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Recent results from OKA setup at U-70 synchrotron

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Recent results from OKA setup at U-70 synchrotron.

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Abstract. Several radiative decays are under study by OKA setup at U-70 synchrotron. First, the radiative decay $K^+ \to \mu^+\nu\gamma(K_{\mu 2\gamma})$ is studied on statistics of about 95K events for 25 MeV< E^*_γ < 150 MeV. A clear destructive interference between bremsstrahlung and structure dependent SD^- term is observed. As a result, the vector and axial-vector form factors difference is measured: $F_V - F_A = 0.134 \pm 0.021(stat.) \pm 0.027(syst.)$ which is 2.3 σ away from $\chi PTO(p^4)$. Moreover, the decay $K^+ \to \pi^+\pi^-\pi^+\gamma$ is studied on statistics of about 450 events for 30 MeV< E^*_γ < 70 MeV. The total and differential branching fractions of the decay are measured. Br$(K^+ \to \pi^+\pi^-\pi^+\gamma) = (7.1 \pm 0.4(stat.) \pm 0.3(syst.)) \cdot 10^{-6}$ to be compared with $\chi PTO(p^4)$ $(6.65 \pm 0.05) \cdot 10^{-6}$. In addition, a search for an up-down photon asymmetry with respect to the hadronic system decay plane is performed.

1. Introduction

The kaon decays provide unique information about the dynamics of the electro-week interactions. It has been a testing ground for such theories as current algebra, PCAC, Chiral Perturbation Theory (ChPT) etc. In this contribution we present a study of $K_{\mu 2\gamma}$ and $K_{3\pi\gamma}$ decays from OKA detector at U-70 Proton Synchrotron.

2. OKA beam and detector

OKA is the abbreviation for "Experiments with Kaons". OKA beam is a RF-separated secondary beam of U-70 Proton Synchrotron of IHEP, Protvino. The beam is described elsewhere [1]. RF-separation with Panofsky scheme is realised. It uses two superconductive Karsruhe-CERN SC RF deflectors [2], donated by CERN. Sophisticated cryogenic system, built at IHEP [3] provides superfluid He for cavities cooling. The resulting beam has up to $\sim 20\%$ of kaons with an intensity of $\sim 10^6$ kaons per 3 sec U-70 spill. The OKA setup is presented on Fig. 1.

Two main triggers have been used during data-taking: $Tr_1 = S_1 \cdot S_2 \cdot S_3 \cdot \overline{\check{C}_1} \cdot \check{C}_2 \cdot \overline{S}_{bk} \cdot (\Sigma_{GAMS} > MIP)$. It is a combination of beam Sc counters, $\check{C}_{1,2}$ threshold Cherenkov counters ($\check{C}_1$ sees pions, $\check{C}_2$- pions and kaons), S_{bk} - a "beam-killer" counter located in the beam-hole of the GAMS gamma-detector. $\Sigma_{GAMS} > MIP$ is a requirement for the analog sum of amplitudes in the GAMS-2000 to be higher than a Minimun Ionizing Particle signal(2.5 GeV). In the second trigger the last component is substituted by the requirement $2 \leq MH \leq 4$, where MH is the multiplicity in the matrix hodoscope. The "OKA" is taking data since 2010, the total statistics corresponds to $N_K \sim 5 \times 10^{10}$ kaons, entering the decay volume.

