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SEMILEPTONIC DECAYS OF CHARMED $D^\pm$ MESON :
MEASUREMENT OF THE LIFETIME AND THE CROSS-SECTION

The ACCMOR Collaboration
Amsterdam¹⁾-Bristol²⁾-CERN³⁾-Cracow⁴⁾-Munich⁵⁾-Rutherford⁶⁾ Collaboration

H. Palka^{5*}, R. Bailey⁷, H. Becker^{5□}, E. Belau⁵, T. Böhringer^{3x}, M. Bosman^{3*},
V. Chabaud³, C. Damerell⁷, C. Daum¹, H. Dijkstra¹, S. Gill⁷, A. Gillman⁷,
R. Gilmore², T. Gooch², Z. Hajduk⁴, C. Hardwick¹, B.D. Hyams³,
J. Kemmer⁶, R. Klanner^{3∇}, U. Kötz^{3†}, S. Kwan², G. Lütjens⁵, G. Lutz⁵,
J. Malos², W. Männer⁵, E. Neugebauer^{5§}, M. Pepé⁷, J. Richardson⁷,
G. de Rijk¹, K. Rybicki⁴, H.J. Seebrunner^{5&}, U. Stierlin⁵, H.G. Tiecke¹,
M. Turala⁴, G. Waltermann⁵, S. Watts⁷, P. Weilhammer³,
F. Wickens⁷, L.W. Wiggers¹, A. Wylie⁵, and T. Zeludziwicz^{5*}

ABSTRACT

Using the ACCMOR spectrometer equipped with a vertex telescope of high resolution silicon microstrip detectors 74 decays $D^\pm \rightarrow \bar{K}^{*0}(892)e^\pm \nu_e$ (and cc.) with $x_F < 0.4$ have been observed in 200 GeV π^- Be interactions. The cross-section for $D^\pm$ production, its x_F -dependence in the central region and the $D^\pm$ lifetime have been measured.

To be submitted to Zeitschrift für Physik C

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- 1) NIKHEF-H, Amsterdam, The Netherlands
  - 2) University of Bristol, Bristol, UK
  - 3) CERN, Geneva, Switzerland
  - 4) Institute of Nuclear Physics, Cracow, Poland
  - 5) Max Planck Institut für Physik, Munich, Fed. Rep. Germany
  - 6) Munich Technical University, Munich, Fed. Rep. Germany
  - 7) Rutherford Appleton Laboratory, Chilton, Didcot, UK
  - *) Visitor from Institute of Nuclear Physics, Cracow, Poland
  - *) Now at MPI Munich, Fed. Rep. Germany
  -) Now at Gesamthochschule, Saarbrücken, Fed. Rep. Germany
  - ∇) Now at DESY, Hamburg, Fed. Rep. Germany
  - †) Visitor from DESY, Hamburg, Fed. Rep. Germany
  - §) Now at Universität - GH Siegen, Siegen, Fed. Rep. Germany
  - &) Now at Fachhochschule Heilbronn, Fed. Rep. Germany
  - x) Now at Université de Lausanne, Switzerland

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Max-Planck-Institut für Physik und Astrophysik, München.

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1. INTRODUCTION

In this paper we present the results obtained in an experiment which identifies charmed particles produced in 200 GeV π^- Be interactions via their semileptonic decay and finite decay length. The analysis is restricted to $K\pi\nu_e$ final states: the e-K charge correlation implied by a Cabibbo allowed $c \rightarrow se^+\nu_e$ transition and a strong $K^*(892)$ signal are used to isolate a sample of $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decays[†].

Semileptonic decays of D mesons have been previously studied in inclusive channels by DELCO [1]. Their fit to the energy spectrum of electrons from D^0 , $D^+ \rightarrow e^+X$ decays yields nearly equal contributions of $K\nu_e$ and $K^*(892)e\nu_e$ states and a very small fraction of $K\pi\nu_e$. Observation of exclusive semileptonic decays of D^0 and D^+ has been reported by the MARK III collaboration [2] who conclude that inclusive semileptonic branching ratios of D mesons are saturated by Cabibbo allowed decays to $K\nu_e$ and $K\pi\nu_e$ with $K\pi$ coming dominantly from $K^*(892)$ decays. A recent reanalysis of this data [3] suggests that almost a half of the $\text{Br}(D^0, D^+ \rightarrow K\pi\nu_e)$ can be attributed to a non-resonant S-wave $K\pi$ component.

