Charm (meson) Semileptonic Decays

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Representing FOCUS

Outline

• Interference in $D^+ \rightarrow K\pi\mu\nu$
  • FOCUS

• New $D^+ \rightarrow K^*\mu\nu/K2\pi$ BR
  • CLEO and FOCUS

• Prognosis for new SL results
New results on $D^+ \rightarrow K\pi\mu\nu$

Our $K\pi$ spectrum like everyone else’s looks like 100% $K^*(890)$

This has been “known” for about 20 years.

But a funny thing happened when we tried to measure the form factor ratios by fitting the angular distributions ...

Right Sign
Wrong Sign

backgrounds are pretty small

Our $K\pi$ spectrum like everyone else’s looks like 100% $K^*(890)$

This has been “known” for about 20 years.
Five observables are studied

A 4-body decay requires 5 kinematic variables: Three angles and two masses.

\[
M_{K\pi} \\
M_W^2 \equiv q^2 \equiv t
\]

Two amplitude sums over W polarization

\[
|A|^2 = \frac{1}{8} (t - m_l^2) \left\{ \begin{array}{l}
\text{right-handed } \mu^+ \\

(1 + \cos \theta_l) \sin \theta_V e^{ix} H_+ \\
-(1 - \cos \theta_l) \sin \theta_V e^{-ix} H_- \\
-2 \sin \theta_l \cos \theta_V H_0
\end{array} \right\}^2
\]

Wigner D-matrices

\[
H_0(q^2), H_+(q^2), H_-(q^2) \text{ are helicity-basis form factors computable by LGT}
\]

left-handed \ \mu^+

\[
\begin{align*}
\sin \theta_l \sin \theta_V e^{ix} H_+ \\
+ \sin \theta_l \sin \theta_V e^{-ix} H_- \\
+2 \cos \theta_l \cos \theta_V H_0 \\
+2 \cos \theta_V H_t
\end{align*}
\]

("mass terms")
An unexpected asymmetry in the $K^*$ decay

We noticed a forward-backward asymmetry in $\cos \theta_V$ below the $K^*$ pole, but almost none above the pole.

Sounds like QM interference
Simplest approach —
Try an interfering spin-0 amplitude

\[ |M|^2 \propto (t - m^2_{\mu}) \left| \left( \frac{(1 + \cos \theta_{l}) \sin \theta_V}{\sqrt{2}} e^{i\chi} B H_+ \right)^2 + \frac{(1 - \cos \theta_{l}) - \sin \theta_V}{\sqrt{2}} e^{-i\chi} B H_- + \frac{-\sin \theta_l}{\sqrt{2}} (\cos \theta_V B + A e^{i\delta}) H_0 \right| \]

where \( B = \frac{\sqrt{m_0 \Gamma}}{m^2 - m_0^2 + i m_0 \Gamma} \)

A \( \exp(i\delta) \) will produce 3 interference terms

We simply add a new constant amplitude: \( A \exp(i\delta) \) in the place where the \( K^* \) couples to an \( m=0 \) \( W^+ \) with amplitude \( H_0 \).
Since $A << B$, interference will dominate.

There will only be three terms as $m_\mu \Rightarrow 0$

$$\text{Intrf.} = 8 \cos \theta_V \sin^2 \theta_l A \Re\left( e^{-i\delta} B_{K^*} \right) H_0^2$$

$$-4(1 + \cos \theta_l) \sin \theta_l \sin \theta_V A \Re\left( B_{K^*} e^{i(\chi-\delta)} \right) H + H_0$$

$$+4(1 - \cos \theta_l) \sin \theta_l \sin \theta_V A \Re\left( B_{K^*} e^{-i(\chi+\delta)} \right) H_- H_0$$

If we average over acoplanarity we only get the first term

$$8 \cos \theta_V \sin^2 \theta_l A \Re\left( e^{-i\delta} B_{K^*} \right) H_0^2$$

This is the term that created our forward-backward asymmetry!

If our model is right:
- The asymmetry will have a particular mass dependence: $\Re\left( e^{-i\delta} B_{K^*} \right)$
- The asymmetry should be proportional to $\sin^2 \theta_l$
- The asymmetry should have a $q^2$ dependence given by $q^2 H_0^2(q^2)$
Studies of the acoplanarity-averaged interference

\[ +8 \cos \theta_V \sin^2 \theta_V A \Re \left( e^{-i\delta} B_{K^*} \right) H_0^2 \]

Extract this interference term by weighting data by \( \cos \theta_V \).

Since all other \( \chi \)-averaged terms in the decay intensity are constant or \( \cos^2 \theta_V \).

We begin with the mass dependence:

\[ \Re \left( e^{-i\delta} B_{K^*} \right) \]

Our weighted mass distribution...

..looks just like the calculation.

A constant 45° phase works great...

