Charm Semileptonic Decays

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I discuss new data on charm semileptonic decay concentrating on two topics involving the decay $D^+ \to K^-\pi^+\mu^+\nu$. The first topic is the observation of interference in this decay by the FOCUS collaboration[1]. The second are new measurements of branching ratio of $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ relative to $D^+ \to K^-\pi^+\pi^+$ from CLEO[2] and FOCUS. Fig. 1 shows the $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ signals of these two groups.

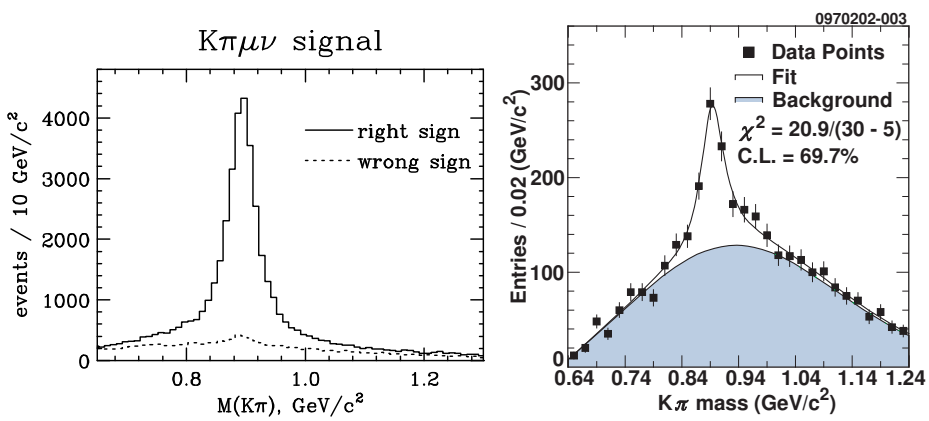

Figure 1: $D^+ \to K^-\pi^+\mu^+\nu$ signal. (left) The FOCUS right-sign and wrong-sign samples are shown. The wrong-sign-subtracted yield is 31 254 events. (right) A partial sample of $D^{*+} \to \pi^0 D^+ \to \pi^0(\overline{K}^{*0}e^+\nu)$ from CLEO. This is the sample form one of their bins in the $D^* - D$ mass difference.

1 Interference in $D^+ \to K^-\pi^+\mu^+\nu$

In our attempts to fit for the form factors controlling the decay $D^+ \to \overline{K}^{*0}\mu^+\nu$, we discovered a large, unexpected asymmetry in the $\cos\theta_V$ distribution shown in Fig. 2. This asymmetry was very strong for events with a $m_{K\pi}$ mass below the pole and weak for events above the pole. It was possible to understand the forward-backward

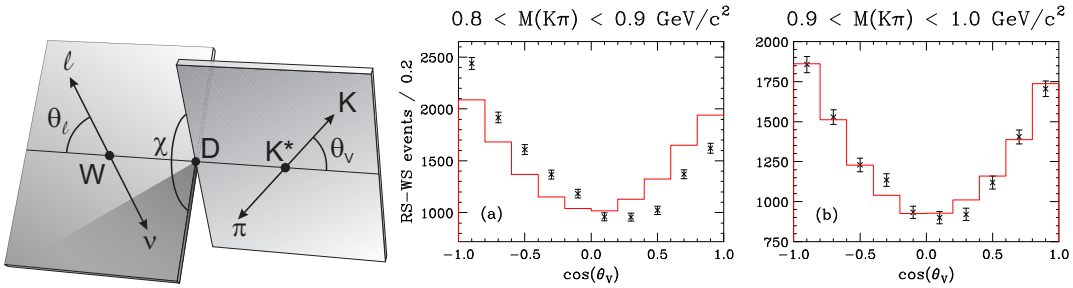

Figure 2: (left) Definition of the three decay angles: $\cos\theta_{\rm V}$ is the decay angle of the kaon in the $\overline{K}^{*0}$ frame, $\cos\theta_\ell$ is the angle of the charged lepton in the virtual W^+ frame. χ is the acoplanarity angle between the two decay planes. (right) Event distribution in $\cos\theta_{\rm V}$, split between samples below and above 0.9 GeV/c^2. The points with error bars are (wrong-sign subtracted) FOCUS data and the solid histogram is a Monte Carlo simulation with efficiency and known charm backgrounds but no interference.

