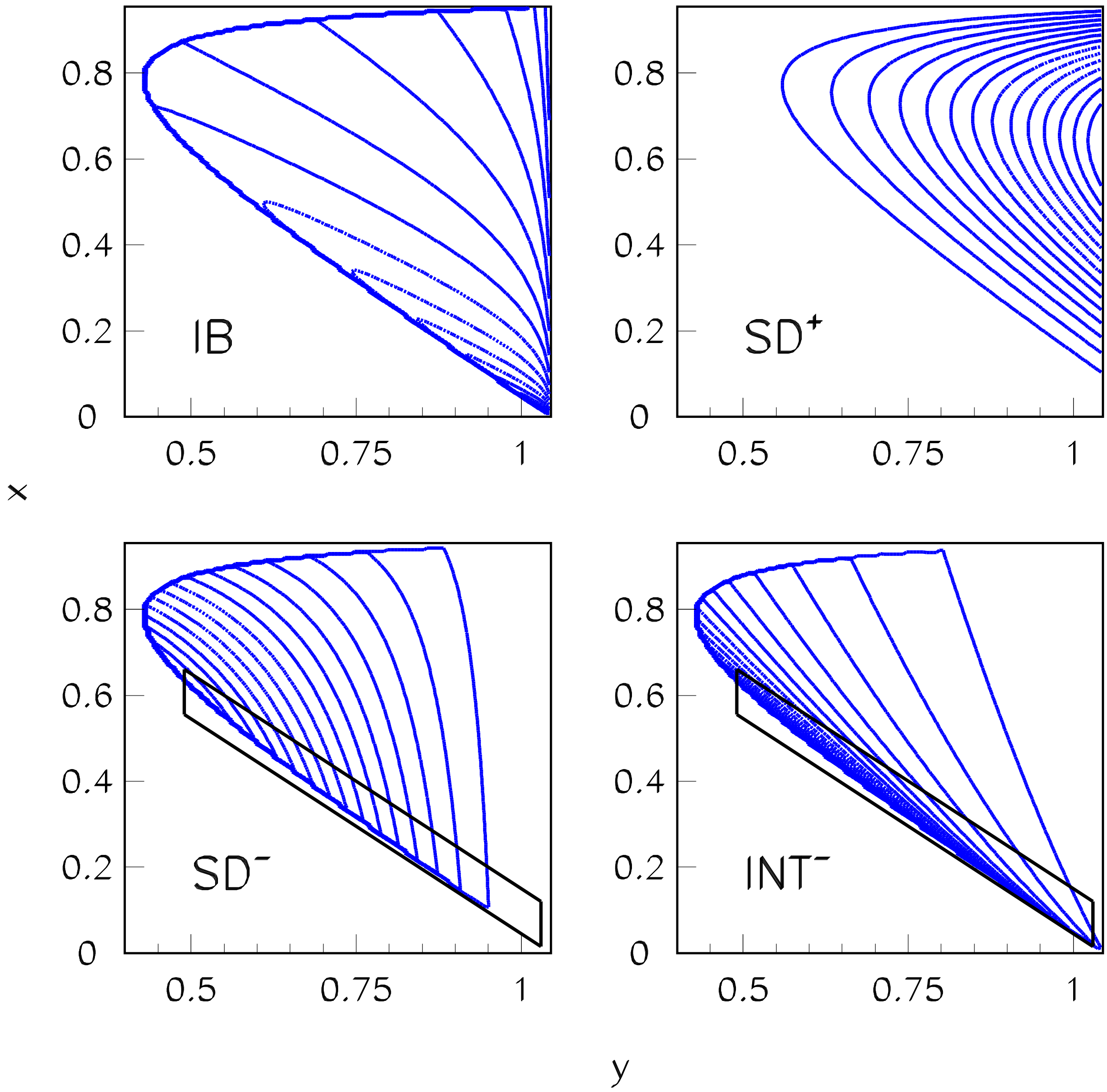

Figure 1. Dalitz plots for IB, SD^+, SD^- and INT^- contributions. The scale for IB is logarithmic. The parallelograms show the region studied.