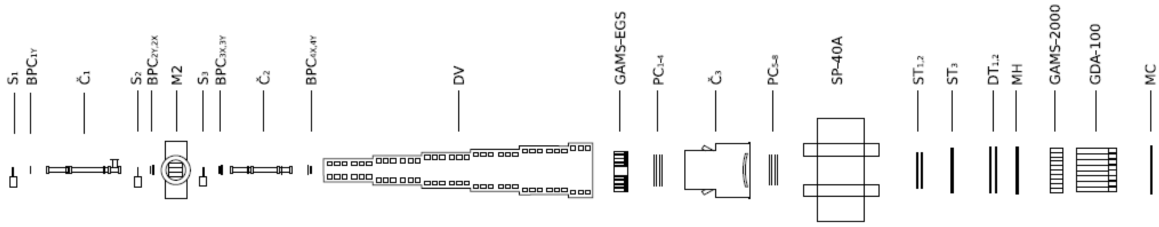

Figure 1. OKA setup includes: Beam spectrometer on the basis of seven 1mm pitch PC's ($BPC_{x,y}$) ∼1500 channels in total; Decay volume(DV) with Veto system, 11m long, filled with He; magnetic spectrometer: 200×140 cm^2 aperture , $\int Bdl \sim$ 1Tm magnet, 5K 2mm pitch PC's, 1K 9mm Straw's and 300 channels of 40mm DT's; The matrix hodoscope (MH) composed of 252 scintillator tiles with WLS+SiPM readout; Gamma detectors: GAMS-2000 ($\sim$ 2000 4×4 cm^2 LG blocks), GAMS-EGS ($\sim$ 1500 LG blocks); Muon detector: GDA-100 Hadron Calorimeter (100 20×20 cm^2 iron-scintillator sandwiches), four 1m^2 Sc counters behind GDA-100 (MC).

3. $K_{\mu\nu\gamma}$ decay study.

The amplitude of the $K^+ \to \mu^+\nu_\mu\gamma$ decay includes: inner bremsstrahlung (IB) , structure dependent (SD) terms and their interference. SD is sensitive to the electroweak structure of the kaon. The differential decay rate can be written in terms of Dalitz-plot variables $x = 2E^*_\gamma/M_K$ and $y = 2E^*_\mu/M_K$, where E^*_γ is the photon and E^*_μ the muon energy in the kaon rest frame. It includes IB, SD$^\pm$ terms and their interference INT$^\pm$. The SD$^\pm$ and INT$^\pm$ terms are determined by two form factors F_V and F_A. The general formula for the decay rate is as follows [4]:
$\frac{d\Gamma}{dxdy} = A_{IB}f_{IB}(x,y) + A_{SD}[(F_V + F_A)^2 f_{SD^+}(x,y) + (F_V - F_A)^2 f_{SD^-}(x,y)] -$
$A_{INT}[(F_V + F_A)f_{INT^+}(x,y) + (F_V - F_A)f_{INT^-}(x,y)]$, where $f_{IB}, f_{SD^+}, f_{SD^-}, f_{INT^+}, f_{INT^-}$ are functions known from theory, $A_{IB} = \Gamma_{K_{\mu2}} \frac{\alpha}{2\pi}\frac{1}{(1-r)^2}$, $A_{SD} = \Gamma_{K_{\mu2}} \frac{\alpha}{8\pi}\frac{1}{r(1-r)^2}[\frac{M_K}{F_K}]^2$,
$A_{INT} = \Gamma_{K_{\mu2}} \frac{\alpha}{2\pi}\frac{1}{(1-r)^2}[\frac{M_K}{F_K}]$. Here α is the fine structure constant, F_K is K^+ decay constant ($F_K = 155.6 \pm 0.4\, MeV$ [5]), $\Gamma_{K_{\mu2}}$ is the $K_{\mu2}$ decay width and $r = (m_\mu/M_K)^2$.

The main goal of the analysis is to measure $F_V - F_A$ by extracting the INT$^-$ term. Other terms are either suppressed by backgrounds or give negligible contribution to the total decay rate with respect to IB. In the lowest order of χPT $O(p^4)$ $F_V - F_A = 0.052 \pm 0.008$ [4]. The first measurement of $F_V - F_A$ was made by the ISTRA+ experiment: $F_V - F_A = 0.21 \pm 0.04(stat.) \pm 0.04(syst.)$ [6]. The study of the $K_{\mu2\gamma}$ decay is based on half of the statistics of 2012 run taken with Tr_1. It corresponds to $N_K \sim 1.2 \times 10^{10}$. The data processing starts with the beam particle reconstruction, then the secondary tracks are looked for and events with one good positive track are selected. The decay vertex is searched for, it is required to be inside DV and a cut is introduced on the vertex quality. The secondary track should be identified as μ in GAMS, GDA and MC. The next step is to look for showers in GAMS-2000 and to select events with one shower with $E > 1$ GeV not associated with the charged track. The last requirement is on the total energy in GS and EGS: $E_{GS} < 10$ MeV; $E_{EGS} < 100$ MeV. The further analysis is based on the fit of the distributions of the events over the Dalitz plot. The procedure starts with dividing the Dalitz plot (x, y) region into strips in x with $\Delta x = 0.05$ width. The following steps are implemented for each x-strip(see Fig. 2): Plotting the distribution of the events over y; Selecting the signal region by a cut $y_{min} < y < y_{max}$ and filling $\cos\theta^*_{\mu\gamma}$ plot, where $\theta^*_{\mu\gamma}$ is an angle between μ and γ in the kaon rest frame. y_{min} and y_{max} are selected from the maximization of signal significance; Applying a cut on $\cos\theta^*_{\mu\gamma}$ to futher reject the background; Plotting the distribution of the selected events over m_k. $m_k^2 = (P_\mu + P_\nu + P_\gamma)^2$, where P_μ,P_ν,P_γ are 4-momenta