asymmetry in $\cos\theta_{\rm V}$ using the simple model summarized by Eqn. 1. Using the notation of [3], we write the decay distribution (in the zero charged lepton mass limit) for $D^+ \to K^-\pi^+\mu^+\nu$ in terms of the three helicity basis form factors: H_+ , H_0 , H_-. We have taken the standard amplitude and added an interfering s-wave amplitude with a constant modulus and phase ($A\ \exp(i\delta)$) that interferes with the $\overline{K}^{*0}$ Breit-Wigner ($\mathrm{B}_{K^{*0}}$) in the one place allowed by angular momentum conservation.

$$\frac{d^5\Gamma}{dm_{K\pi}\ dq^2\ d\cos\theta_{\rm V}\ d\cos\theta_\ell\ d\chi} \propto q^2 \left| \begin{array}{l} (1+\cos\theta_\ell)\sin\theta_{\rm V} e^{i\chi}\mathrm{B}_{K^{*0}} H_+ \\ -(1-\cos\theta_\ell)\sin\theta_{\rm V} e^{-i\chi}\mathrm{B}_{K^{*0}} H_- \\ -2\sin\theta_\ell(\cos\theta_{\rm V}\mathrm{B}_{K^{*0}} + Ae^{i\delta})H_0 \end{array} \right|^2 \qquad (1)$$

Assuming the s-wave amplitude is small (or the effect would have been discovered already) it will be primarily observable through three interference terms:
$8\cos\theta_{\rm V}\sin^2\theta_\ell A\Re\left(e^{-i\delta}\mathrm{B}_{K^{*0}}\right)H_0^2$, $-4(1+\cos\theta_\ell)\sin\theta_\ell\sin\theta_{\rm V}\ A\Re\left(e^{i(\chi-\delta)}\mathrm{B}_{K^{*0}}\right)H_+H_0$, and $+4(1-\cos\theta_\ell)\sin\theta_\ell\sin\theta_{\rm V}\ A\Re\left(e^{-i(\chi+\delta)}\mathrm{B}_{K^{*0}}\right)H_-H_0$. Only the first of these terms will survive averaging over the acoplanarity, χ. This was the term responsible for creating the $\cos\theta_{\rm V}$ asymmetry shown in Fig. 2 since it is proportional to $\cos\theta_{\rm V}$. If we further weight our wrong-sign subtracted, azimuthally averaged data by $\cos\theta_{\rm V}$, this is the only term that will survive in the full decay amplitude (given our nearly uniform angular acceptance). It will have a distinct dependence on the $m_{K\pi}$ mass: $\Re\left(e^{-i\delta}\mathrm{B}_{K^{*0}}\right)$, as well as on $\cos\theta_\ell$: $(1-\cos^2\theta_\ell)$.

Figure 3 shows two $\cos\theta_{\rm V}$-weighted, wrong sign subtracted distributions for $K\pi\mu\nu$. The left plot is the asymmetry weighted $m_{K\pi}$ distribution which should resemble