0) We select events with good charged track having two reconstucted ($x-z$ and $y-z$) projections and the number of hits in the matrix hodoscope MH below 3.

1) Events with the reconstructed vertex inside the interval $400 < z < 1600$ cm are selected.

2) The measured missing energy $E_{mis} = E_{beam} - E_{\mu} - E_{\gamma}$ is required to be above zero.

3) The events with missing momentum pointing to the SP_1 working aperture are selected in order to suppress some $\pi^-\pi^\circ$ background ($r > 10$ cm, here r is the distance between the impact point of the missing momentum and the SP_1 center in the SP_1 transverse plane).

4) We require also the absence of the signal above the threshold in the calorimeter SP_2 and the guard veto system GS.

We look for a signal in the distributions over the effective mass $m(\mu^-\gamma\nu)$, where ν four-momentum is calculated using the measured missing momentum and assuming $m_\nu = 0$. Effective mass spectra for the parallelogram region in Fig. 1 are shown in Figs. 2, 3 and 4 for y-interval 0.49—1.03 with the step $\delta y = 0.03$.

The effective mass spectra have been parametrized by the sum of a signal and of a background. The signal form have been found from the signal Monte Carlo events parametrized by the sum of two Gaussians. The background have been found using the histogram smoothing of the MC background mass spectra by the HQUAD routine from the HBOOK package [11]. This background does not ideally describe the real data, especially at low effective masses, this is possibly due to the underestimate of the event pileup in our MC. This discrepance has been taken into account by addition of a sixth degree polynomial to the background. First parameter of the fit gives the number of events in the kaon peak, second — the position of the peak, third — normalization of the MC background, last seven parameters are the coefficients of the polynomial.

At small y the signal is rather small, at large y, especially in the IB region, it dominates over the background. The peak at the effective mass 0.43–0.45 GeV, seen in the histograms m), n) and o) is the reflection of the $K_{\pi 2}$ decay mode.

The resulting event distribution in the interval $0.49 < y < 1.00$ have been parametrized by the $\frac{d\Gamma}{dxdy}$ integrated over δy in the parallelogram region. The results of the fit are shown in Fig. 5, where the first parameter is $F_V + F_A$ fixed at the value 0.155 taken from [4], the second parameter is $F_V - F_A$ and the third parameter is the normalization factor. In fact, the fit results are insensitive to the value $F_V + F_A$ since the SD^+ and INT^+ contributions are negligible, see Fig. 5.

The fit is satisfactory, χ^2/NDF$= 26.71/(17-2)$ and $F_V - F_A = 0.197 \pm 0.052$. Our sensitivity to the sign of the second parameter is illustrated in Fig. 6 with this parameter taken with the minus sign. This assumption is clearly improbable since χ^2 increases by a factor of five to the value χ^2/NDF$= 143.8/(17-2)$.

We have tried also the fit without q^2 dependence of the form factors. The $\chi^2/NDF = 26.23/(17-2)$ and $F_V - F_A = 0.231 \pm 0.050$.

The main source of systematics is poor knowledge of the background shape. The systematic error has been estimated as follows. Effective mass spectra have been fitted using fourth degree polynomial instead of sixth degree one, the difference in the number of events (our estimate of systematics in each bin) has been added in quadrature to the statistical error. The result of the fit with enlarged errors, see Fig. 7, is $F_V - F_A = 0.190 \pm 0.112$. The difference between second parameters of two fits equal to 0.0068 is our estimate of systematics due to the background shape. The use of different y intervals during fit gives the variation of the $F_V - F_A$ in the region between 0.188 and 0.219, leading to the possible error 0.0155 (the half of this interval).

