Fermi National Accelerator Laboratory

FERMILAB-Pub-97/029-E
E687

Search for Rare and Forbidden Decays of the Charmed Meson D^+

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P.O. Box 500, Batavia, Illinois 60510

February 1997

Submitted to *Physics Letters B*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy

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Abstract

We report on the results of a search for fourteen flavor changing neutral current, lepton number violating, or lepton family number violating decays of the charmed meson D^+ in the large charm sample recorded by the Fermilab photoproduction experiment E687. No evidence is seen for these rare and standard-model-forbidden decays, of the form $D^+ \to h^\pm \ell^\mp \ell^+$ (with $h = \pi, K$ and $\ell = e, \mu$); we determine 90% confidence level upper limits on their absolute branching fractions in the range (9–20)$\times 10^{-5}$.

In this paper we present the results of our search for fourteen rare and standard-model-forbidden semileptonic decays of the D^+ meson. The modes can be split into three categories: flavor changing neutral current (FCNC) decays: $D^+ \to h^+\ell^+\ell^-$, lepton family number violating (LFNV) decays: $D^+ \to h^+\ell_1^+\ell_2^-$, and lepton number violating (LNV) decays: $D^+ \to h^-\ell_1^+\ell_{1,2}^+$ (with $h = \pi, K$ and $\ell = e, \mu$). Charge conjugate modes are assumed throughout this paper. The standard model forbids LFNV and LNV decays, and predicts [1] extremely small branching fractions for FCNC charm decays. Observation of any of these decays would be evidence for physics beyond the standard model [1], [2]. Recently, the E791 collaboration has published [3] limits on the branching fractions for two FCNC modes: $D^+ \to \pi^+e^+e^-$ and $D^+ \to \pi^+\mu^+\mu^-$, while the CLEO collaboration [4] has published limits on several D^0 modes from each of the above categories. These limits are in the range $(1.3 - 120) \times 10^{-5}$. We see no evidence for any of the fourteen D^+ decay modes included in our search, and set 90% confidence level upper limits in the range $(9 - 20) \times 10^{-5}$ for these modes. The majority of the limits we report improve previous limits [5], [6] by factors of 2–70.

The data for this analysis were collected in the 1990–91 run of the Fermilab photoproduction experiment E687. The detector [7] is a large aperture fixed target multiparticle spectrometer which features excellent particle identification and vertexing for charged hadrons and leptons. A photon beam is derived from the bremsstrahlung of secondary electrons ($\langle E \rangle = 350$ GeV) produced from the Tevatron proton beam. This beam strikes a beryllium target; charged particles which emerge from the target are tracked by four stations (12 planes) of silicon microstrip detectors. These detectors provide high resolution separation of primary (production) and secondary (decay) vertices. The momentum of charged particles is determined by measuring their deflections in two analysis magnets of opposite polarity with five stations (20 planes) of multiwire proportional chambers. Three multicell threshold Čerenkov counters are used to identify electrons, pions, kaons and protons. There are two electromagnetic calorimeters. The inner calorimeter covers the forward solid angle and detects particles which pass the apertures of both magnets. The outer calorimeter covers the outer angular region populated by particles that pass the first magnet but not the second. Muons are identified in the forward solid angle by a system of three scintillator arrays and four proportional tube planes divided into two sections by thick steel muon filters.

This analysis begins with a skim of the full E687 data sample which requires evidence for secondary charm decay vertices [9] in the events. To minimize systematic uncertainties, we determine relative branching ratios:

$$R = \frac{B(D^+ \to h^\pm\ell^\mp\ell^+)}{B(D^+ \to K^-\pi^+\pi^+)} = \frac{N_{\text{obs}}(h\ell\ell)}{\epsilon(h\ell\ell)} \frac{\epsilon(K\pi\pi)}{N_{\text{obs}}(K\pi\pi)}$$

where ϵ is the acceptance times efficiency for each mode, and N_{obs} is the number of observed decays (or the upper limit on that number). With the exception of lepton identification, we apply the same cuts to candidates for the $h\ell\ell$ modes and for the normalizing $K\pi\pi$ mode. For example, since we only identify muons in the "inner" acceptance region of the spectrometer, corresponding pion(s) in the $K\pi\pi$ mode are required to be in the same region.

