$D_s^+ \to f_0(980)\, e^+\nu$ and Implications for $B_s \to J/\psi\, f_0(980)$

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We study $D_s^+\to f_0(980)e^+\nu$, $f_0(980)\to\pi^+\pi^-$ and $D_s^+\to\phi e^+\nu$, $\phi\to K^+K^-$ using $e^+e^-\to D_sD_s^*$ interactions at 4170 MeV collected with the CLEO-c detector. By examining the rate as a function of the four-momentum transfer, q^2, we measure the ratio of f_0/ϕ rates at $q^2 = 0$ to be (42±11)%, thus indicating that the decay $B_s\to J/\psi f_0(980)$, could be useful for measuring the "$\overline{B}_s$-B_s mixing phase" $-2\beta_s$. Properties of the f0(980) are also studied.

Introduction

"B_s-$\overline{B}_s$ mixing phase" $-2\beta_s$: a place to look for New Physics

- Measurements of *CP* violation in the B meson system are sensitive to the presence of heavy, as yet undiscovered, particles.
- The SM value $\sin(2\beta_s) = 0.037 \pm 0.002$ is small, where
  $2\beta_s \equiv 2\arg[-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*]$
- Both CDF and D0 have investigated $-2\beta_s$ using $B_s\to J/\psi\,\phi$ decays. The central value has been found far from the expected SM value, but the error is large and the significance of the possible discrepancy is in the 2-3σ range.

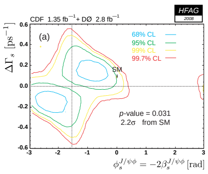

FIG. 1: $-2\beta_s$ from $B_s \to J/\psi\phi$

$B_s\to J/\psi\, f_0(980)$

- The $s\bar{s}$ quarks not only can form a ϕ, but also η, η' and $f_0(980)$ mesons. The scalar f_0 state, however, has not been previously considered.
- From BESII, we know $f_0(980)$ decay is dominated by $\pi^+\pi^-$, which is more useful than the η, η' modes because of poor photon efficiency at current hadron collider experiments.
- The f_0 (& η, η') modes are pure *CP*-eigenstates, and thus an angular analysis is unnecessary. Since the final state $J/\psi\phi$ is not a *CP*-eigenstate, an angular analysis is necessary, which requires large statistics compared to CP eigenstates.

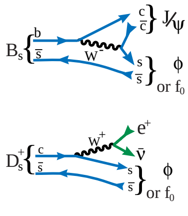

FIG. 2: Diagrams for $B_s \to J/\psi\phi$ (f_0) and $D_s^+\to \phi$ (f_0) $e^+\nu$

Estimate using D_s^+ semileptonic decays

Stone and Zhang [1] argued that the branching ratio $B_s\to J/\psi\, f_0(980)$, $f_0\to\pi^+\pi^-$ to $J/\psi\,\phi$, $\phi\to K^+K^-$ could be estimated by the ratio of decay widths at $q^2 = 0$, where q^2 is the e^+ and neutrino invariant mass squared

$$\frac{\Gamma(B_s\to J/\psi f_0(980), f_0\to\pi^+\pi^-)}{\Gamma(B_s\to J/\psi\phi,\phi\to K^+K^-)} \approx \frac{\Gamma(D_s^+\to f_0(980)e^+\nu, f_0\to\pi^+\pi^-, q^2=0)}{\Gamma(D_s^+\to \phi e^+\nu,\phi\to K^+K^-, q^2=0)}$$

The Feynman diagrams in B_s and D_s^+ are analogous: J/ψ in B_s and virtual W^+ in D_s^+ are both spin-1 objects. The available energy in B_s, m_{Bs}-$m_{J/\psi}$=2.27 GeV, is comparable to m_{Ds}=1.97 GeV, so $q^2 = 0$ in the D_s^+ semileptonic decays give good estimation for the B_s case.

CLEO-c Technique

Tag Method: We use $e^+e^-\to D_sD_s^*$ at 4170 MeV with 600 pb^{-1} of data. We fully reconstruct one D_s^- and also the γ from D_s^* as a "tag", then examine the properties of the other D_s^+. The D_s^- tags we reconstructed can come from either directly produced D_s mesons or those that result from the decay of a D_s^* mesons.