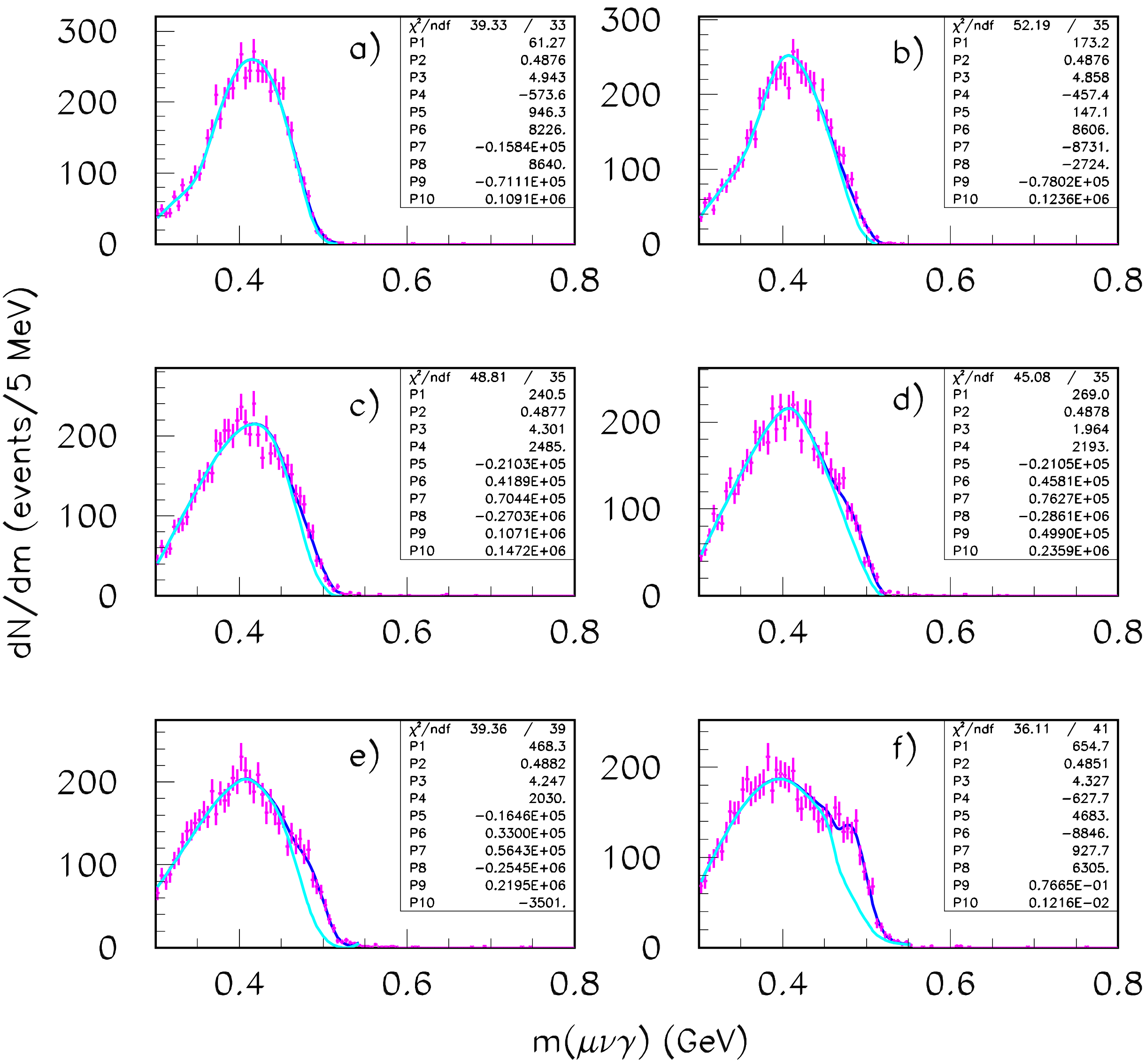

Figure 2. Effective mass m($\mu^-\nu\gamma$) spectra for the y-interval 0.49—0.67 with the step $\delta y = 0.03$.