Selection of candidates for $D^+ \to h^\pm\ell^\mp\ell^+$ and $D^+ \to K^-\pi^+\pi^+$ begins by forming all three track combinations in an event with the correct particle identification and charge. Tracks are defined as candidate kaons if they are consistent with a Čerenkov hypothesis of kaon or kaon/proton ambiguous. For the roughly 20% of the kaons in these decays with momentum greater than 60 GeV/c, the Čerenkov system cannot discriminate between pions and kaons. If such tracks are kaon/pion ambiguous, they are also accepted as kaon candidates. No Čerenkov requirements are made [10] on pion candidates.

To identify muons, tracks are projected into the muon system and the closest hits in that system are noted. The confidence level that the track produced these hits is calculated and required to be larger than 1%. If the track does not pass these initial requirements, then the hits in up to two proportional tube planes are dropped and the confidence level is recalculated. Missing hits are allowed as well but in all cases there must be hits in at least two of the four proportional tube planes and two of the three scintillator planes. This algorithm is 93% (71%) efficient in the 1990 (1991) data. The lower 1991 efficiency is due to a hole that was cut in the system to allow the photon beam to pass through to a downstream experiment. This hole also increased the misidentification probability. Therefore, for the decay mode $D^+ \to K^-\mu^+\mu^+$ we require hits in 3 proportional planes to reduce feeddown from $D^+ \to K^-\pi^+\pi^+$ decay (1991 data only).

Tracks with associated electromagnetic showers in one of the two electromagnetic calorimeters are identified as electrons if they are consistent with an electron hypothesis in the Čerenkov counters. Electron-positron pairs from the conversion of additional beam photons are eliminated by removing candidates consistent with having a zero degree angle with respect to the beam direction. To reduce unwanted contamination from other charged particles produced in charm decays, we also require $0.8 < E/p < 1.5$, where E is the energy the electron deposit on the inner electromagnetic calorimeter and p is the momentum of the track. The efficiency of these requirements, set primarily by the shower finding algorithm, is approximately 60%.

Each of the resulting three track combinations is subjected to vertex cuts. The combination is fit to a common vertex (the secondary vertex), and the confidence level of this fit required to be at least 1%. If the combination survives its momentum vector is used as a seed to nucleate, with at least one other charged track, a primary (production) vertex [7], and this vertex is required to be in the beryllium target. The significance of detachment, ℓ/σ, is defined as the distance ℓ between the secondary and primary vertices divided by the error σ in this distance. For this analysis ℓ/σ is required to be greater than or equal to 8. We then require that the primary vertex be isolated from the secondary vertex ("primary isolation cut"). Tracks assigned to the secondary vertex are added one at a time to the primary vertex, a fit to the new "primary" is performed, and the secondary candidate is eliminated if the confidence level of any of the fits to the primary is greater than 50%.

For the $K\mu\mu$ and $K\mu e$ modes, the above cuts are optimal. Modes where the daughter hadron is a pion have larger combinatoric backgrounds, as do modes where both leptons are electrons. For the pion modes ($\pi\ell_1\ell_{1,2}$) we add a cut on the isolation of the secondary vertex. Tracks not assigned to either the primary or secondary vertex are added one at a time to the secondary vertex. The D^+ candidate is rejected if the confidence level of the fit to any of the resulting vertices is greater than 10^{-7}. For hee modes, we also find it necessary to increase the significance of detachment cut to 12 and to require that there be at least three tracks (including the D) in the primary vertex.

