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A Measurement of the Branching Ratio of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Decays in the HyperCP Experiment

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A Measurement of the Branching Ratio of $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$ Decays in the HyperCP Experiment

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Abstract: Large samples of hyperon and kaon decays were collected with the HyperCP spectrometer during two fixed-target runs at Fermilab. Based on an analysis of 110 million $K^{\pm}$ decays from the 1997 data sample we present a branching ratio for $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$. This is the first observation of $K^{-} \to \pi^{-}\mu^{+}\mu^{-}$ decay.

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1. Introduction

In the Standard Model of weak interactions the flavor changing neutral current does not exist at the tree level. The decay of $K^{\pm} \to \pi^{\pm}l^{+}l^{-}$, where l is either electron, e, or muon, μ, is a second-order effect. It is known that these decays are dominated by the long-distance one-photon exchange [1]. A recent Chiral Perturbation Theory (ChPT) calculation [2] describes the form factor and branching ratio of those decays in a model-independent manner. It predicts that the ratio of branching fractions, R, of $K^{+} \to \pi^{+}\mu^{+}\mu^{-}$ to $K^{+} \to \pi^{+}e^{+}e^{-}$ is greater than 0.23. The decay of $K^{+} \to \pi^{+}\mu^{+}\mu^{-}$ has been observed and the branching ratio was previously measured in two experiments. The BNL E787 experiment reported a result of $[5.0 \pm 0.4(\text{stat}) \pm 0.7(\text{syst}) \pm 0.6(\text{th})] \times 10^{-8}$ [3]. The BNL E865 experiment measured $[9.22 \pm 0.60(\text{stat}) \pm 0.49(\text{syst})] \times 10^{-8}$ [4]. These results are more than three standard deviations apart from each other, and thus there is a need for another measurement to resolve the discrepancy. Also, when combined with the Particle Data Group (PDG) average branching ratio $B(K^{+} \to \pi^{+}e^{+}e^{-}) = (2.88 \pm 0.13) \times 10^{-7}$ [5] the

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BNL E787 result gives $R = 0.17 \pm 0.03$ which is uncomfortably low in comparison with the ChPT prediction. The BNL E865 measurement gives $R = 0.32 \pm 0.03$ in agreement with the prediction.

2. HyperCP experiment

The HyperCP (FNAL E871) is an experiment designed to search for CP violation in hyperon decays at the 10^{-4} level. 800-GeV protons interact in a copper target and the produced secondary beam is channeled through a 1.6 T, 6-m-long dipole magnet (Hyperon magnet) that deflects charged particles upward with a central momentum of 167 GeV/c, as illustrated in Figure 1. The selected secondary particles enter a 13 m vacuum decay pipe. The decay products first go through a set of four multi-wire proportional chambers (MWPC), C1-C4, with a pitch of 1 to 1.25 mm with 4 planes each. They then enter a set of two momentum analyzing dipole magnets, with a total field integral of 4.75 T-m, followed by a set of four 4-plane MWPCs, C5-C8, with a pitch of 1.5 to 2 mm. The main trigger required coincidence hits in hodoscopes on both sides of the spectrometer and a minimum energy deposition in the hadronic calorimeter placed on the side of decay products with charge opposite to that of the secondary beam. The sign of the charge of the secondary beam was changed periodically by switching the polarity of both Hyperon and Analysis magnets. At the rear of the spectrometer were two muon identification systems positioned on either side of the spectrometer. They consisted of three layers of 81 cm steel blocks followed by horizontal and vertical proportional tubes of 2.54 cm pitch, and a set of muon trigger hodoscopes at the end. Further details of the spectrometer can be obtained from Ref. [6]. HyperCP collected data during the 1997 and 1999 FNAL fixed-target runs. The results reported here are based on the 1997 data set.

