Study of the Decays of Charm Mesons with the BaBar Experiment

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Outline

- Hadronic Form Factors and q^2 -dependence of $D^0 \rightarrow K^- e^+ \nu_e$ and $D_s^+ \rightarrow \phi e^+ \nu_e$ decay channels.
- Measurement of rare decays Branching Ratios:
 $D^+ \rightarrow \pi^+ \pi^0$ and $D^+ \rightarrow K^+ \pi^0$ (first observation),
 $D^0 \rightarrow \pi^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- K^+ \pi^0$.
- Conclusions.

Semileptonic D decay Form Factor Motivation

- Weak decay well understood, Strong interactions complicate the picture $\Rightarrow$ great laboratory to study QCD effects
- Computations are within the reach of lattice calculations
- Large effort from Lattice community (FNAL, MILC,...) to improve computation methods (unquenched, staggered fermions...)
- Semileptonic decays of charm hadrons provide a way to calibrate lattice results through the measurement of Form Factors
- This effort can give confidence in B sector lattice results ($f_B, \dots$)

Analysis principle $D^0 \rightarrow K^- e^+ \nu$

- Use continuum events: $e^+e^- \rightarrow c\bar{c}$ ($\sigma = 1.3$ nb)

- Determine $q^2 = (p_D - p_K)^2 = (p_l + p_\nu)^2 \rightarrow$ two constrained fits
- Reduce the background $\rightarrow$ Fisher discriminant ($b\bar{b}$ and $c\bar{c}$ events)
- Extract the Form Factor $\rightarrow$ Unfolding with Singular Value Decomposition (SVD) method

$D^0 \rightarrow K^- e^+ \nu$ sample

- Novel technique provides huge sample of $D^0 \rightarrow K^- e^+ \nu_e$ candidates

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Form Factor in $D^0 \rightarrow K^- e^+ \nu$

- Form Factor q^2 distribution, corrected for reconstruction efficiency and finite resolution:

- Decay Rate:

$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs}|^2 p_K^3(q^2) |f_+(q^2)|^2$$

- Fit to pole mass model:

$$|f_+(q^2)| = \frac{f_+(0)}{1 - \frac{q^2}{m_{pole}^2}}$$

$$m_{pole} = (1.854 \pm 0.016 \pm 0.020) \text{ GeV}/c^2$$

- Fit to modified pole mass model:

$$|f_+(q^2)| = \frac{f_+(0)}{\left(1 - \frac{q^2}{m_{D_s^*}^2}\right) \left(1 - \frac{\alpha_{pole} q^2}{m_{D_s^*}^2}\right)}$$

$$\alpha_{pole} = 0.43 \pm 0.03 \pm 0.04$$

$$\alpha_{pole}(\text{lattice}) = 0.50 \pm 0.04 \text{ [hep-ph/0408306]}$$

Experiment	$m_{pole} \text{ (GeV}/c^2)^2$	α_{pole}	Statistics
CLEO III	$1.98 \pm 0.03 \pm 0.02$	$0.19 \pm 0.05 \pm 0.03$	281 pb^{-1}
FOCUS	$1.93 \pm 0.05 \pm 0.03$	$0.28 \pm 0.08 \pm 0.03$	13 k evt
BELLE	$1.82 \pm 0.04 \pm 0.03$	$0.52 \pm 0.08 \pm 0.06$	282 fb^{-1}
BaBar	$1.854 \pm 0.016 \pm 0.020$	$0.43 \pm 0.03 \pm 0.04$	75 fb^{-1}

Vector Form Factors

$$D_s^+ \rightarrow \phi e^+ \nu$$

- Pseudoscalar lv decay: one form factor and known angular distribution
- Vector lv decay : 3 helicity states, 5 kinematic variables
 $\Rightarrow$ More statistics needed
- Current most precise measurement use $D \rightarrow K^* e \nu$ decay
- Most recent $D_s^+ \rightarrow \phi e^+ \nu$ measurement:
 FOCUS Collaboration [Phys.Lett. B586 (2004), 183-190]
- q^2 dependency of Form Factors never studied experimentally