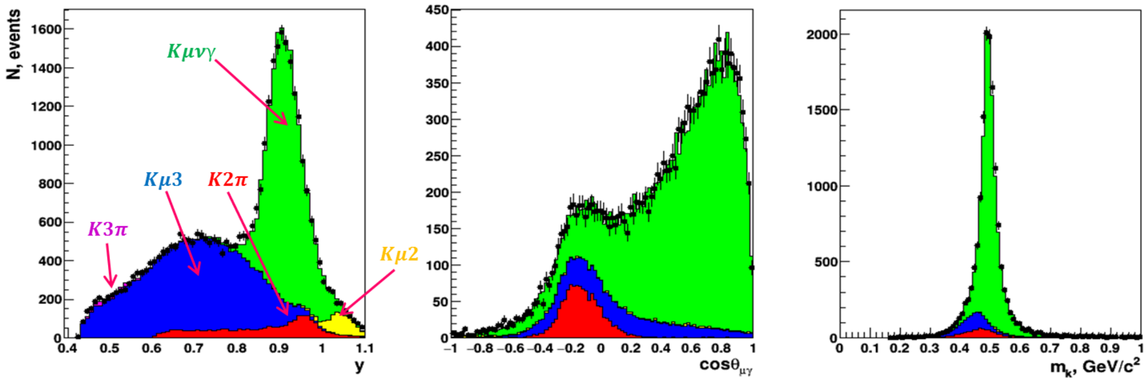

Figure 2. Simultaneous fit in the strip 2 ($0.15 < x < 0.20$): y, $\cos\theta^*_{\mu\gamma}$, m_k. Black points with errors - data, blue - $K\mu3$, red - $K2\pi$, yellow - $K\mu2$, violet - $K3\pi$, green - signal. $\chi^2/NDF = 1.7$.

of the decay particles in the laboratory frame, $\vec{p}_\nu = \vec{p}_K - \vec{p}_\mu - \vec{p}_\gamma$, $E_\nu = |\vec{p}_\nu|$. m_k peaks at the kaon mass for the signal. The last step is a simultaneous fit of all 3 histograms $(y, \cos\theta^*_{\mu\gamma}, m_k)$ with the MINUIT tool [7] where the signal and backgrounds normalization factors are the fit parameters. For the correct estimation of the statistical error σ_{exp}, only the m_k histogram is used. The MINOS program [7] is run once with the initial parameters values equal to those obtained in the simultaneous fit. Statistical errors were extracted from the MINOS output.

3.1. Results and comparison with theory

For each x-strip the number of signal events N_{Data} is extracted from the simultaneous fit and the IB event number N_{IB} is obtained from MC. Their ratio is plotted as a function of x (Fig. 3). For the signal containing IB only this ratio would be equal to 1. It is the case for small x, when the IB is dominating and INT$^-$ is negligible. For large x the INT$^-$ term gives significant negative contribution resulting in smaller values of N_{Data}/N_{IB}.

The N_{Data}/N_{IB} distribution is fitted with a function $p_{signal}(x) = p_0(1+p_1(\phi_{INT^-}(x)/\phi_{IB}(x)))$,

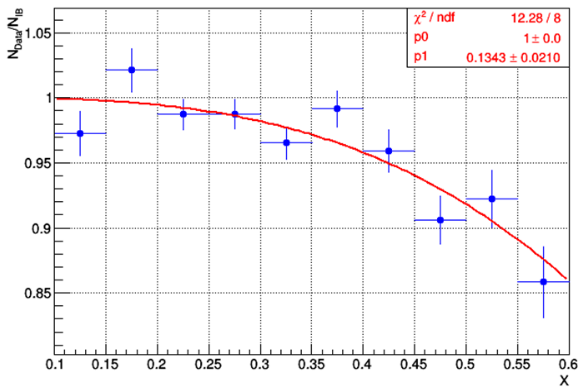

Figure 3. N_{Data}/N_{IB} ratio as a function of x (blue points with errors) and result of the fit with $p_{signal}(x)$ (red line). For the definition of $p_{signal}(x)$, see the text.