2. THE EXPERIMENT

The experiment was performed at the CERN SPS, using the ACCMOR spectrometer in a 200 GeV π^- beam. A schematic layout of the spectrometer is shown in Fig. 1. The beam is focused ($\text{FWHM}_{\text{hor}} = 12$ mm, $\text{FWHM}_{\text{ver}} = 0.3$ mm) onto a Be target of 20 mm length, 0.5 mm height, and 20 mm width.

The data have been recorded with a single electron trigger. It selects interactions containing an electron from the reaction

$$\pi^- + \text{Be} \rightarrow C + \bar{C} + X \text{ or } cc.$$

$$\quad \quad \quad \downarrow$$

$$\quad \quad \quad e + X$$

(C represents any charmed particle), with the multicellular Cerenkov counter Q (π threshold of 12 GeV, π/e discrimination of 0.1%) and the lead scintillator calorimeter E-CAL ($E_e^{\text{min}} = 2.8$ GeV, π/e separation of 2%). A second-stage trigger uses the information from the multiwire proportional chambers P2 and the calorimeter E-CAL in order to reduce background in the single electron trigger from hadrons, photons and conversion pairs [4].

[†] In this paper the D^+ meson will refer to both $D^{\pm}$ charge states.

The parts of the spectrometer used for the offline reconstruction of the event are:

- Six microstrip silicon detectors (MSDs) to measure the incident beam at the Be target with a precision $\sigma_{\text{hor}} = 25 \mu\text{m}$ and $\sigma_{\text{vert}} = 6 \mu\text{m}$.
- Six MSDs, arranged in three pairs with strips at an angle of $\pm 14^\circ$ to the horizontal plane, to measure the charged particles produced in the reaction. Each detector has an area of $24 \text{ mm} \times 36 \text{ mm}$ and a spatial resolution of $4.5 \mu\text{m}$ ($7.8 \mu\text{m}$) in the central (outer) region. The measurement accuracy of tracks extrapolated to the primary vertex is $10 \mu\text{m}$ perpendicular to the beam, typically allowing a reconstruction of the position of the primary vertex along the beam with a precision of $150 \mu\text{m}$. The spatial resolution decreases to approximately $20 \mu\text{m}$ ($40 \mu\text{m}$) in the central (outside) region of the detector if the distance between two particle tracks is smaller than $\approx 120 \mu\text{m}$ ($240 \mu\text{m}$) within one projection. Further details on the detectors can be found in refs. [5,6].
- Forty eight planes of large area drift chambers (DC) and two spectrometer magnets (M1, M2) to measure the momenta of the charged particles ($\Delta p/p = 0.25\text{--}2.0\%$). The mass resolution of the spectrometer at the D meson mass varies between 5 and 20 MeV depending on the kinematics.
- Three large multicellular threshold Cerenkov counters C1, C2, C3 to identify π , K and p in the momentum range 4–80 GeV/c.

3. THE DATA ANALYSIS

The data sample used in this analysis comes from $4.3 \cdot 10^6$ triggers. Offline single electron selection reduces the sample to $2.5 \cdot 10^5$ events fully reconstructed in drift chambers and silicon detectors. For $1.1 \cdot 10^5$ events at least one charged kaon candidate in an event was found. The search for secondary vertices using the MSD information is restricted to these events.