Vector Form Factors

$$D_s^+ \rightarrow \phi e^+ \nu$$

- Decay Rate:

$$\frac{d^4\Gamma}{dq^2 d\cos\theta_V d\cos\theta_e d\chi} \propto p_{KK} q^2 \left| \begin{array}{l} (1 + \cos\theta_e) \sin\theta_V e^{i\chi} H_+ \\ - (1 - \cos\theta_e) \sin\theta_V e^{-i\chi} H_- \\ - 2 \sin\theta_e \cos\theta_V H_0 \end{array} \right|^2$$

- Helicity Form Factors are combinations of two axial and one vector form factors:

$$H_{\pm}(q^2) = (m_D + m_{\phi}) A_1(q^2) \mp 2 \frac{m_D p_{\phi}}{m_D + m_{\phi}} V(q^2)$$

$$H_0(q^2) = \frac{1}{2m_{\phi}\sqrt{q^2}} \left[(m_D^2 - m_{\phi}^2 - q^2)(m_D + m_{\phi}) A_1(q^2) - 4 \frac{m_D^2 p_{\phi}^2}{m_D + m_{\phi}} A_2(q^2) \right]$$

- Pole dominance parameterization:

$$A_i(q^2) = \frac{A_i(0)}{1 - q^2/m_A^2} \quad V(q^2) = \frac{V(0)}{1 - q^2/m_V^2}$$

$$\begin{array}{l} 1^+ (D_{sJ}(2460), D_{s1}(2536)) \\ \rightarrow m_A = 2.5 \text{ GeV} \end{array}$$

$$\begin{array}{l} 1^- (D_s^*) \leftarrow c\bar{s} \text{ states} \\ \rightarrow m_V = 2.1 \text{ GeV} \end{array}$$

- Two parameters are measured, ratios of the FF at $q^2=0$:

$$r_V = V(0)/A_1(0) \quad \text{and} \quad r_2 = A_2(0)/A_1(0)$$

Analysis principle

$$D_s^+ \rightarrow \phi e^+ \nu$$

- Use D_s continuum events
- Event reconstruction:
 - Define 2 hemispheres and require that K^+K^-e are in the same hemisphere
 - Compute D_s direction ($-\mathbf{p}_{\text{all tracks} \neq K+K-e}$)
 - Compute missing energy in the lepton hemisphere
 - Fit $\mathbf{p}_{D_s} = \mathbf{p}_{K^+} + \mathbf{p}_{K^-} + \mathbf{p}_e + \mathbf{p}_\nu$
 - Compute kinematic variables
- Cuts:
 - Reduce the background
 - Fisher discriminant ($b\bar{b}$ and $c\bar{c}$ events)
 - $1.01 < m_\phi < 1.03 \text{ GeV}/c^2$ $p_{e(\text{CM})} > 0.5 \text{ GeV}/c$

Experimental Results

$$D_s^+ \rightarrow \phi e^+ \nu$$

- Projected distributions of the reconstructed values of the 4 kinematic variables
- Points represent data, histograms correspond to the result of the fit.

$$N_S = 12886 \pm 129,$$

$$r_V = 1.636 \pm 0.067$$

$$r_2 = 0.705 \pm 0.056$$

Experimental Results

$$D_s^+ \rightarrow \phi e^+ \nu$$

- Ratios of FF at $q^2=0$:

$$r_V = V(0)/A_1(0) = 1.636 \pm 0.067 \pm 0.037 \text{ and } r_2 = A_2(0)/A_1(0) = 0.705 \pm 0.056 \pm 0.029$$

- BaBar results compatible with other experiments but 4-times more accurate:

- Accuracy similar to $D \rightarrow K^* e \nu$
- First measurement of axial pole mass using the pole mass model and floating m_A :

$$r_V = V(0)/A_1(0) = 1.633 \pm 0.081 \pm 0.068, \quad r_2 = A_2(0)/A_1(0) = 0.711 \pm 0.111 \pm 0.096$$

$$\text{and } m_A = (2.53_{-0.35}^{+0.54} \pm 0.54) \text{ GeV}/c^2.$$

$D^+ \rightarrow \pi^+ \pi^0$ and $D^+ \rightarrow K^+ \pi^0$

Branching Fractions

- Motivation: provide insight into violation of SU(3) flavor symmetry.
- $D^+ \rightarrow K^+ \pi^0$ is doubly Cabibbo suppressed.
- Method: reconstruct $D^{*+} \rightarrow D^+ \pi^0$ chain using $\Delta m = m(D^{*+}) - m(D^+)$ to suppress background.
- Measurement relative to $D^+ \rightarrow K^- \pi^+ \pi^+$
- Problem:
Background from D^+ not coming from $D^{*+} \rightarrow D^+ \pi^0$ decays
 $\Rightarrow \Delta m$ sideband subtraction

Results

$D^+ \rightarrow \pi^+ \pi^0$ and $D^+ \rightarrow K^+ \pi^0$

ref: $D^+ \rightarrow K^- \pi^+ \pi^+$

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■ Un-binned maximum likelihood fit results (124.3fb^{-1}):

$$\text{BF}(D^+ \rightarrow \pi^+ \pi^0) / \text{BF}(D^+ \rightarrow K^- \pi^+ \pi^+) = (1.33 \pm 0.11(\text{stat}) \pm 0.09(\text{syst})) \times 10^{-2}$$

$$\text{BF}(D^+ \rightarrow K^+ \pi^0) / \text{BF}(D^+ \rightarrow K^- \pi^+ \pi^+) = (2.68 \pm 0.50(\text{stat}) \pm 0.26(\text{syst})) \times 10^{-3}$$

■ Using reference WA: $\text{BF}(D^+ \rightarrow K^- \pi^+ \pi^+) = (9.4 \pm 0.3) \times 10^{-2}$ (ref)

$$\text{BF}(D^+ \rightarrow \pi^+ \pi^0) = (1.25 \pm 0.10(\text{stat}) \pm 0.09(\text{syst}) \pm 0.04(\text{ref})) \times 10^{-3} \quad \text{WA: } \text{BF}(D^+ \rightarrow \pi^+ \pi^0) = (1.33 \pm 0.22) \times 10^{-3}$$

$$\text{BF}(D^+ \rightarrow K^+ \pi^0) = (2.52 \pm 0.47(\text{stat}) \pm 0.25(\text{syst}) \pm 0.08(\text{ref})) \times 10^{-4} \quad \text{WA: } \text{BF}(D^+ \rightarrow K^+ \pi^0) < 4.2 \times 10^{-4} \text{ at 90\% CL}$$

$D^0 \rightarrow \pi^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- K^+ \pi^0$

Branching Fractions

- Two body decays of D^0 are well measured and show anomalous suppression of $D^0 \rightarrow \pi^- \pi^+ (1.38 \pm 0.05) \times 10^{-3}$ versus $D^0 \rightarrow K^- K^+ (3.89^{+0.12}_{-0.15}) \times 10^{-3}$
- Three body decays could help explain this puzzle but are poorly measured
- Analysis method:
 - reconstruct $D^{*+} \rightarrow D^0 \pi^+$ with $D^0 \rightarrow (\pi^- \pi^+ \pi^0, K^- K^+ \pi^0, K^- \pi^+ \pi^0)$
 - Use $\Delta m = m(D^{*+}) - m(D^0)$ to suppress background
 - Fit $K^- \pi^+ \pi^0$ reflection in the $\pi^- \pi^+ \pi^0$ and $K^- K^+ \pi^0$ distributions
 - Remove $D^0 \rightarrow K_S^0 \pi^0$ as background from $D^0 \rightarrow \pi^- \pi^+ \pi^0$
- Recover non-uniform reconstruction efficiency weighting events with:
 $W = 1/\text{efficiency} \Rightarrow$ no assumptions on Dalitz plot structure
- Measurements performed relative to $D^0 \rightarrow K^- \pi^+ \pi^0$ decay mode.