where p_0 is normalization factor, $p_1 = F_V - F_A$ is the difference of vector and axial-vector form factors, $\phi_{INT^-}(x)$ is the x-distribution for the reconstructed MC-signal events taken with the weights $(M_K/F_K)f_{INT^-}(x_{true}, y_{true})$, $\phi_{IB}(x)$ is a similar distribution for the same MC sample, but with the weights $f_{IB}(x_{true}, y_{true})$. Here x_{true}, y_{true} are "true" MC values of x and y.

The result of the fit is $F_V - F_A = 0.134 \pm 0.021$. The normalization factor is $p_0 = 1.000 \pm 0.007$. The total number of selected $K^+ \to \mu^+ \nu_\mu \gamma$ decay events is ~ 95000.
The following sources of systematic errors are investigated: non ideal description of signal and background by the MC($\sigma_{shape} = 0.015$); the fit range in $x(\sigma_x < 0.006)$; width of x-strips ($\sigma_{\Delta x} = 0.011$); y limits in x-strips($\sigma_y = 0.008$); possible contribution of INT$^+$. The INT$^+$ term is added to the final fit. The value $|F_V + F_A| = 0.165 \pm 0.013$ measured by the E787 experiment is used [8]. Two fits were repeated for the minimal (-0.178) and maximal (+0.178) possible values of $F_V + F_A$. The maximal difference between obtained values of $F_V - F_A$ and the main one is $\sigma_{INT^+} = 0.018$. Summing up quadratically all the systematic errors the total error is found to be 0.027. The final result is $F_V - F_A = 0.134 \pm 0.021(stat.) \pm 0.027(syst.)$ which is $\sim 2.3\sigma$ away from $\chi PTO(p^4)$ [4]. A recent calculation in the framework of the gauged nonlocal effective chiral action($E\chi A$) gives $F_V - F_A = 0.081$ [9], 1.6σ away from the OKA result.

4. Study of the decay $K^+ \to \pi^+\pi^-\pi^+\gamma$.

The present experimental status of $K^+ \to \pi^+\pi^-\pi^+\gamma$ is rather meagre. It was observed in one experiment with a statistics of 7 events [10]. The photon energies in these events were low, that did not allow to search for deviations from a simple QED process of photon emission. In the present analysis we have a possibility for more detailed study of this decay using larger data sample collected by the OKA experiment. This decay has certain interest for the theory, in particular for the chiral perturbation theory, which gives an appropriate framework for the analysis of such decays. A deatiled theoretical elaboration was done in [11]. It is interesting to compare these results to the experimental data.

In a decay in the beauty sector $B^+ \to K^+\pi^+\pi^-\gamma$ the LHCb experiment has found significant up-down asymmetry of the photon with respect to the hadronic system decay plane [12]. This observable is both P and T-odd. We perform an analogous study for the radiative kaon decay $K \to 3\pi\gamma$ to search for new physics effects.

4.1. Event selection

To select $K^+ \to \pi^+\pi^-\pi^+\gamma$ decay channel in off-line analysis a set of requirements is applied:
– the momentum of the beam track should be measured;
– the number of the secondary charged tracks equals three, their net charge is +1;
– the decay vertex should have good χ^2 and should be with a margin inside the DV;
– the charged tracks are not identified as electrons in the GAMS-2000 e.m. calorimeter;
– the squared missing mass to each positive pion $M^2_{miss}(\pi^+) = (P_{K^+} - P_{\pi^+})^2 > 0.07$ GeV^2;
– the event should contain one and only one photon with the energy $E_\gamma > 0.5$ GeV;
– the invariant mass of the photon with each pion ($M(\pi\gamma)$) should be greater than 0.17 GeV;
– the square of the transverse momentum of the $3\pi\gamma$ system is less than 0.001 GeV^2;
– $0.95 < p_{3\pi\gamma}/p_{beam} < 1.05$.
The cut on the square of the missing mass to each positive pion $M^2_{miss}(\pi^+)$ is used for the suppression of the background from the decay $K^+ \to \pi^+\pi^0$ with $\pi^0 \to e^+e^-\gamma$. The main source of the background for the $K^+ \to \pi^+\pi^-\pi^+\gamma$ decay is the decay of kaon to three charged pions when the pions produce hadron showers in the electromagnetic calorimeter and, because of fluctuations, a part of a shower is not associated with a charged track by the reconstruction algorithm. To suppress such kind of background a cut on $M(\pi\gamma)$ is done. The invariant mass distribution of the $3\pi\gamma$ system after application of all the cuts listed above is shown in Fig. 4. We see clear separation of the signal, peaking around the nominal value of the kaon PDG [5] mass and the background concentrating at higher masses. The number of events in the signal region is about 450.