The strategy of pattern recognition in the MSDs is described in [7]. Tracks found in the drift chambers are used as guides to search for tracks in the MSDs. For 84% of all tracks a match between drift chamber tracks and MSD-tracks is found. Tracks not found in the MSDs either miss the sensitive area of the vertex telescope or are due to γ conversions or secondary interactions downstream of the telescope. For tracks found in the MSDs a global vertex fit is performed taking into account experimentally determined measurement errors. A secondary vertex search is

performed in the sample of $3.4 \cdot 10^4$ events which are not compatible with a single vertex hypothesis ($\chi^2_{\text{vertex}}/\text{ndf} > 3$). This search is done in the region between the interaction point and the first MSD plane (50 mm). We apply here essentially the same algorithm as we used in the analysis of hadronic decays of D mesons [8]. The distance between the secondary and primary vertex has to be greater than 3σ ($\langle\sigma\rangle = 300\text{ }\mu\text{m}$). The decay tracks must not point back to the primary vertex. The impact parameters are required to be greater than 2σ for two of the tracks and greater than 1σ for the third. We also demand that at most one of the well measured tracks cannot be assigned to either primary or secondary vertices. In cases where ambiguous solutions for a secondary vertex in the event are found, we accept the vertex with the smallest χ^2 . This happens in less than 15% of the events and is mainly due to two different π tracks which can both be assigned to the vertex.

4. THE RESULTS

Using the secondary vertex finding procedure described above, we searched for events with displaced vertices of the trigger electron with one kaon and one pion track. 331 events pass the selection criteria and for approximately half of them (172) the electron and kaon have opposite charges. These events are candidates for Cabibbo favoured $c \rightarrow se^+\nu$ transitions, whereas e-K same sign events, once K and π are correctly identified, are not.

4.1 The Invariant Mass Spectra

4.1.1 General features

The $eK\pi$ invariant mass distributions for e-K opposite and e-K same sign events are shown in Figs. 2a,b. The events with $eK\pi$ masses above the D meson mass are obviously not D^+ decays and therefore are not considered in the subsequent analysis. There are 17% of such events in the e-K opposite sign sample and 26% in the e-K same sign sample. The $K\pi$ invariant mass distributions for both samples are shown in Figs. 3a and 3b. The distribution for e-K opposite charge events is dominated by the $K^*(892)$ peak. We have checked the $K\pi$ mass distribution for events with $m_{eK\pi} > m_D$ and did not find any significant $K^{*0}(892)$ signal. The $K\pi$ mass distribution for the e-K same sign events resembles the shape of the non-resonant part of the $K\pi$ mass distribution of the sample of e-K opposite sign events. However, the number of the e-K same sign events exceeds the e-K opposite sign non-resonant continuum by 60%.

Another feature in which both data samples differ is their electron-positron ratio. For e-K opposite sign events it is 1.31, consistent with the ratio of D^-/D^+ production rates in the π^- beam [9]. The sample of e-K same sign events contains 30% more positrons than electrons.

The average lifetime[†] of events in a 200 MeV wide mass region around the $K^{*0}(892)$ peak position, below and above it is (8.3 ± 0.8) , (4.8 ± 1.8) and $(2.8 \pm 0.5) \cdot 10^{-13}$ sec respectively. One of the events from the low mass region has a particularly long lifetime of $56.2 \cdot 10^{-13}$ sec. The average lifetime excluding this event is $(2.6 \pm 0.5) \cdot 10^{-13}$ sec. The average lifetime of the e-K same sign events is equal to $(3.2 \pm 0.4) \cdot 10^{-13}$ sec.

4.1.2 The $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ signal

The three signatures (i) a good 3 prong secondary vertex including a well identified electron, (ii) the $K\pi$ system forming a distinct $K^*(892)$ resonance for opposite sign e-K charges and (iii) the absence of the $K^*(892)$ peak for events with equal e-K charges, identify the signal as due to semileptonic decays of a charmed particle.