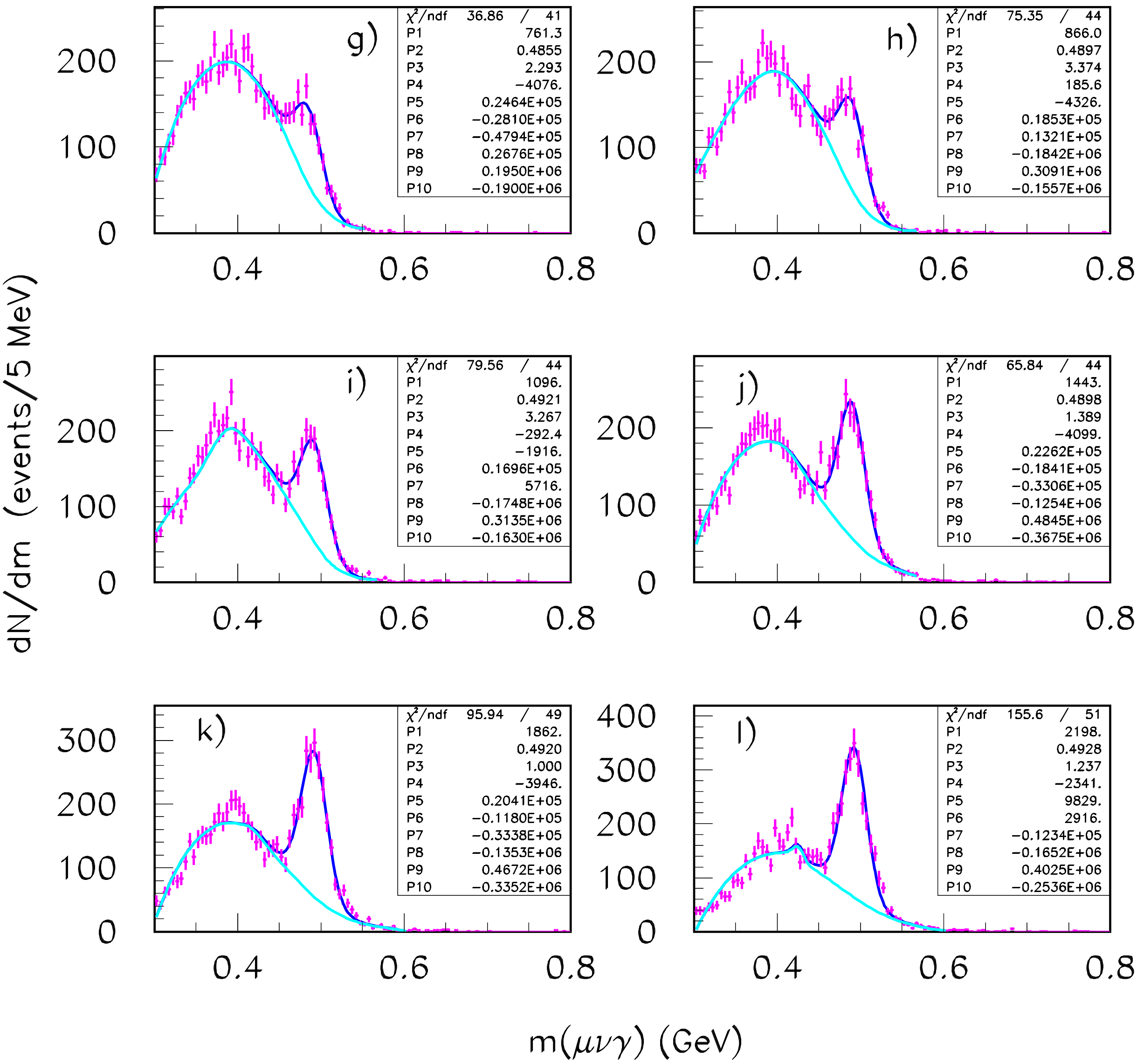

Figure 3. Effective mass m($\mu^- \nu \gamma$) spectra for the y-interval 0.67—0.85 with the step $\delta y = 0.03$.