The cuts described above for each mode were chosen to optimize our sensitivity. Our sensitivity for each mode depends on the efficiency relative to the normalizing mode

$(\epsilon(h\ell\ell)/\epsilon(K\pi\pi)$, determined from Monte Carlo studies), the number of observed events in the normalizing mode (determined from a fit to the relevant mass plot), and the amount of background in the signal region (determined using sidebands in the corresponding mass plot). Figure 1 shows the invariant mass spectra for each of the fourteen exclusive decay modes searched for in this analysis. We do not observe any evidence for these rare and forbidden decays. Mass spectra for the normalizing mode $D^+ \to K^-\pi^+\pi^+$ are shown in Figure 2.

The expected signal shape and reconstruction efficiency relative to $K^-\pi^+\pi^+$ for each mode is computed using the PYTHIA [8] photon-gluon fusion production Monte Carlo program combined with a detailed simulation of the spectrometer. Expected signal shapes are shown in Fig. 1, normalized to the upper limit on the number of signal events found using the method described below. The efficiency relative to $K^-\pi^+\pi^+$ for each mode is given in Table I. Differences in relative efficiencies for the modes are due primarily to the differences in electron and muon identification efficiency and to the radiative tails present in electron modes.

To calculate a 90% confidence level upper limit (N^*) on the number of signal events in each mass plot, we use Monte Carlo signal shapes and background shapes derived from data. The primary backgrounds in this analysis come from misidentification of hadrons. We determine the shape of the background using three-track combinations that pass the same cuts as the mode we are searching for except we do not require lepton identification cuts. Instead we weight each lepton candidate by the probability that it is a hadron misidentified as a lepton. We determine the momentum dependent misidentification probability using pions from K^0_s decay.

If the expected number of signal events in the mass range shown in the histograms is μ_s, and μ_b is the expected number of background events, then the expected content of bin "i" is $\mu_i = \mu_s s_i + \mu_b b_i$, where s_i is the normalized [11] signal shape and b_i is the normalized background shape. The 90% confidence level upper limit (N^*) on the number of signal events in each mass plot is calculated from

$$0.9 = \frac{\int_0^{N^*}\int_0^\infty P(\mu_s,\mu_b)d\mu_b d\mu_s}{\int_0^\infty\int_0^\infty P(\mu_s,\mu_b)d\mu_b d\mu_s}, \qquad \text{where} \qquad P(\mu_s,\mu_b) = \prod_i P_i(n_i;\mu_s,\mu_b)$$

and $P_i(n_i;\mu_s,\mu_b) = \mu_i^{n_i} e^{-\mu_i} \, / \, n_i!$ is the probability of observing n_i events in bin "i". Table I shows the N^* we obtain for each mode.

The systematic errors in this analysis come from uncertainty in the relative efficiency for each mode, which in turn is due to uncertainty in the kaon and lepton particle identification efficiency and the decay matrix element. The particle identification uncertainty is estimated to be 5%, 2%, and 10% for kaons, muons, and electrons respectively. Since the matrix elements for these rare or standard model forbidden decay modes are not known, we have tried a variety of matrix elements. The reconstruction efficiency varies by less than 2%, so this is the value we use for our systematic error on the matrix element. To get the total systematic error for each mode we add the appropriate combination of the above errors in quadrature. The resulting systematic errors are shown in Table I.

Using the information in the second through fourth columns of Table I, one can determine our limit on the relative branching ratio for each mode. Column six gives our limits on the branching fraction for each mode, which is obtained by multiplying the relative branching ratio limit by the particle data group [12] value for $B(D^+ \to K^-\pi^+\pi^+) = 0.091 \pm 0.006$. The error on this value has been included in the final systematic error used for each mode. Systematic errors have been taken into account by decreasing the relative efficiency for each mode by one sigma. The majority of the limits shown in Table I represent an improvement of a factor of 2–70 over the previous best limits.