The $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decay is the dominant contribution to the signal: the D_s^+ cannot decay into $\bar{K}^{*0}e^+\nu_e$ and charmed baryons (e.g. $\Lambda_c^+ \rightarrow \bar{K}^{*0}(892)ne^+\nu_e$) as the source of the observed $\bar{K}^{*0}(892)e^+$ signal are unlikely because of the small cross-section for Λ_c^+ production in π^- interactions ($\sigma = 4 \pm 4 \mu\text{b}$ at 300 GeV [10]) and the small inclusive semileptonic branching ratio of a Λ_c^+ to final states containing neutral nonstrange baryons (1.6% [11]). Furthermore a strong contribution of Λ_c^+ decays to the signal is ruled out by a check on our data. We calculate the square of the maximal missing mass :

$$m_{\text{miss}}^2 = m_D^2 + m_{eK\pi}^2 - 2m_D \sqrt{m_{eK\pi}^2 + (p_{eK\pi}^T)^2}$$

where $p_{eK\pi}^T$ is the sum of the transverse momenta of the observed tracks with respect to the line of flight of the D. The distribution of m_{miss}^2 is shown in Fig. 4a together with a prediction of a simple Monte Carlo model in which we assume pure phase-space $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decays and take into account only measurement errors for relative distances of the primary and secondary vertices. In Fig. 4b we show the same distribution calculated with the Λ_c^+ mass as the decaying mass and compare it to Monte Carlo predictions for $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decays calculated

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[†] See a discussion of a lifetime calculated for unconstrained decays in section 4.3.

with $m(D^+)$ replaced by $m(\Lambda_C^+)$ (solid line) and for $\Lambda_C^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decays (broken line). It can be seen that the Monte Carlo calculations reproduce the main features of the data reasonably well for D^+ decay and rule out a large contribution of Λ_C^+ decays. The distribution of Fig. 4a is peaked at zero being compatible with the neutrino mass. The precision on m_{miss}^2 is not sufficient to determine the contamination due to missings π 's. Based on the experimental results of Refs. [1-3], a strong contribution of channels with missing pions can be excluded. All examined sources of non-charm background contribute equally to both e-K sign correlation samples. Since we do not observe a $K^{*0}(892)$ peak for the e-K same sign events, this background cannot exceed a few events. We can thus identify the $K^{*0}(892)$ signal as being dominantly due to $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decays.

4.1.3 The non-resonant $K\pi$ continuum

In the next two paragraphs we discuss the origin of the e-K same sign events and e-K opposite sign events from the non-resonant $K\pi$ continuum. The possible sources are background events due to reconstruction problems, secondary interactions, weak decays of strange particles and finally charmed particles decays. To estimate the background due to reconstruction errors we repeated the above vertex search by exchanging the electron with a pion in the momentum range of the trigger electron[†]. This allows a study of the background with the kinematics similar to the eK π vertices. Using the charge of the real electron in the event as a tag, events with opposite e-K charges have been selected as a measure of the background of non-charm origin (e-K same sign events can be due to decays of charmed particles). From this study we deduce an upper limit of 30% of the events in the continuum (both in the e-K same sign sample and e-K opposite sign sample) for background due to reconstruction errors. The background due to secondary interactions is small, since the secondary vertices involve a single electron and events with γ conversions have been effectively removed in the offline analysis. The contribution of weakly decaying strange hadrons to these samples is small too, despite their large production cross-sections, because either they do not decay to 3-prong final states or their decay probability in a 50 mm long decay volume is small and it requires the misidentification of one or more of the particles.

[†] Nearly all of the events (98%) contain at least one pion in the trigger momentum range.

The rest of the events are probably due to charm decays: we discuss the possible sources but no quantitative description can be given. A part of them could be due to wrong assignment of the electron coming from the semileptonic decay of one charmed particle to the $K\pi$ decay vertex of the partner. These events contribute to the e-K same sign sample. Another charm explanation for the e-K same sign events would be semileptonic $D_s^+ \rightarrow K^+ \pi^- e^+ \nu_e$ decays. However, because of the Cabibbo suppression and in addition a small cross-section and expected small semileptonic branching ratio for the D_s^+ meson, this source of e-K same sign events should be rather weak. Decays of $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ contribute to the e-K unlike sign events from the non-resonant $K\pi$ continuum. However, because the average lifetime of events outside the $K^{*0}(892)$ peak is small this source cannot be strong. Finally, some fraction of the events from both data sample can be due to semileptonic charm decays in cases where there is an identification ambiguity between π and K or p and K.

