Resonance Searches at HERA

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-03/Karshon

Inclusive production of $K^0_S K^0_S$ in ep collisions was studied with the ZEUS detector. Significant production of $J^{PC} = 2^{++}$ tensor mesons and of the 0^{++} glueball candidate $f_0(1710)$ was seen. Masses and widths were compared with previous experiments. The H1 Collaboration saw a charm pentaquark candidate in the D^*p spectrum at 3.1 GeV, which was not confirmed by a ZEUS higher statistics search. With the full HERA statistics, H1 did not see a signal in this region. Masses, widths and helicity parameters of excited charm and charm-strange mesons were measured by ZEUS. Rates of c quarks hadronising into these mesons were determined and a search for a radially excited charm meson was performed.

1 Introduction

The HERA *ep* collider operated with electrons or positrons at 27.6 GeV and protons at 820 or 920 GeV. Each of the two general purpose experiments H1 and ZEUS collected during 1995 - 2000 ("HERA I") $\approx 120\ pb^{-1}$ and during 2003 - 2007 ("HERA II") $\approx 370\ pb^{-1}$. Two kinematic regions have been explored: Deep inelastic scattering (DIS) with photon virtuality $Q^2 > 1$ GeV^2, where the scattered electron is visible in the main detector and photoproduction (PHP) with $< Q^2 > \approx 3 \cdot 10^{-4}$ GeV^2, where the virtual photon radiated from the incoming electron is quasi-real. The sample is dominated by PHP events.

2 Glueball search in the $K^0_S K^0_S$ system

Glueballs are predicted by QCD. The lightest glueball is expected to have $J^{PC} = 0^{++}$ and a mass in the range 1550-1750 MeV [1] and can mix with $q\bar{q}$ scalar meson nonet I=0 states of similar mass. There are four such established states: $f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$, but only two can fit into the nonet. The $f_0(1710)$ state is considered as a possible glueball candidate. The $K^0_S K^0_S$ system can couple to $J^{PC} = 0^{++}$ and 2^{++}. Therefore, it is a good place to search for the lowest lying 0^{++} glueball.

2.1 Previous results

The e^+e^- experiments TASSO and L3 studied the exclusive reaction $\gamma\gamma \to K^0_S K^0_S$. L3 [2] saw 3 peaks and attributed them to $f_2(1270)/a_2(1320)$, $f_2^{'}(1525)$ and $f_0(1710)$. A maximum likelihood fit with 3 Breit-Wigner (BW) functions plus background yielded $f_2^{'}(1525)$ mass and width values consistent with the Particle Data Group (PDG) [1] and a 4 standard deviation (s.d.) signal for $f_0(1710)$ with mass and width values above PDG. The TASSO [3] $K^0_S K^0_S$ spectra had no $f_2(1270)/a_2(1320)$ signal and a sizable $f_2^{'}(1525)$ enhancement. The result was interprated by interference effects between the 3 $J^P = 2^+$ resonances $f_2(1270)$, $a_2(1320)$ and $f_2^{'}(1525)$ and the spectra was fitted as a sum of 3 coherent BW functions. Based on SU(3) symmetry arguments [4], the sign of the $a_2(1320)$ term for $K^0_S K^0_S$ is negative and the coefficients of the $f_2(1270)$, $a_2(1320)$ and $f_2^{'}(1525)$ BW amplitudes are +5, -3 and +2, respectively.

2.2 This analysis

The reaction $e^{\pm}p \rightarrow K^0_S K^0_S + X$ was studied [5] with the full HERA luminosity of 0.5 fb^{-1}. Both PHP and DIS events were included. No explicit trigger requirement was applied for selecting the above reaction.

K^0_S mesons were identified via their decay mode $K^0_S \rightarrow \pi^+\pi^-$. A clean K^0_S signal was seen for events with $\geq 2K^0_S$ candidates. The number of $K^0_S K^0_S$ pairs found in the K^0_S mass range $481 < M(\pi^+\pi^-) < 515$ MeV is $\approx 672,000$.