We wish to acknowledge the assistance of the staffs of the Fermi National Accelerator Laboratory, the INFN of Italy, and the physics departments of the collaborating institutions. This research was supported in part by the National Science Foundation, the U.S. Department of Energy, the Italian Istituto Nazionale di Fisica Nucleare and Ministero dell'Università e della Ricerca Scientifica e Tecnologica, the Korean Science and Engineering Foundation, and the Vanderbilt University Research Council.

TABLES

TABLE I. Summary of upper limits on the branching fraction for fourteen FCNC, LFNV, or LNV decays of the D^+.

Decay Mode	N^*	$N_{K\pi\pi}$	Relative Efficiency	Systematic Error	Limit (10^{-5})	Previous Limit (10^{-5})
$\pi^+e^+e^-$	2.4	11469	0.21	17%	11	6.6 [3]
$K^+e^+e^-$	4.4	14249	0.16	16%	20	480 [5]
$\pi^+\mu^+\mu^-$	2.5	4566	0.61	9%	8.9	1.8 [3]
$K^+\mu^+\mu^-$	2.7	5854	0.47	8%	9.7	32 [6]
$\pi^+\mu^+e^-$	2.6	6993	0.31	13%	13	330 [5]
$K^+\mu^+e^-$	2.7	8921	0.27	13%	12	340 [5]
$\pi^+\mu^-e^+$	2.4	6993	0.32	13%	11	330 [5]
$K^+\mu^-e^+$	3.0	8921	0.26	13%	13	340 [5]
$\pi^-e^+e^+$	2.3	11469	0.19	17%	11	480 [5]
$K^-e^+e^+$	2.7	14249	0.16	16%	12	910 [5]
$\pi^-\mu^+\mu^+$	2.4	4566	0.59	9%	8.7	22 [6]
$K^-\mu^+\mu^+$	2.4	5854	0.33	8%	12	32 [6]
$\pi^-\mu^+e^+$	2.4	6993	0.32	13%	11	370 [5]
$K^-\mu^+e^+$	2.8	8921	0.25	13%	13	400 [5]

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[1] see, for example: J. L. Hewett,"Searching for New Physics with Charm", in Proceedings of the LISHEP'95, Session C: Heavy Flavour Physics, Centro Brasiliero de Pesquisas Fisicas, Rio de Janeiro, Brazil, February 21-23, 1995, edited by F. Caruso, et al., Editions Frontieres, Gif-sur-Yvette, Cedex - France, 1995, pages 171-187; S. Pakvasa, page 85, "Charm as Probe of New Physics", in Proceedings of the CHARM2000 Workshop, Fermilab, June 7–9, 1994; A. J. Schwartz, Modern Phys. Lett. **A8**, 967 (1993).

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[9] All combinations of pairs of good microstrips were fit to a vertex. The significance of separation between vertices that passed minimal quality cuts was then calculated, and a cut was made on the largest such significance. This algorithm is 80–90% efficient for the charm events of interest, and rejects a significant majority of non-charm events.

[10] Our Čerenkov algorithms are tuned to identify heavy hadrons (kaons and protons) and have not been optimized for the selection of the far more copious pions.

[11] By normalized we mean such that $\sum s_i = 1$.