Tag Reconstruction: We first reconstruct D_s^- from 9 decay modes and require the beam constrained mass of candidates in the interval of [2.015, 2.067] GeV to pre-select $D_sD_s^*$ events. We then detect the photon from the D_s^* decay by looking for an additional photon candidate in the event that satisfies our shower shape requirement. We calculate the missing mass squared MM*² recoiling against the photon and the D_s^- tag,

$$\mathrm{MM}^{*2} = (E_{CM} - E_{Ds} - E_\gamma)^2 - (\mathbf{p}_{CM} - \mathbf{p}_{Ds} - \mathbf{p}_\gamma)^2$$

Single Tag Yields: To obtain number of D_s with γ tags, we simultaneously fit to the invariant mass (M_{Ds}) and MM*². We obtain the total number of single tags 30848±695±925 in the invariant mass signal region (± 17.5 MeV from the D_s mass) and MM² ∈ [3.782, 4.0] GeV².

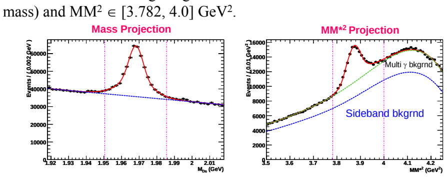

FIG. 3: D_s invariant mass and MM*² distributions from 9 tag modes (for detail see PRD 79, 052001 (2009))

Signal Reconstruction & Data Distribution

Candidate events are selected that contain only $\pi^+\pi^-$ or K^+K^- and a track with opposite charge to the tag, which we identify as an electron. The electron identification requires the track makes an angle >25.8° with respect to the beam line and momentum >200 MeV. In addition we require that there not be any photon detected in the calorimeter with energy greater than 300 MeV. The missing mass squared, MM², evaluated by taking into account the observed f_0 (ϕ) meson, e^+, D_s^-, and γ should peak at zero;

$$\mathrm{MM}^2 = (E_{CM} - E_{Ds} - E_\gamma - E_e - E_{f_0(\phi)})^2 - (\mathbf{p}_{CM} - \mathbf{p}_{Ds} - \mathbf{p}_\gamma - \mathbf{p}_e - \mathbf{p}_{f_0(\phi)})^2$$

We use a set of kinematical constraints and fit each event to two hypotheses one of which is that the D_s^- tag is the daughter of a D_s^{*-} and the other that the D_s^{*+} decays into γD_s^+, with the D_s^+ subsequently decaying into signal. In addition, we constrain the invariant mass of the D_s^- to the known D_s mass. This gives us a total of 7 constraints. The missing neutrino four-vector needs to be determined, so we are left with a three-constraint fit. We perform a standard iterative fit minimizing χ². We choose the fitted MM² from the hypothesis giving the smaller χ².

We simultaneously fit the D_s invariant mass, MM² and $\pi^+\pi^-$ or K^+K^- invariant mass. A large mass window for dipion is chosen to measure the $f_0(980)$ mass and width. Here a relativistic Breit-Wigner function $BW(m^2)$ is used to fit the data distribution, where

$$BW(m^2) = \frac{m_0\Gamma(m^2)}{(m^2-m_0^2)^2 + (m_0\Gamma(m^2))^2}, \quad \Gamma(m^2) = \Gamma_0\frac{\sqrt{m^2/4-m_\pi^2}}{\sqrt{m_0^2/4-m_\pi^2}}\frac{m_0}{m}$$

The fit gives $m_0 = 968 \pm 9$ MeV and $\Gamma_0 = 92^{+28}_{-21}$ MeV *(Preliminary)*.

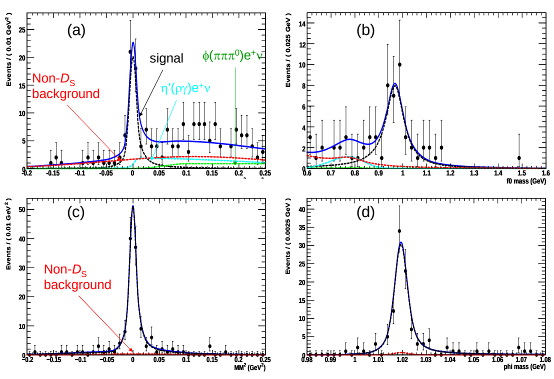

FIG. 4: Distributions of (a) MM² and (b) $m_{\pi^+\pi^-}$ for $f_0e^+\nu$ and (c) MM² and (d) $m_{K^+K^-}$ for $\phi e^+\nu$, superimposed with the total fitting function and each of its components in colors.