Figure 1 shows the $K^0_S K^0_S$ mass distribution reconstructed by combining two K^0_S candidates selected in the above mass window. Three peaks are seen around 1.3, 1.5 and 1.7 GeV. No state heavier than 1.7 GeV was observed. The invariant-mass spectrum, m, was fitted as a sum of relativistic Breit-Wigner (RBW) resonances and a smoothly varying background $U(m) = m^A exp(-Bm)$, where A and B are free parameters.

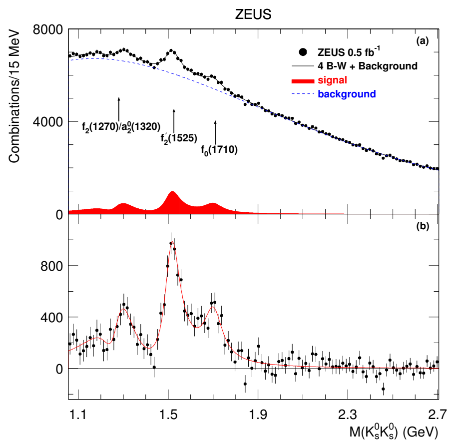

Figure 1: (a)The $K^0_S K^0_S$ distribution (dots). Solid line is the coherent fit (see text); background function is given by the dashed line. (b)Background-subtracted $K^0_S K^0_S$ distribution (dots); solid line is the fit result.

Two types of fit, as performed for the reaction $\gamma\gamma \rightarrow K^0_S K^0_S$ by L3 [2] and TASSO [3], respectively, were tried. The first fit (not shown) is an incoherent sum of three modified RBW resonances, R, of the form $F(m) = C_R(\frac{M_R \Gamma_R}{(M_R^2 - m^2)^2 + M_R^2 \Gamma_R^2})$, representing the peaks $f_2(1270)/a_2(1320)$, $f_2^{'}(1525)$ and $f_0(1710)$. Here C_R is the resonance amplitude and M_R and Γ_R are the resonance mass and width, respectively. The goodness of this fit is reasonable ($\chi^2/ndf = 96/95$); however, the dip between the $f_2(1270)/a_2(1320)$ and $f_2^{'}(1525)$ is not well reproduced.

Figure 1 shows a coherent fit motivated by SU(3) predictions[4]. Each resonance amplitude, R, is described by the RBW form [3] $BW(R) = \frac{M_R\sqrt{\Gamma_R}}{M_R^2 - m^2 - iM_R\Gamma_R}$. The decays of the tensor ($J^P = 2^+$) mesons $f_2(1270)$, $a_2^0(1320)$ and $f_2^{'}(1525)$ into the two pseudoscalar ($J^P = 0^+$) mesons $K^0\bar{K}^0$ are related by SU(3) symmetry with a specific interference pattern. The intensity is the modulus-squared of the sum of these 3 amplitudes plus the incoherent addition of $f_0(1710)$ and a non-resonant background.

Assuming SU(3) symmetry and a direct coupling of the 2^+ states to the exchanged photon, the fitted function to the $m(K^0_S K^0_S)$ spectra is given by $F(m) = a[5 \cdot BW(f_2(1270)) - 3 \cdot BW(a_2(1320)) + 2 \cdot BW(f_2^{'}(1525))]^2 + b[BW(f_0(1710))]^2 + c \cdot U(m)$, where a,b,c as well as the resonance masses and widths were free parameters in the fit. The background-subtracted mass spectrum is shown in Fig.1(b). The fit quality is good ($\chi^2/ndf = 86/97$). The peak around 1.3 GeV is suppressed due to the destructive interference between $f_2(1270)$ and $a_2(1320)$ and the dip between $f_2(1270)/a_2(1320)$ and $f_2^{'}(1525)$ is well reproduced. The number of fitted $f_0(1710)$ events is 4058 ± 820, which has ≈ 5 s.d. significance. Its mass is consistent with a $J^{PC} = 0^{++}$ glueball candidate, but it cannot be a pure glueball if it is the same state as in $\gamma\gamma \rightarrow K_S^0 K_S^0$.