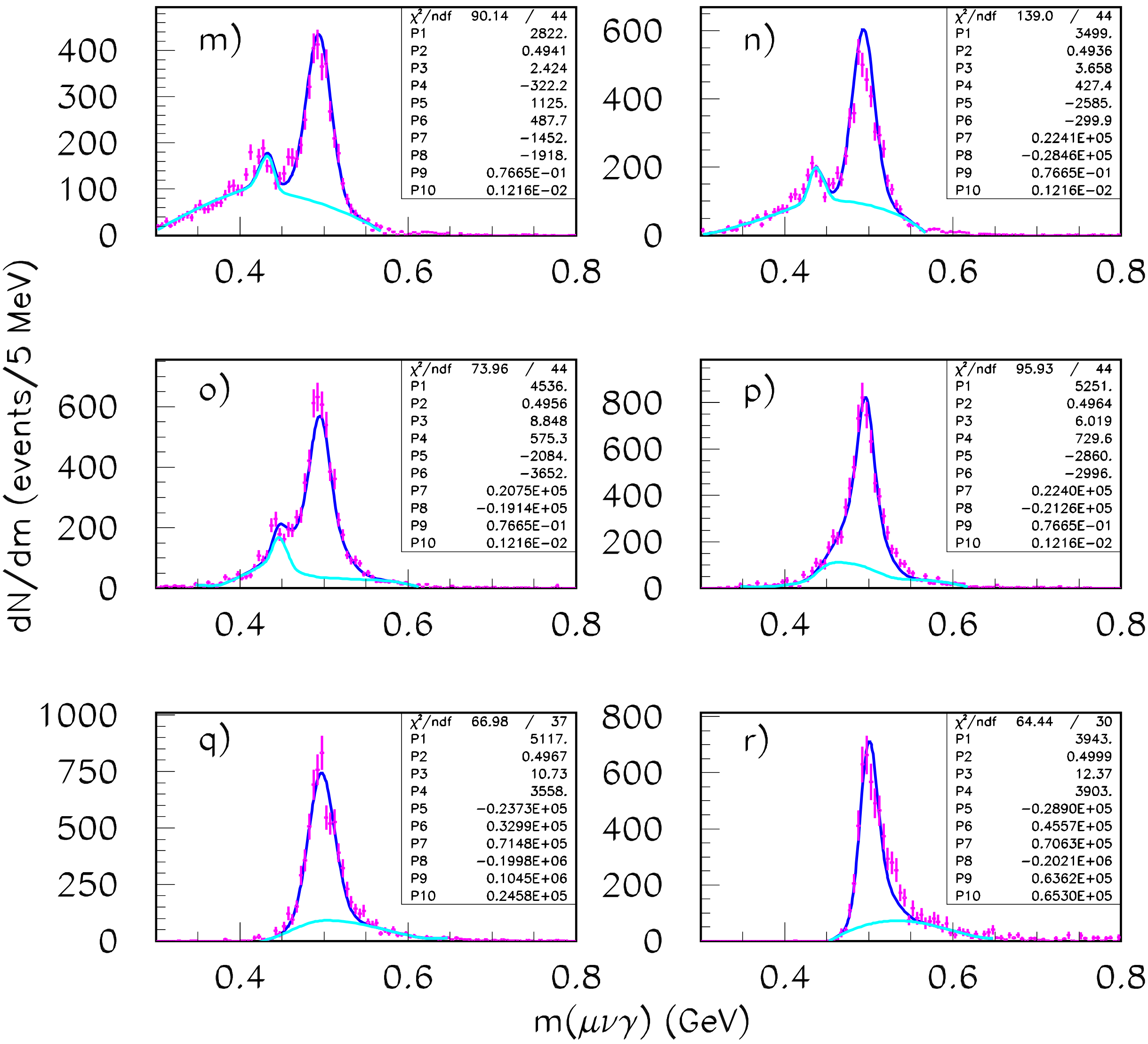

Figure 4. Effective mass m($\mu^-\nu\gamma$) spectra for the y-interval 0.85–1.03 with the step $\delta y = 0.03$.