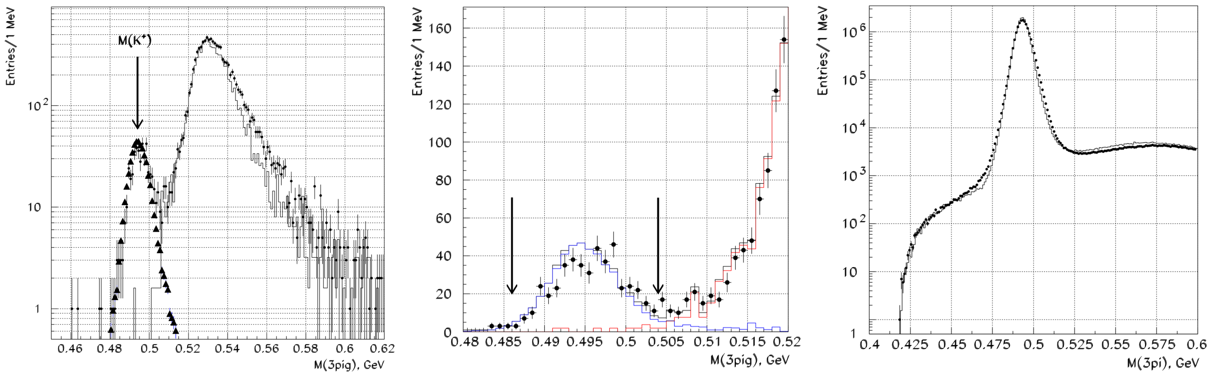

Figure 4. left: The mass distribution of the $3\pi\gamma$ system for the data (black circles), main sources of background (histogram) and the MC signal (black triangles). Middle: zoom of the signal region. data (black circles), the signal (blue histogram), the background (red histogram) and the sum of the signal and the background (black histogram). The arrows show the signal region used in the analysis. Right: the mass distribution of three charged pions for the data (black circles) and for the Monte Carlo for six main channels of the kaon decay(histogram).

4.2. Measurement of the branching ratio of the $K^+ \to \pi^+\pi^-\pi^+\gamma$ *decay*

The mass distribution of the $3\pi\gamma$ system in the range 0.48–0.52 GeV is shown in Fig. 4(middle). We define the mass range of 0.486–0.504 GeV as the signal region. The number of the $K \to 3\pi\gamma$ decays is determined as the difference of the number of the data events in the signal region and the expected number of events from the background. The expected background contribution is determined using Monte Carlo events for six main channels of the kaon decays. The decay $K \to 3\pi$ is used for the normalization. It is triggered with the same multiplicity trigger as the signal and selected with the same criteria as for the pions of the $3\pi\gamma$ decay, thus we expect a cancellation of many systematic effects. The invariant mass spectrum of the system of three charged pions is shown in Fig. 4(right).

The branching fraction of the decay $K \to 3\pi\gamma$ is determined in the following way:

$$Br(3\pi\gamma) = Br(3\pi)_{PDG} \times \epsilon(3\pi) \times N(3\pi\gamma)_D/\epsilon(3\pi\gamma)/N(3\pi)_D \ ,$$