...but a broad resonance is fine as well.
Dependence of asymmetry on $\cos \theta_l$

$$8 \cos \theta_V \sin^2 \theta_l A \Re \left( e^{-i \delta} B_{K^*} \right) H_0^2$$

- We plot the asymmetry versus $\cos \theta_l$ and expect a parabola in $\cos^2 \theta_l$ since $\sin^2 \theta_l = (1 - \cos^2 \theta_l)$

0.8 < $M(K\pi)$ < 0.9 GeV/c$^2$

Looks $\propto - (1 - \cos^2 \theta_l)$. Some modulation due to efficiency and resolution
q² dependence of asymmetry

\[ 8 \cos \theta_V \sin^2 \theta_A A \Re \left( e^{-i\delta} B_{K^*} \right) H_0^2(q^2) \]
Acoplanarity dependent interference terms

The interference adds two new terms to the acoplanarity dependence.

\[-4(1 + \cos \theta_l) \sin \theta_l \sin \theta_V A \text{Re}(B_{K*} e^{i(\chi-\delta)})H + H_0\]
\[+4(1 - \cos \theta_l) \sin \theta_l \sin \theta_V A \text{Re}(B_{K*} e^{-i(\chi+\delta)})H - H_0\]

Without s-wave interference, the acoplanarity terms are even in $\chi$: Only $\cos \chi$ and $\cos 2\chi$ dependencies are present.

The interference produces $\sin \chi$ terms which break $\chi$ to $-\chi$ symmetry.
Our first brush with $\sin \chi$ was frightening!

$$\chi(D^+) \rightarrow -\chi(D^-)$$

Same sign convention used for $D^+$ and $D^-$

Yikes! CP violation?

Interference with the new amplitude breaks $\chi$ to $-\chi$ symmetry.

When CP is handled properly, the $D^+$ and $D^-$ acoplanarity distributions become consistent.
The correct acoplanarity convention

The sine of the acoplanarity requires 5 vectors to specify

\[ \sin \chi = \frac{\vec{P}_{K\pi} \cdot \left[ (\vec{K} \times \vec{\pi}) \times (\vec{\mu} \times \vec{v}) \right]}{|\vec{P}_{K\pi}| \left| \vec{K} \times \vec{\pi} \right| \left| \vec{\mu} \times \vec{v} \right|} \]

Under CP: \( D^+ \Rightarrow D^- \), all 5 vectors will reverse as will \( \sin \chi \) under our convention. Interference produces a "false" CP violation between the acoplanarity distribution between \( D^+ \) versus \( D^- \) unless we explicitly take \( \chi \) to \( -\chi \).
But surely an effect this large must have been observed before?

\[ 0.8 < M(K\pi) < 0.9 \text{ GeV/c}^2 \]

Although the interference \textit{significantly} distorts the decay intensity....

...the interference is nearly invisible in the $K\pi$ mass plot.
New results on $D^+ \rightarrow K^*\mu\nu/K2\pi$ branching ratio

CLEO (partial) signal for

$$D^{*+} \rightarrow \pi^0 D^+ \rightarrow \pi^0 (\bar{K}^{*0} e^+ \nu)$$

Quoted result from this sample

**Baseline**

- RS
- WS

**Quoted result from this sample**
The CLEO result might resolve an old problem

Quark models predicted a
\[ \Gamma(D^+ \rightarrow K^{*0} \mu^+ \nu) \propto |A_1(0)|^2 \]
\[ \approx \text{twice as high as existing data.} \]

The recent CLEO number raises this width considerably .. thus partially resolving this long standing problem.
The **preliminary** FOCUS result

\[
\frac{\Gamma(D^+ \to K^{*0} \mu^+ \nu)}{\Gamma(D^+ \to K^- \pi^+ \pi^+)} = 0.602 \pm 0.010 \text{ (stat)} \pm 0.021 \text{ (sys)}
\]

Still under study!

We multiply muon results by 1.05 to compare to electron results.

Our preliminary number is 1.59 standard deviations **below** CLEO and 2.1 standard deviations **above** E691.

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### Graph Description

- **Axes:**
  - Y-axis: \(\Gamma(K^*1/\nu)/\Gamma(K_{\pi\pi})\)
  - X-axis: Data sets

- **Data Sets:**
  - Cleo 1
  - Cleo 2
  - Omega
  - Focus
  - E687
  - Argus
  - E653
  - Electrons
  - Muons

- **Notations:**
  - 0.62±0.02

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**PRELIMINARY**
Summary

(1) S-wave interference in $D^+ \rightarrow K\pi\mu\nu$ of form

$$|H_0|^2 \left| 0.36 \exp\left(i \frac{\pi}{4}\right) + \frac{\cos \theta_v \sqrt{m_0} \Gamma}{(m - m_o)^2 + i m_0 \Gamma} \right|^2$$

The new amplitude is small:

- $\approx 7\%$ of BW peak amplitude in the $H_0$ part.
- $\approx 6\%$ of all $K\pi\mu\nu$ over the full $K\pi$ range

(2) New results on $D^+ \rightarrow K^*\mu\nu/K2\pi$

- CLEO value $0.74 \pm 0.04 \pm 0.05$ (is higher than previous data)
- FOCUS preliminary value is $0.60 \pm 0.01 \pm 0.02$ ($1.57\sigma$ lower than CLEO)

(3) Many interesting results are on the way:

- New measurements of $D_s^+ \rightarrow \phi\mu\nu/\phi\pi$
- New $r_v$ and $r_2$ form factor measurements for $K^*\mu\nu$ and $\phi\mu\nu$
- $f(q^2)$ measurement for $D^0 \rightarrow K\mu\nu$
- Cabibbo suppressed ratios: $D^+ \rightarrow \rho\mu\nu/K^*\mu\nu$ & $D^0 \rightarrow \pi\mu\nu/K\mu\nu$
Once we demand a decay out of the target segments, the backgrounds are matched by our Monte Carlo. This is a “c,cbar” MC with events containing a $\phi\mu\nu$ decay excluded.

Work is being done on the branching ratio measurement, and I hope to work on the form factor measurement.

Perhaps we will see interference with the $f_0(980)$?