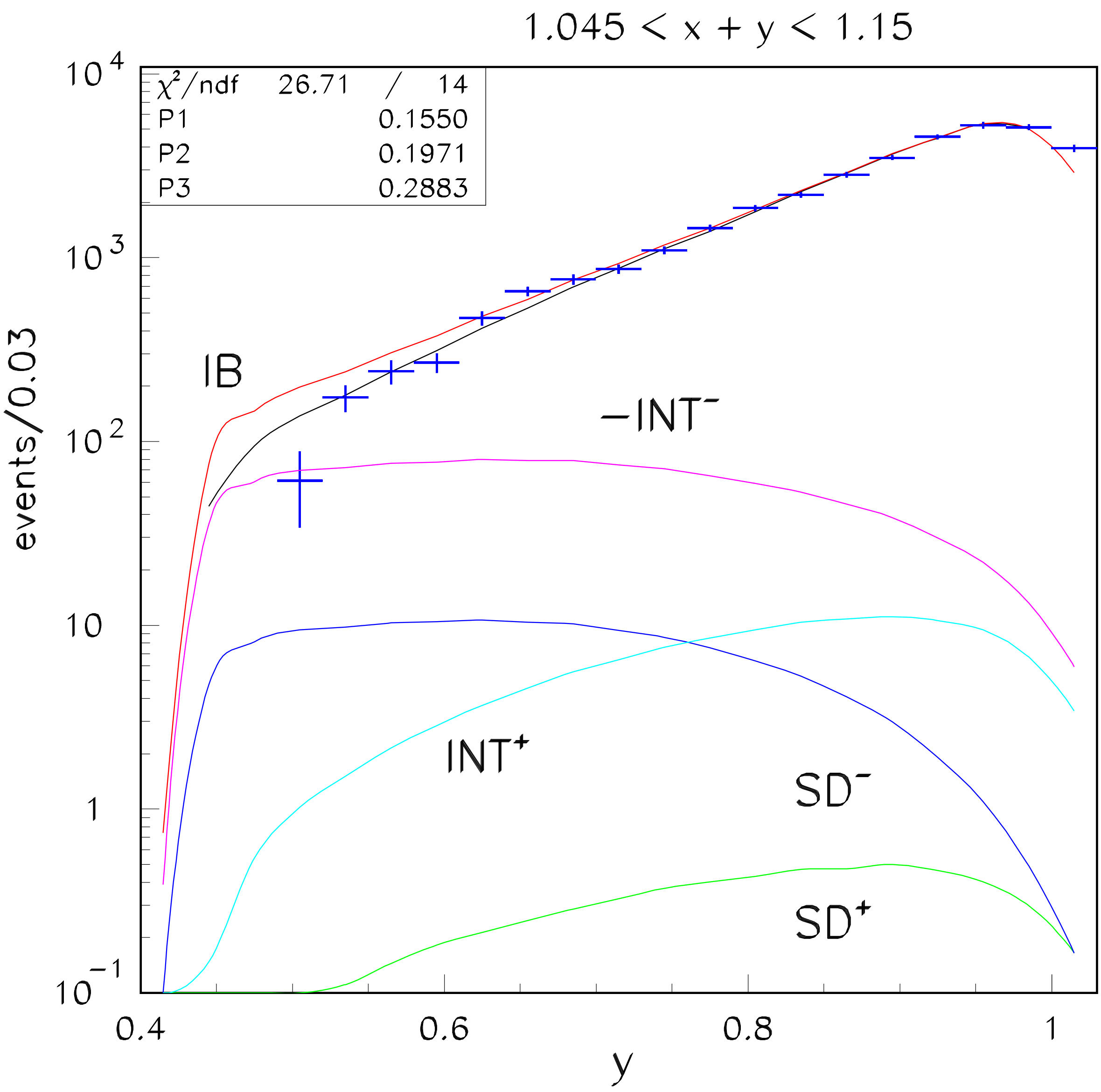

Figure 5. Results of fit of the event distribution.