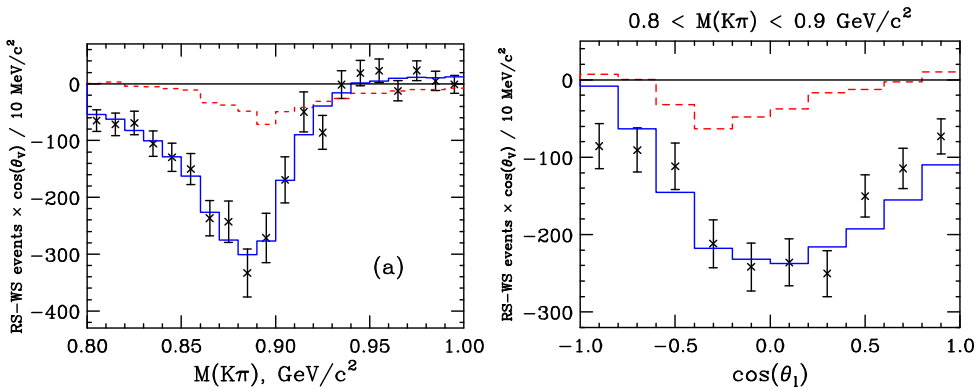

Figure 3: (left) The $\cos\theta_{\rm V}$-weighted distribution in $K\pi$ invariant mass. The data are the points with error bars. The dashed (red) histogram have no s-wave amplitude (null hypothesis). The solid (blue) histogram includes an s-wave amplitude of 0.36 $\exp(i\pi/4)$ GeV^{-1}. (right) The $\cos\theta_{\rm V}$-weighted distribution in $\cos\theta_{\rm V}$ compared to the null (red) and amplitude (blue) simulations.

$\Re\left(e^{-i\delta}{\rm B}_{K^{*0}}\right)$. For $\delta = 0$, $\Re\left(e^{-i\delta}{\rm B}_{K^{*0}}\right)$ is odd function of $m_{K\pi}$ - $m_{K^{*0}}$, while for $\delta = \pi/2$ this form is even in $m_{K\pi}$ - $m_{K^{*0}}$. The data strongly resembles the expected plot for $\delta = \pi/4$. The right half of Fig. 2 is the asymmetry weighted $\cos\theta_\ell$ distribution with masses in the region $0.8 < m_{K\pi} < 1.0$ GeV/c^2. It resembles the expected parabola in $\cos\theta_\ell$ with some modulation due to acceptance and resolution.

In the absence of the s-wave interference, all acoplanarity dependent terms in the $D^+ \to \overline{K}^{*0}\mu^+\nu$ decay intensity are functions of $\cos\chi$ and $\cos 2\chi$. The s-wave interference includes additional acoplanarity dependent s-wave terms of the form: $+4(1-\cos\theta_\ell)\sin\theta_\ell\sin\theta_{\rm V}\, A\Re\left(e^{-i(\chi+\delta)}{\rm B}_{K^{*0}}\right) H_- H_0$ which brings in a $\sin\chi$ dependence thereby breaking $\chi \leftrightarrow -\chi$ symmetry. Figure 4 shows the wrong-sign subtracted χ distribution separately for D^+ and D^- events in the range $0.8 < m_{K\pi} < 1.0$ GeV/c^2 Initially we were surprised by the inconsistency between the D^+ and D^- acoplanarity until we realized that there is a sign change in the χ convention between the particle and antiparticle. After applying the correct convention, the D^+ and D^- distributions become consistent, and the odd χ contributions brought in through the s-wave interference become very evident. Why has the s-wave interference in $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ never been reported before, given that it has been a process studied for nearly twenty years by several experiments? One answer is that an amplitude of this strength and form creates a very minor modulation to the $m_{K\pi}$ spectrum as shown in Figure 4. Another reason is that this effect is much more evident when one divides the data above and below the $\overline{K}^{*0}$pole. Finally, the FOCUS data set has significantly more clean $D^+ \to K^-\pi^+\mu^+\nu$ events than previously published data.

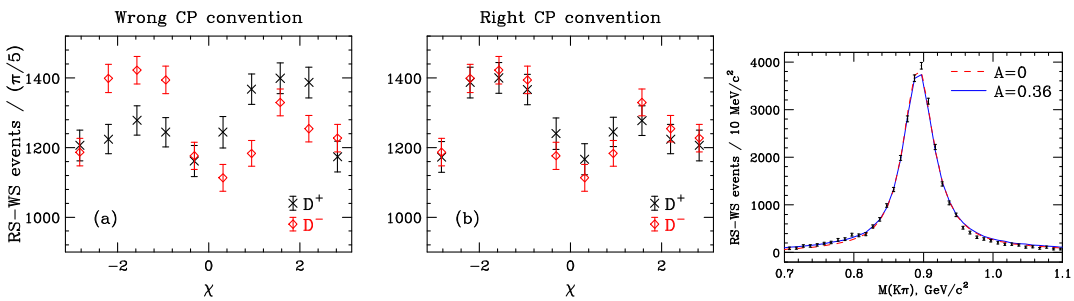

Figure 4: (left) The wrong-sign subtracted acoplanarity distribution separated by charm. The "x" points are for the D^+ while the "diamond" points are for the D^-. (a) compares the distributions without the required change in the χ convention as discussed above. (b) compares the distributions with the correct χ sign convention change. (right) The $m_{K\pi}$ mass distribution in data (with error bars) compared to our null hypothesis (red) and s-wave (blue) Monte Carlos. The two predicted $m_{K\pi}$ spectra are nearly identical.