Results (Preliminary)

$D_s^+\to f_0\, e^+\nu$ form factors

The decay rate can be written in terms of as $\pi^+\pi^-$ invariant mass (m) and q^2

$$\frac{d\Gamma(D_s^+\to f_0e^+\nu)}{dm^2dq^2} = \frac{G_F^2|V_{cs}|^2}{192\pi^4 m_{D_s}^3} p_{f_0}^3(m,q^2)|f_+(q^2)|^2 P(m^2) \quad (1)$$

where G_F is the Fermi constant, p_{f_0} is the momentum of the f_0 in the D_s^+ rest frame, $|V_{cs}|$ is a CKM matrix element, $f_+(q^2)$ is function called form-factor, and $P(m^2)$ is the PDF of the f_0 mass distribution.

The q^2 distribution and branching fractions

We separate data into 5 q^2 bins, and perform similar fits as used before but fix the f_0 mass and width to the observed values. The yields, efficiencies and efficiency corrected yields in the 5 q^2 bins are shown in Table 1. The branching fractions can be extracted by dividing the efficiency corrected yields sums in each mode by the number of tags. We find $\mathcal{B}(D_s\to f_0\, e^+\nu, f_0\to\pi^+\pi^-) = (0.20\pm0.03\pm0.01)\%$ and $\mathcal{B}(D_s\to\phi\, e^+\nu) = (2.36\pm0.23\pm0.13)\%$

Table 1: Preliminary number of events and efficiency e in q2 intervals. (The errors on e are about 1%.)

q^2 interval (GeV²)	# $f_0e^+\nu$	$\epsilon(f_0)$ (%)	# f_0 corrected	# $\phi e^+\nu$	$\epsilon(\phi)$ (%)	# ϕ corrected
0-0.2	14.6±3.9	45.5	32.1±8.6	30.5±5.1	25.9	118±20
0.2-0.4	12.3±3.5	50.2	24.5±7.0	30.5±5.3	22.9	133±23
0.4-0.6	12.4±3.5	53.6	23.1±6.5	22.3±4.4	21.5	104±20
0.6-0.8	4.2±2.2	56.9	7.4±3.9	21.5±4.7	15.6	138±30
0.8-2.0	0±1.0	55.9	0±1.8	1.6±1.1	9.8	16±11
Sum	43.5±6.7		87.1±13.5	106.4±9.8		508±49

We fit the efficiency corrected q^2 distribution. For the $f_0e^+\nu$, the fit function is Eq. (1) integrated over m, and a simple pole model $f_+(q^2)=1/(1-q^2/m_A^2)$ is used. For the $\phi e^+\nu$, we use the *BABAR* measured shape [2].

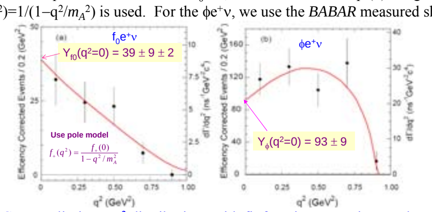

FIG. 5: Preliminary q^2 distributions with fit functions superimposed.

We obtain a preliminary value of the pole mass $m_A = 1.7^{+4.5}_{-0.7} \pm 0.2$ GeV and preliminary ratio

$$\frac{\Gamma(D_s^+\to f_0(980)e^+\nu, f_0\to\pi^+\pi^-, q^2=0)}{\Gamma(D_s^+\to \phi e^+\nu,\phi\to K^+K^-, q^2=0)} = (42\pm11)\%$$

$f_0(980)$ Properties

- In the earlier $\pi^+\pi^-$ invariant mass fit, we did not take into account the fact that the phase space for the larger f_0 masses is somewhat smaller than that for smaller f_0 masses, due to the finite D_s mass.
- To take into account this effect, we need integrate Eq. (1) over q^2 in the allowed region $[0, (m_{Ds}-m)^2]$. Here we use $P(m^2)=BW(m^2)$.
- We used our fitted form-factor shape for $f_+(q^2)$.
- We obtain $m_0 = (977^{+11}_{-9}\pm1)$ MeV and $\Gamma_0 = (91^{+30}_{-22} \pm3)$ MeV. The systematic errors are determined by varying the form-factor by ± one error width.