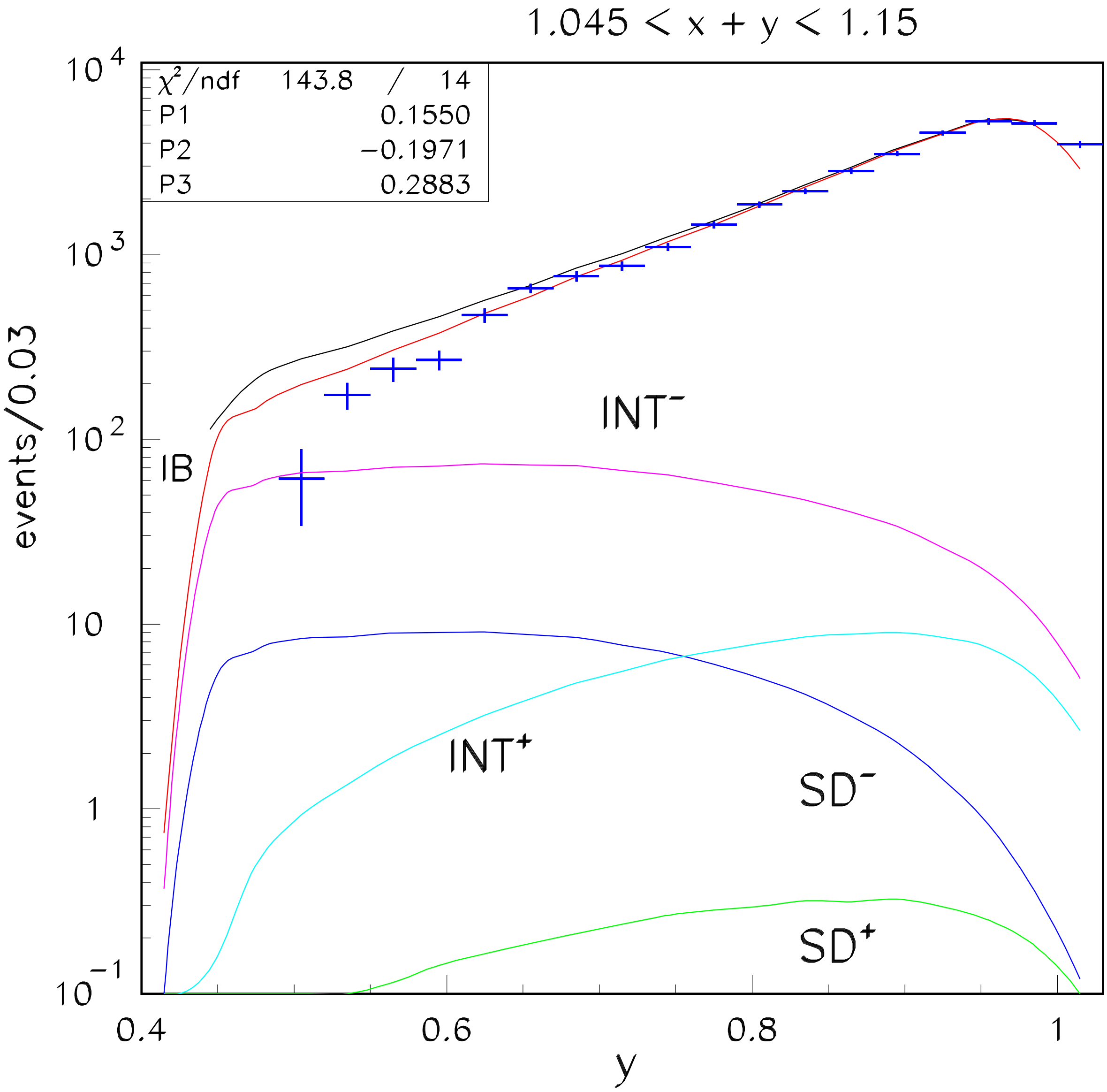

Figure 6. The “fit” with $F_V - F_A$ having negative sign.