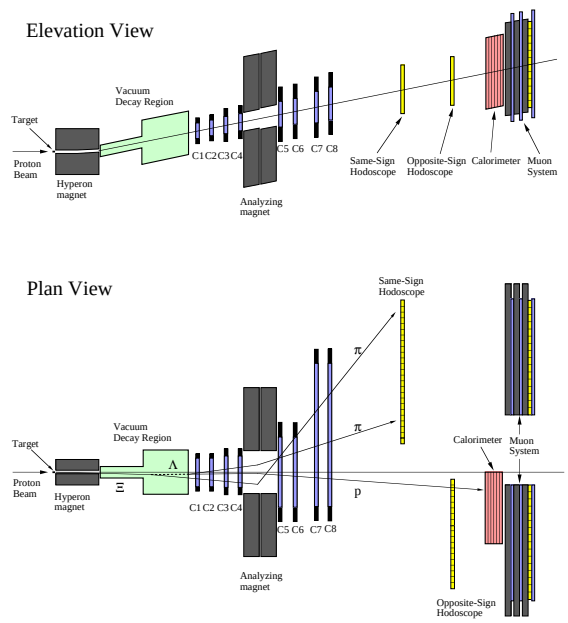

Figure 1: The HyperCP spectrometer.

3. The Measurement of the Branching Ratios.

The branching ratios were determined from the formula

$$B(K \to \pi\mu^+\mu^-) = \left(\frac{N^{obs}_{\pi\mu\mu}}{A_{\pi\mu\mu} \cdot \epsilon^{sel}_{\pi\mu\mu} \cdot \epsilon^{\mu\mu} \cdot \epsilon^{tr}_{rel}}\right) / \left(\frac{N^{obs}_{3\pi} \cdot 200}{A_{3\pi} \cdot \epsilon^{sel}_{3\pi} \cdot B(K \to 3\pi)}\right),$$

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where $N^{obs}_{\pi\mu\mu}$ is the number of observed $K \to \pi\mu^+\mu^-$ decays, $A_{\pi\mu\mu}$ is the geometric acceptance, $\epsilon^{sel}_{\pi\mu\mu}$ is the efficiency of event selection, $\epsilon^{\mu\mu}$ is the efficiency of identifying dimuon events, and ϵ^{tr}_{rel} is the relative efficiency of the signal to normalizing sample triggers. Similarly, $N^{obs}_{3\pi}$, 200, $A_{3\pi}$, $\epsilon^{sel}_{3\pi}$, $B(K \to 3\pi)$ represent the number of observed events, the trigger prescale factor, the geometrical acceptance, the event selection efficiency, and the branching ratio of the normalizing mode of $K \to \pi\pi^+\pi^-$. The basic event selection was identical for the signal and normalizing events. We required the reconstruction of two tracks on the left and one track on the right side of the spectrometer with at least two of them on opposite sides pointing to the fiducial volumes of the muon identification systems. The total momentum of the decay candidate had to be within the expected range of 120 to 250 GeV/c. The decay particle had to originate at the x and y positions of the target within ± 5 mm. The z position of the decay vertex had to be well within the decay pipe region, between about 100 and 1300 cm. The topology of the decay had to be consistent with the single-vertex decay. The average separation of the tracks at the z position of closest approach had to be smaller than 2 mm and the χ^2 per degree of freedom of the geometric fit of the 3 tracks to a single vertex, as constructed from the track segments upstream of the Analysis magnet, had to be smaller than 2.5. That gave a strong rejection of background events coming from hyperon decays with two-vertex topology. The acceptances and efficiencies are summarized in Table 1. The normalizing events were required to satisfy a trigger, prescaled by a factor of 200, consisting of coincidence between left- and right-hodoscope hits. The number of decays was obtained from the invariant-mass distribution of the three tracks assumed to be pions. A Gaussian fit with

	K^+	K^-
$A_{\pi\mu\mu}$	0.475	0.477
$A_{3\pi}$	0.944	0.942
$\epsilon^{sel}_{\pi\mu\mu}$	0.803	0.783
$\epsilon^{sel}_{3\pi}$	0.779	0.760
$\epsilon^{\mu\mu}$	0.938	0.938
ϵ^{tr}_{rel}	0.866	0.866

Table 1: Summary of acceptance and efficiencies.