4.2 The D^+ Lifetime

Since one of the decay products (ν) is not observed, the momentum of the decaying parent particle, needed for lifetime determination is not known. To estimate the lifetime of D^+ we apply the method described in [12] where it is shown that the mean value of the ratio m_D/p_D and the mean value of the ratio of the invariant mass and momenta of seen decay products are proportional. The scaling is a property of Lorentz transformation in cases where the angular distribution of decay products in the parent particle rest system is approximately uniform. The proportionality factor is close to one and can be determined by Monte Carlo calculations. In our case the constant is equal to 1.02 and depends only weakly on the D^+ momentum. We checked also that it is insensitive to the model assumptions that we made in the Monte Carlo calculations. Different assumptions on the production mechanism result in only 4% change of the constant. The method has been checked on hadronic D decays observed in our experiment. The lifetimes calculated using this method agree with the direct measurements within 2%.

We calculate individual lifetimes using the observed invariant mass and momentum. From the measured decay path we subtract the minimum detectable decay path below which our secondary vertex selection criteria reject the event, thus obtaining a corrected lifetime. For the lifetime determination 137 events with $K\pi$ masses between the threshold and 1.28 GeV are selected and a simultaneous likelihood fit to the invariant masses and lifetimes is performed [8]. We assume a

Breit-Wigner with the $K^*(892)$ parameters [11] for the signal, whereas the background is parametrised by $a + b \cdot m_{K\pi}$. The lifetime distributions are assumed to be exponential. The fitted parameters are the slope of the background parametrisation, the number of signal events N_{D^+} and mean lifetimes of the signal $\langle\tau_{D^+}\rangle$ and the background $\langle\tau_{BG}\rangle$. We find :

$$\begin{aligned} N_{D^+} &= 74.3 \pm 8.6, \\ \langle\tau_{D^+}\rangle &= (10.9 \pm 1.4) \cdot 10^{-13} \text{ s}, \\ \langle\tau_{BG}\rangle &= (1.4 \pm 0.4) \cdot 10^{-13} \text{ s}. \end{aligned}$$

The errors quoted are the errors coming from the likelihood fit and are statistical only. We found that the number of fitted events N_{D^+} and the lifetime $\langle\tau_{D^+}\rangle$ are not sensitive to the background shape. By varying the selection criteria we do not find any systematic errors which are not smaller than the statistical errors. The result of the fit to the $K\pi$ mass spectrum and the lifetime distribution is shown as a solid line in Fig. 5 a,b. The lifetime of the non-resonant $K\pi$ background is very short, and thus any substantial contribution of $D^+ \rightarrow K^- \pi^+ e^+ \nu_e$ decays is unlikely. We are unable, however, to make a quantitative estimate of this contribution.

4.3 The Cross-Section and its x_F -Dependence

The electron trigger has the highest acceptance for electrons emitted at 90° in the c.m.s. of the D mesons. Thus, we are able to measure the D^+ cross-section for small x_F 's (Fig. 6a) where other data suffer from a small and/or rapidly changing acceptance. The knowledge of the cross-section in the low x_F region is essential for resolving controversies on the contribution of a central component to the hadronic charm production process [9,10, 13].

Because of the missing neutrino we can study only the inclusive x_F distribution for x_F 's calculated from visible momenta. However, for $x_F > 0$ the difference between the observed x_F and the true value is small as the Monte Carlo simulation shows (Fig. 6b). The measured and acceptance corrected x_F distributions for events with $0.78 < m(K\pi) < 1.0$ GeV are shown in Fig. 7. The distributions are corrected for background using events from side bands. The fit of the corrected distribution with $(1-x_F)^n$ parametrisation gives $n = 4.0 \pm 1.3$. If we fit the x_F distributions for D^- (leading meson i.e. containing a quark of the projectile) and D^+ (nonleading) separately, the fit yields $n = 4.4 \pm 2.4$ for D^- and $n = 3.8 \pm 1.7$ for D^+ . The ratio of production rates of D^- and D^+ mesons is equal to 1.5 ± 0.4 . Thus, we are not in agreement with the claim of Refs. [13,14] that most of the D production

cross-section (80%) is characterised by a $(1-x_F)^n$ dependence with $n \approx 8$. Also, contrary to Ref. [14], we do not observe any statistically significant difference in the x_F -dependence of cross-sections for leading and non-leading D mesons, but observe more abundant production of leading D's than nonleading ones. These results confirm our previous results on the hadronic charm production mechanism coming from the analysis of hadronic D decays observed in the same experiment [9].