2 New Measurements of $\frac{\Gamma(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)}$

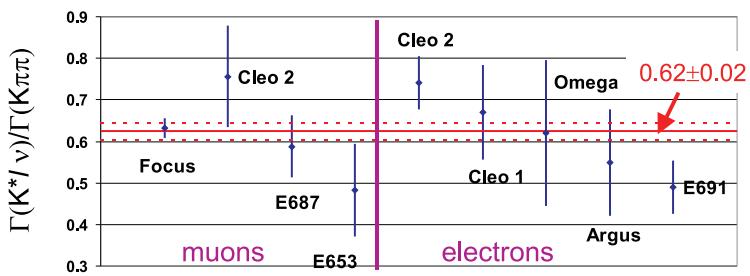

Figure 5: Summary of measurements on $\frac{\Gamma(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)}$. The muon data, on the left, has been scaled by a factor of 1.05 to compare to the electron data. Our preliminary FOCUS point is plotted first. The new CLEO2 electron plot is the first "electron" point. I also show an informal weighted average of these measurements including our preliminary FOCUS point.

The CLEO Collaboration has made a new measurement of $\frac{\Gamma(D^+ \to \overline{K}^{*0} \ell^+ \nu_\ell)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)} = 0.74 \pm 0.04 \pm 0.05$ that is somewhat higher than previous measurements and significantly higher than the previous high precision measurement by E691 as shown in Fig. 5. The new CLEO measurement can be interpreted as helping to resolve an old problem

with theory theory over-predicting the $\Gamma\left(D^+ \to \overline{K}^{*0}\ell^+\nu_\ell\right)$ by a rough factor of two.

FOCUS is in the process of making a new measurement of $D^+ \to \overline{K}^{*0}\mu^+\nu$ using a Monte Carlo that includes the s-wave interference described above. Our preliminary number is $\frac{\Gamma(D^+\to\overline{K}^{*0}\ell^+\nu_\ell)}{\Gamma(D^+\to K^-\pi^+\pi^+)} = 0.60 \pm 0.01$ with a systematic error expected to be roughly twice the statistical error. After multiplying this relative muon branching ratio by 1.05 to compare to the electron branching ratio[4], our preliminary number lies about 1.6 σ below the new CLEO number.

To summarize: I presented evidence for an s-wave interference with the dominant $D^+ \to \overline{K}^{*0}\mu^+\nu$ contribution to $D^+ \to K^-\pi^+\mu^+\nu$ decay. This interference creates a strong ($\approx 20\%$) forward-backward asymmetry in the $\overline{K}^{*0}$ decay angular distribution, but creates very minimal distortion to the $K^-\pi^+$ mass distribution. The dependence of the asymmetry on the $m_{K\pi}$ suggests that it has a phase of 45° near the $\overline{K}^{*0}$ pole and amplitude that is roughly 7% of the Breit-Wigner amplitude at the pole mass in the H_0 helicity contribution.

CLEO recently published branching ratio of $D^+ \to \overline{K}^{*0}\ell^+\nu_\ell$ relative to $D^+ \to K^-\pi^+\pi^+$ that was somewhat higher than the previous world average and would help resolve a discrepancy with theoretical predictions. A preliminary number from FOCUS with better precision than previously reported is 1.6 σ lower than this CLEO number.

We can look forward to new measurements of the $D^+ \to \overline{K}^{*0}\mu^+\nu$ form factors, the $D_s^+ \to \phi\mu\nu/\phi\pi$ and their form factors, studies of the q^2 dependence of the $D^0 \to K^-\mu^+\nu$ form factor, and Cabibbo suppressed ratios such as $D^+ \to \rho\mu\nu/\overline{K}^{*0}\mu\nu$ and $D^0 \to \pi^-\mu^+\nu/K^-\mu^+\nu$.

I am grateful to the FOCUS Collaboration and organizers of this excellent conference.

References

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