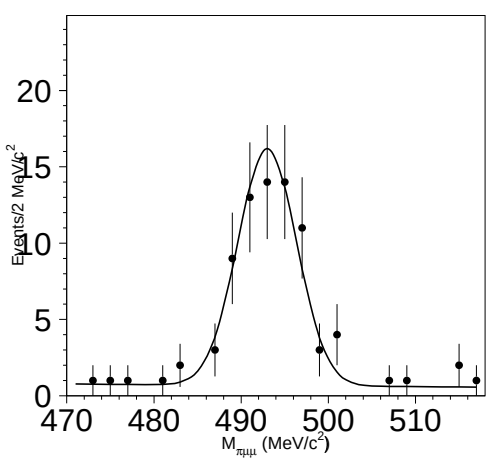

Figure 2: Signal events likelihood fit for the positive secondary beam.

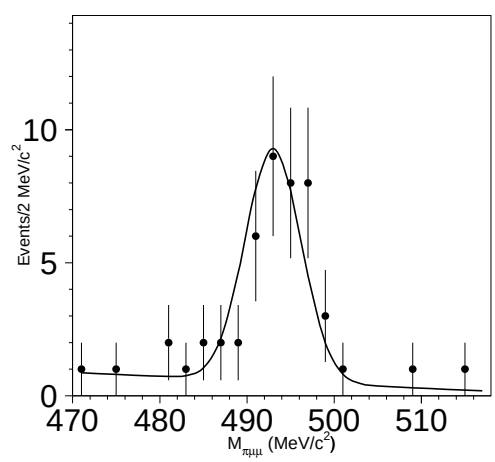

Figure 3: Signal events likelihood fit for the negative secondary beam.

linear background was used to obtain the values of $N^{obs}_{3\pi}$ equal to $(4.45 \pm 0.01) \times 10^5$ for the positive and $(2.32 \pm 0.01) \times 10^5$ for the negative modes. The uncertainty in the background was obtained from the difference between the results when varying the fit parameters within

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the errors. The branching ratio used for $K \to 3\pi$ was $(5.59 \pm 0.05)\%$ [5].

The signal events, in addition to the selection criteria described above, were required to satisfy a dimuon trigger and have two identified muon tracks of opposite charges. A muon track must have at least two out of three proportional tube plane hits, and two out of three horizontal and vertical muon hodoscope hits within its projected path. The dimuon trigger consisted of a coincidence between left- and right-hodoscope hits, and left- and right-muon-hodoscope hits. The $\pi\mu\mu$ invariant mass was fit within the range of $470-520$ MeV/c^2 with a Gaussian signal and a linear background using the unbinned-maximum-likelihood method, see Figures 2 and 3. The fit resulted in 65.3 ± 8.2 observed $K^+ \to \pi^+\mu^+\mu^-$ decays and 35.2 ± 6.6 $K^- \to \pi^-\mu^+\mu^-$ decays. Events coming from charged kaons decaying to three charged pions with pion punch-throughs or pion decay in flight to muons were well isolated from the signal mass peak due to the excellent mass resolution of the spectrometer (see Figure 4).

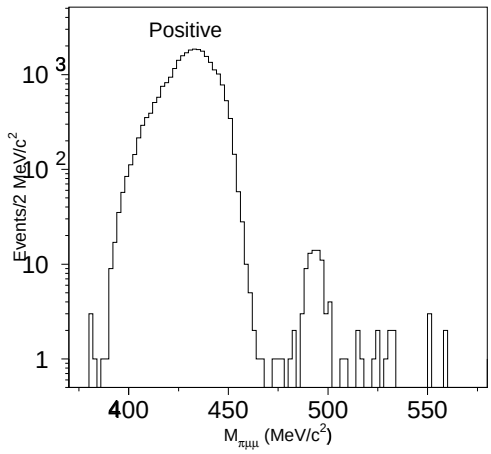

Figure 4: The invariant mass of $\pi\mu\mu$ of selected events for positive secondary beam. The small peak around K^+ mass are the signal events. The large peak are $K^+ \to \pi^+\pi^+\pi^-$ events with the pion punch-throughs and pion decays in flight to muons.