Using the events from the signal sample we estimate the the D^+ production cross-section per nucleon assuming a linear dependence on the atomic number of the target material. In the calculations we use the same corrections factors accounting for various losses as those determined for hadronic D decays [9]. An overall acceptance for $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ obtained from Monte Carlo simulation in which we assumed a symmetric x_F distribution, is equal to 1.5%. For the branching ratio we take the value determined by the MARK III experiment [3] : $BR(D^+ \rightarrow \nu_e e^+ K^- \pi^+) = 3.9 \pm 0.8 \pm 0.7\%$. We obtain :

$$\sigma(\pi^- \rightarrow D^+ X) = 30.0 \pm 3.5 \pm 12.6 \text{ } \mu\text{b/nucleon}$$

The second error is systematic and it is mainly due to the error on the branching ratio. The result is in agreement within errors with the value obtained from our analysis of $D^+ \rightarrow K^- \pi^+ \pi^+$ decays ($\sigma(D^+) = 20 \pm 4 \pm 5 \text{ } \mu\text{b/nucleon}$).

5. SUMMARY

We report the observation of the decay $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ in π^- Be interactions at 200 GeV. The mean lifetime of the 74 signal events is :

$$\langle \tau_{D^+} \rangle = (10.9 \pm 1.4) \cdot 10^{-13} \text{ s} .$$

For the D^+ production cross-section at 200 GeV we find :

$$\sigma(\pi^- \text{Be} \rightarrow D^+ X) = 30.0 \pm 3.5 \pm 12.6 \text{ } \mu\text{b/nucleon} .$$

The x_F dependence of the cross-section for $0 < x_F < 0.4$ is well described by $(1-x_F)^n$ with $n = 4.0 \pm 1.3$. We do not observe any significant difference of the shapes of the x_F distributions for leading and nonleading mesons, but find 50% more D^- (leading) than D^+ (nonleading).

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Figure captions

Fig. 1 : Top view of the ACCMOR spectrometer showing the target (Be), the silicon microstrip detectors (MSD), the magnets (M1,M2), the drift chambers (DC), the Cerenkovs (Q,C), the multiwire proportional chambers (P), the scintillator arrays (MA,MB) and the electron (photon) calorimeters (E-CAL,G).

Fig. 2 : The $eK\pi$ invariant mass distributions for e-K opposite sign (a) and e-K same sign events (b). The vertical lines show the cut at the D^+ mass.

Fig. 3 : The $K\pi$ invariant mass distributions for e-K opposite sign (a) and e-K same sign (b) events with $eK\pi$ masses below the D-meson mass.

Fig. 4 : (a) The distribution of the maximal missing mass squared m_{miss}^2 calculated with m_D as a decay mass. The curve is the Monte Carlo prediction.
 (b) The distribution of m_{miss}^2 calculated with $m(D^+)$ replaced by $m(\Lambda_C^+)$ and the Monte Carlo prediction (solid line). The broken line shows the Monte Carlo result for $\Lambda_C^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ decays.

Fig. 5 : The solid line shows the result of the maximum likelihood fit to (a) the $K\pi$ mass spectrum and (b) the lifetime distribution. The dashed line in (a) and (b) shows the background contribution.

Fig. 6 : a) The acceptance as a function of x for decays $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$.
 b) $\Delta x_F = x_F^D - x_F^{eK\pi}$ as a function of x_F^D obtained from the Monte-Carlo simulation.

Fig. 7 : The observed and acceptance corrected distribution for $D^+ \rightarrow \bar{K}^{*0}(892)e^+\nu_e$ with the result of the fit to a $(1-x_F)^n$ parametrization with $n = 4.0 \pm 1.3$.

Fig. 1

Fig.2

Fig. 4

Fig.5

Fig.6

Fig. 7