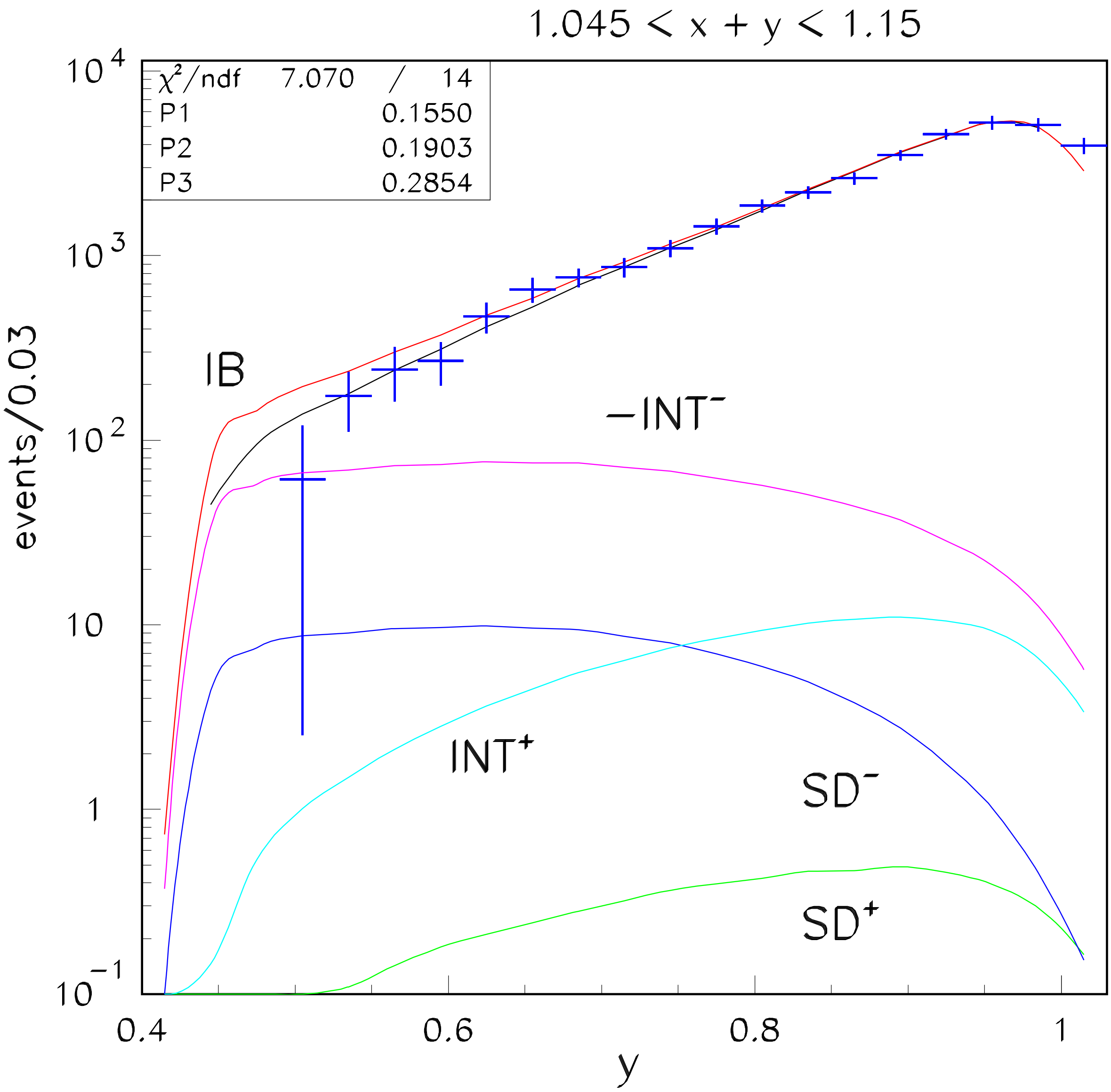

Figure 7. The fit with enlarged errors.

Our final result is: $F_V - F_A = 0.197 \pm 0.052(\text{stat}) \pm 0.017(\text{syst})$.

Conclusions

Our conclusion is as follows:

The measurement of the radiative kaon decay $K^-_{\mu 2\gamma}$ in the region where SD^- and INT^- terms have a maximum gives the value $F_V - F_A = 0.197 \pm 0.052(\text{stat}) \pm 0.017(\text{syst})$. This value is 2.6 standard deviation above $O(p^4)$ ChPT prediction, equal to 0.055, and indicates the need for higher order calculations.

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