Results

$D^0 \rightarrow \pi^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- K^+ \pi^0$

■ Dramatic improvement on BR measurement error:

D^0 decay mode	Our Current Results(%)	PDG Results(%) 2006
$B(\pi^- \pi^+ \pi^0) / B(K^- \pi^+ \pi^0)$	$10.59 \pm 0.06 \pm 0.13$	8.40 ± 3.11
$B(K^- K^+ \pi^0) / B(K^- \pi^+ \pi^0)$	$2.37 \pm 0.03 \pm 0.04$	0.95 ± 0.26

Statistically significant difference

Conclusions

- Presented hadronic form factor measurements of $D^0 \rightarrow K^- e^+ \nu_e$ and $D_s^+ \rightarrow \phi e^+ \nu_e$ with:
 - Dramatically reduced measurement error
 - First q^2 -dependent study of $D_s^+ \rightarrow \phi e^+ \nu_e$
- First observation at $> 6.5\sigma$ level of doubly-Cabibbo suppressed $D^+ \rightarrow K^+ \pi^0$ decay mode:
$$BF(D^+ \rightarrow K^+ \pi^0) = (2.52 \pm 0.47(\text{stat}) \pm 0.25(\text{syst}) \pm 0.08(\text{ref})) \times 10^{-4}$$
- Improved measurements of Cabibbo-suppressed to Cabibbo-favored Branching Ratios for $D^0 \rightarrow \pi^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- K^+ \pi^0$ decay modes.

Backup Slides

The BaBar Experiment at PEP-II

e^+e^- CM energy ~ 10.58 GeV

Boost: $\beta\gamma \sim 0.56$

- Data sample $\sim 387 \text{ fb}^{-1}$.

Particle identification (PID)
through Cherenkov radiation.
Separation $K-\pi > 3.4\sigma$ for
 $p < 3.5 \text{ GeV}/c$

Unfolding Procedure

- Extraction of the q^2 dependence of the form factor:

$$\frac{d\Gamma}{dq^2} = \frac{G_f^2 |V_{q_1 q_2}|^2 p_{P'}^3}{24\pi^3} |f_+(q^2)|^2$$

→ Unfolding the measured q^2 distribution

Single Value Decomposition* approach:

- ⌘ SVD of the reconstruction matrix $S[q_{\text{rec}}^2, q_{\text{sim}}^2]$
- ⌘ algorithm imposing a minimum curvature condition
- ⌘ results tested with Toy generated experiments

* SVD; A. Höcker, V. Kartvelishvili [[hep-ph/9509307](https://arxiv.org/abs/hep-ph/9509307)]

Results

$D^0 \rightarrow \pi^- \pi^+ \pi^0$ and $D^0 \rightarrow K^- K^+ \pi^0$

- Naïve computation of average matrix element on 3-body Dalitz:

$$\Gamma = \langle |M|^2 \rangle \cdot \Phi$$

where M = decay matrix element

Φ = 3-body phase space

= area of the Dalitz plot

D^0 decay mode	3-body decay	2-body decay
$ M ^2(\pi^- \pi^+) / M ^2(K^- \pi^+)$	$0.0668 \pm 0.0004 \pm 0.0008$	0.0338 ± 0.0009
$ M ^2(K^- K^+) / M ^2(K^- \pi^+)$	$0.0453 \pm 0.0006 \pm 0.0008$	0.1114 ± 0.0023
$ M ^2(K^- K^+) / M ^2(\pi^- \pi^+)$	$0.6781 \pm 0.0007 \pm 0.0011$	3.5289 ± 0.0026

Significant difference