where $Br(3\pi)_{PDG}$ is the $K \to 3\pi$ branching from PDG [5]; $N(3\pi\gamma)_D$ and $N(3\pi)_D$ are the numbers of the decays of $K \to 3\pi\gamma$ and $K \to 3\pi$ in the data. Efficiencies $\epsilon(3\pi)$ and $\epsilon(3\pi\gamma)$, determined from the Monte Carlo, are 0.120 ± 0.002 and 0.024 ± 0.001, respectively. The obtained result is $Br(3\pi\gamma) = (0.71 \pm 0.04(stat.)) \times 10^{-5}$. The main source of the systematic error is the uncertainty in the estimate of the background contribution to the signal region. To estimate that we varied the normalization of the background distribution. This leads to the systematic uncertainty of about $0.027\cdot 10^{-5}$ in the branching fraction. Another source of systematic error is related to the applied cuts. To estimate that, the cuts were varied within experimental resolution around nominal value and the branching was recalculated. The maximal change in the branching ratio was considered as the systematic error. The total systematic error is $0.03 \cdot 10^{-5}$. The final result is: $Br(3\pi\gamma) = (0.71 \pm 0.04(stat.) \pm 0.03(syst.)) \cdot 10^{-5}$, $\mathrm{E}^*_\gamma > 0.03$ GeV. The theory prediction is $Br_{th} = (0.665 \pm 0.005) \cdot 10^{-5}$ [11]. To perform a measurement of the differential branching over photon energy, we split the data sample into four 10 MeV bins and apply the procedure of the previous section to each of the bins. The $3\pi\gamma$ mass spectra for this bins are shown in Fig. 5(left). The obtained values of the branchings are shown in Fig. 5(middle).

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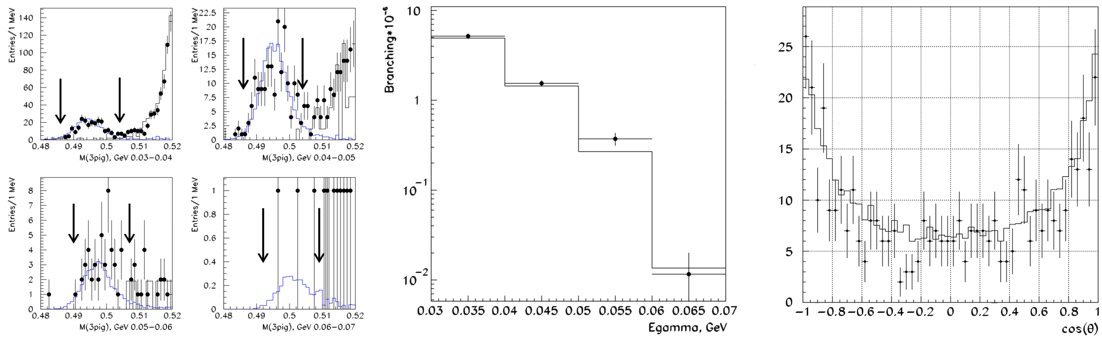

Figure 5. Left: The mass plots of the $3\pi\gamma$ system for the data (black circles), signal (blue histogram) and main sources of the background (black histogram) for the different energies of the photon. The arrows show the signal regions used in the analysis. Middle: Differential branching fractions over photon energy for the decay $K \to 3\pi\gamma$ for the data (black circles) and for the CHPT prediction from [11] (histogram). Right: The distribution (black circles) of the cosine of the angle of the photon direction with respect to the hadronic system decay plane(see the text). The histogram shows the Monte Carlo prediction for the decay $K \to 3\pi\gamma$ with the matrix element from [11].

5. Search for a photon up-down asymmetry

In Fig. 5(right) we show the distribution of the cosine of the angle of the photon direction with respect to the pion system decay plane in the 3-pion rest frame: $cos(\theta) = n_\gamma \cdot [p_f(\pi) \times p_s(\pi)]/|[p_f(\pi) \times p_s(\pi)]|$, where n_γ is the unit vector of photon direction in the 3-pion rest frame, $[p_f(\pi) \times p_s(\pi)]$ is the vector product of the momenta of the fastest and slowest pions in the same frame. For comparison, we show the same distribution for the Monte Carlo signal events with the matrix element from [11]. The observed asymmetry in the data is: $A = (N(cos\theta > 0) - N(cos\theta < 0))/N_{total} = 0.03 \pm 0.05(stat.) \pm 0.03(syst.)$
The main source of the systematic error comes from the experimental resolution in $cos(\theta)$. The alternative choice to define the decay plane is to use the fastest and slowest π^+. This results is $A^+ = -0.04 \pm 0.05(stat.) \pm 0.03(syst.)$. In both cases the observed asymmetry is consistent with zero within errors. The expected theoretical value for the asymmetry is $\sim 10^{-3}$.

Acknowledgements

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