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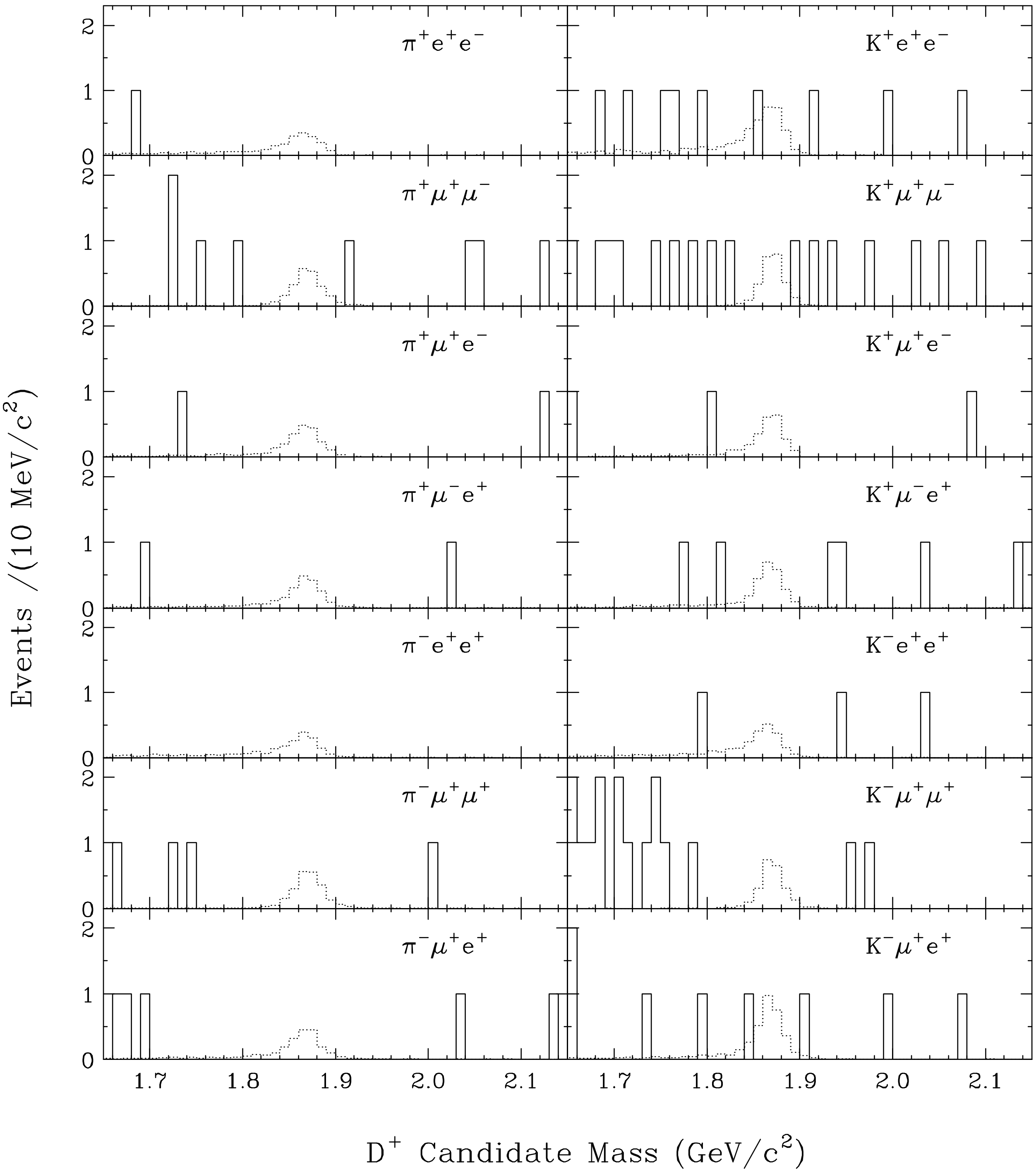
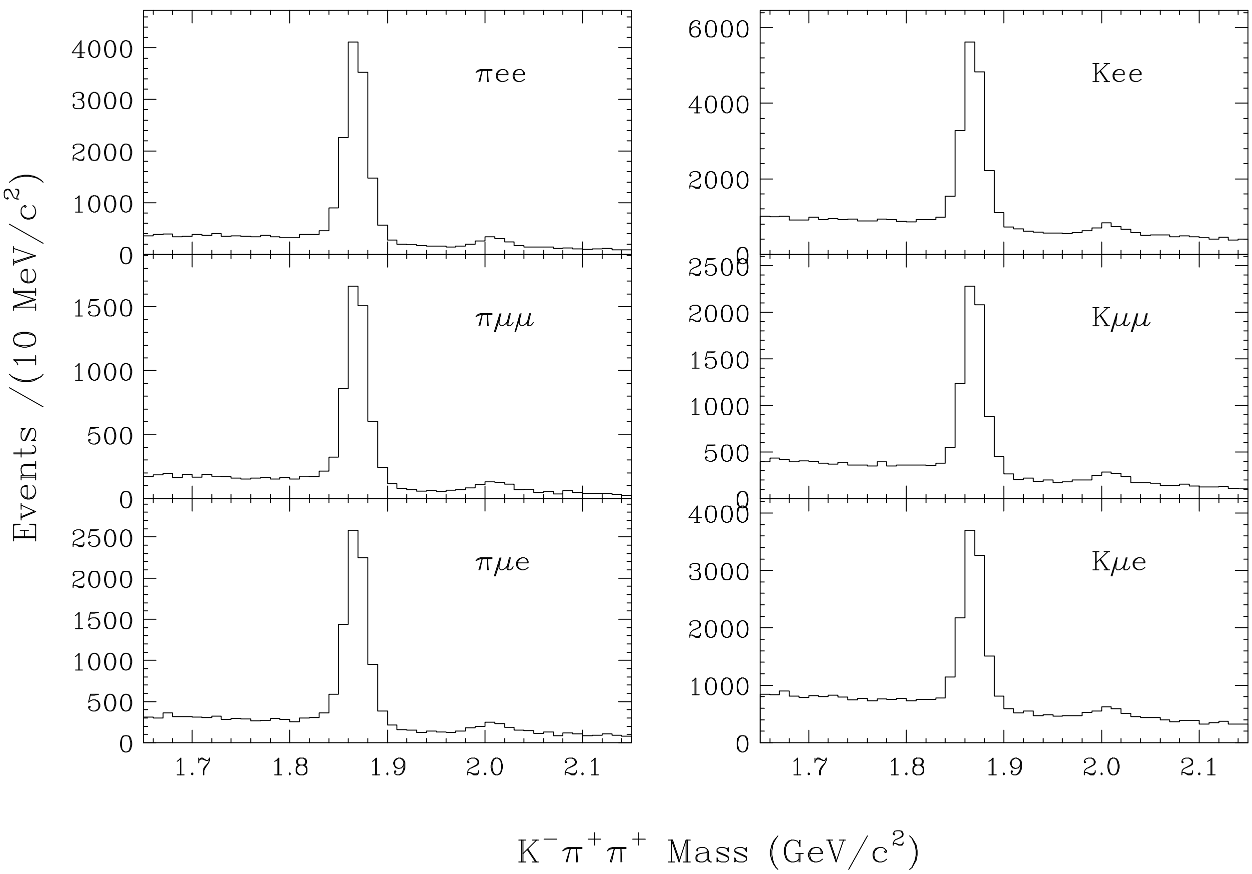
FIGURES

FIG.1. Invariant mass distribution for the fourteen rare and standard-model-forbidden decays of the D^+ for which we are searching. Superimposed are the expected signal shapes, normalized to the 90% C.L. upper limit on that signal reported in this paper.

FIG.2. $D^+ \to K^-\pi^+\pi^+$ signals used as normalization with the same selection cuts as for the indicated modes.



π⁺e⁺e⁻
K⁺e⁺e⁻
π⁺μ⁺μ⁻
K⁺μ⁺μ⁻
π⁺μ⁺e⁻
K⁺μ⁺e⁻
π⁺μ⁻e⁺
K⁺μ⁻e⁺
π⁻e⁺e⁺
K⁻e⁺e⁺
π⁻μ⁺μ⁺
K⁻μ⁺μ⁺
π⁻μ⁺e⁺
K⁻μ⁺e⁺
Events /(10 MeV/c²)
D⁺ Candidate Mass (GeV/c²)
0
1
2
1.7
1.8
1.9
2.0
2.1



πee
Kee
πμμ
Kμμ
πμe
Kμe
Events /(10 MeV/c²)
K⁻π⁺π⁺ Mass (GeV/c²)