4. Summary of Systematic Uncertainties.

A detailed Monte Carlo (MC) simulation was used to study systematic uncertainties. The MC parameters were tuned to give distributions that agree closely with those obtained from data. The effect of varying those parameters resulted in the "Data and MC disagreement"

Source	$\sigma_B/B(\%,+)$	$\sigma_B/B(\%,-)$	Combined
Data and MC disagreement	0.4	0.4	0.4
Beam targeting	1.1	0.9	1.0
Magnetic field	0.5	0.4	0.5
Trigger efficiency	3.1	3.1	3.1
Muon identification	0.3	0.3	0.3
Normalization background est.	0.2	0.3	0.2
Signal background est.	2.4	6.4	3.6
Dalitz parameters	0.3	0.3	0.3
Form factor parameter	0.2	0.3	0.2
B($K \to \pi\pi\pi$)	0.9	0.9	0.9
Total	4.2	7.3	5.0

Table 2: Summary of systematic uncertainties.

entry in Table 2. The stability of running conditions was studied, and the variation was

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used to estimate the corresponding uncertainty. The horizontal and vertical positions of the proton beam on the target was varied within ±0.5 mm. The magnetic fields of the Hyperon and Analysis magnets varied within ±0.1%. The relative trigger efficiency was found with 2.7% uncertainty. The muon identification efficiency varied by ±0.3%. The difference in the number of normalizing-mode events obtained from the uncertainty of the number of background events was taken into account. The variation in the number of signal events when the mass range was shifted by ±5 MeV/c^2 in the likelihood fit was included. The values of the Dalitz parameters in the normalization mode were varied within the known accuracy, $g = -0.2154 \pm 0.0035(-0.217 \pm 0.007)$ and $h = 0.012 \pm 0.008(0.010 \pm 0.006)$ [5], for positive (negative) charge of the secondary beam. The variation of the parameter δ in the form factor, $d\Gamma/dm_{\mu\mu} \sim (1+\delta\, m^2_{\mu\mu}/m^2_K)^2$ [2], over a wide range of values showed little sensitivity due to the low statistics of the signal. Finally, the uncertainty in the branching ratio of the normalization mode was included.

5. Results and Conclusions.

Based on the results described above we obtain from the 1997 data sample a measurement of the branching ratio of $K^+ \to \pi^+\mu^+\mu^-$ as $[9.7 \pm 1.2(\text{stat}) \pm 0.4(\text{syst})] \times 10^{-8}$ [7]. We observe for the first time the charge-conjugate decay and measure its branching ratio, $B(K^- \to \pi^-\mu^+\mu^-) = [10.0 \pm 1.9(\text{stat}) \pm 0.7(\text{syst})] \times 10^{-8}$. The CP asymmetry is consistent with zero:

$$\Delta = \frac{B(K^+ \to \pi^+\mu^+\mu^-) - B(K^- \to \pi^-\mu^+\mu^-)}{B(K^+ \to \pi^+\mu^+\mu^-) + B(K^- \to \pi^-\mu^+\mu^-)} = -0.02 \pm 0.11(\text{stat}) \pm 0.04(\text{syst}).$$

Assuming CP symmetry is valid, the combined result is

$$B(K^\pm \to \pi^\pm\mu^+\mu^-) = [9.8 \pm 1.0(\text{stat}) \pm 0.5(\text{syst})] \times 10^{-8}.$$

This is in good agreement with the BNL E865 measurement and gives a ratio of $B(K \to \pi\mu\mu)/B(K \to \pi ee)$ consistent with that predicted by ChPT. We expect a sample at least three times larger from the 1999 data set that should improve the statistical uncertainty of our measurements by a factor of two.

References

[1] G. Ecker, A. Pich and E. de Rafael, Nucl. Phys. **B291**, 692 (1987).

[2] G. D'Ambrosio, G. Ecker, G. Isidori and J. Portolés, JHEP **8**, 4 (1998).

[3] S. Adler *et al.*, Phys. Rev. Lett. **79**, 4756 (1997).

[4] H. Ma *et al.*, Phys. Rev. Lett. **84**, 2580 (2000).

[5] Particle Data Group, D.E. Groom *et al.*, Eur. Phys. J. C**15**, 1 (2000).

[6] W.S. Choong, Ph.D. thesis, University of California, Berkeley (2000).

[7] H.K. Park *et al.*, FERMILAB-Pub-01/320-E E871 (2001).

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