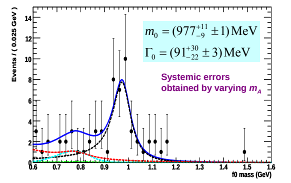

FIG 6: Invariant mass distribution for $\pi^+\pi^-$. The signal shape is a relativistic Breit-Wigner modified by phase space and form-factor effects. For the meanings of the curves, see FIG 4 (a).

$f_0(980)$ in D_s Hadronic Decays

- Stone and Zhang [1] also use branching fractions of $D_s^+\to K^+K^-\pi^+$ and $\pi^+\pi^-\pi^+$ from CLEO and the *BABAR* Dalitz analysis of the 3π mode [3] (Fig. 7) to derive

$$\frac{\Gamma(D_s^+\to f_0\pi^+, f_0\to\pi^+\pi^-)}{\Gamma(D_s^+\to\phi\pi^+,\phi_0\to K^+K^-)} = (20\sim30)\%,$$

where the $\pi^+\pi^-$ mass is within ±90 MeV of the $f_0(980)$ mass.

- Fig. 8 shows the diagram for D_s decay into π^+ plus an $s\bar{s}$ system.

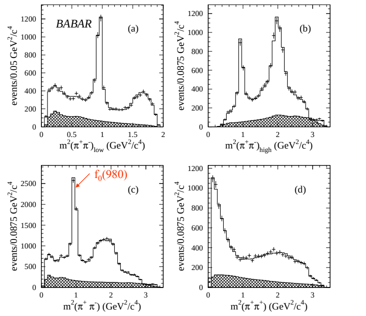

FIG. 7: Dalitz plot projections (dots with error bars) and fit results (solid histogram). The hatched histograms show the background contribution. From the *BABAR* Collaboration [3].

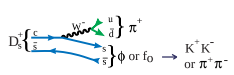

FIG. 8: Diagram for a D_s^+ decay into π^+ plus an $s\bar{s}$ system.

Conclusions (Preliminary)

- We present an updated result for the first measurement of $\mathcal{B}(D_s^+\to f_0(980)e^+\nu, f_0\to\pi^+\pi^-) = (0.20\pm0.03\pm0.01)\%$.
- Assuming a simple pole model for the form-factor, $|f_+(q^2)|$, we estimate the pole mass as $1.7^{+4.5}_{-0.7}\pm0.2$ GeV.
- In the final state the only hadron present is the f_0. This provides a particular clean environment that allows us to measure the mass and width as $(977^{+11}_{-9}\pm1)$ MeV and $(91^{+30}_{-22}\pm3)$ MeV, respectively.
- We update our measurement of $\mathcal{B}(D_s^+\to\phi e^+\nu) = (2.36\pm0.23\pm0.13)\%$.
- We measure the ratio of decay rates at $q^2 = 0$ of $\frac{\Gamma(D_s^+\to f_0(980)e^+\nu, f_0\to\pi^+\pi^-, q^2=0)}{\Gamma(D_s^+\to\phi e^+\nu,\phi\to K^+K^-, q^2=0)} = (42\pm11)\%$.
- This ratio has been predicted by Stone and Zhang [1] to equal $\frac{\Gamma(B_s\to J/\psi f_0(980), f_0\to\pi^+\pi^-)}{\Gamma(B_s\to J/\psi\phi,\phi\to K^+K^-)}$. Our measurement indicates that the $B_s\to J/\psi\, f_0$ may indeed be a useful place to measure *CP* violation in the B_s system since the rate can be ~ 40% that of the $J/\psi\,\phi$ mode, especially since an angular analysis is not necessary as the $J/\psi\, f_0$ mode is a CP-eigenstate.

References

[1] S. Stone and L. Zhang "S-waves and the measurement of CP violation phases in B_s decays," Phy. Rev. D 79, 074024 (2009).

[2] B. Aubert et. al. (*BABAR*) , "Study of the decay $D_s^+\to K^+K^-e^+\nu$," Phy. Rev. D 78, 051101 (R) (2008).

[3] B. Aubert et. al. (*BABAR*) , "Dalitz plot analysis of $D_s^+\to\pi^+\pi^-\pi^+$," arXiv:0808.0971