Fit	No interference		Interference		PDG 2007 Values	
χ^2/ndf	96/95		86/97			
in MeV	Mass	Width	Mass	Width	Mass	Width
$f_2(1270)$	1304 ± 6	61 ± 11	1268 ± 10	176 ± 17	1275.4 ± 1.1	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$			1257 ± 9	114 ± 14	1318.3 ± 0.6	107 ± 5
$f_2'(1525)$	$1523 \pm 3^{+2}_{-8}$	$71 \pm 5^{+17}_{-2}$	$1512 \pm 3^{+2}_{-0.6}$	$83 \pm 9^{+5}_{-4}$	1525 ± 5	73^{+6}_{-5}
$f_0(1710)$	$1692 \pm 6^{+9}_{-3}$	$125 \pm 12^{+19}_{-32}$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+8}_{-19}$	1724 ± 7	137 ± 8

Table 1: *Fitted masses and widths for* $f_2(1270)$, $a_2^0(1320)$, $f_2^{'}(1525)$ *and* $f_0(1710)$ *from the incoherent and coherent fits compared to PDG. The first error is statistical. For* $f_2^{'}(1525)$, $f_0(1710)$ *the second errors are systematic uncertainties.*

The masses and widths obtained from both fits are shown in Table 1 and compared to PDG [1]. The no-interference fit yields a narrow width for the combined $f_2(1270)/a_2(1320)$ peak, as was also seen by L3 [2]. The fit with interference yields widths close to the PDG values for all observed resonances. The $a_2^0(1320)$ mass is below the PDG value. The $f_2^{'}(1525)$ and $f_0(1710)$ masses are somewhat below PDG with uncertainties comparable with the PDG ones. A fit without $f_0(1710)$ is strongly disfavoured with $\chi^2/ndf = 162/97$.

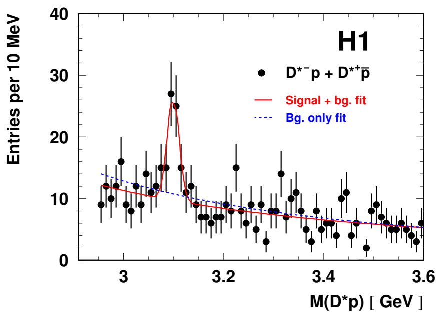

Figure 2: $M(D^{*\pm}p^{\mp})$ from H1 DIS HERA I, compared with fit results where both signal and background components are included and where only background is included.

3 Charm pentaquark search in the D^*p system

A narrow exotic baryon with strangeness $+1$ around 1530 MeV decaying into K^+n or K^0p was seen by various experiments and attributed to the $\Theta^+ = uudd\bar{s}$ pentaquark state predicted by Diakonov et al.[6]. If a strange pentaquark exists, charmed pentaquarks, $\Theta_c^0 = uudd\bar{c}$, could also exist. If $M(\Theta_c^0) > M(D^*) + M(p) = 2948$ MeV, it can decay to $D^{*\pm}p^{\mp}$.

The H1 Collaboration saw [7] in a DIS HERA I sample of ≈ 3400 $D^{*\pm} \rightarrow D^0\pi_S^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi_S^{\pm}$ a narrow signal of 50.6 ± 11.2 events in the $D^{*\pm}p^{\mp}$ invariant mass at 3.1 GeV (Fig.2) with a width consistent with the mass resolution and a rate of $\approx 1\%$ of the visible D^* production.

ZEUS searched for a Θ_c^0 signal in the $D^{*\pm}p^{\mp}$ mode with the full HERA I PHP + DIS data sample [8]. Clean $D^{*\pm}$ signals were seen in the $\Delta M = M(D^{*\pm}) - M(D^0)$ plots. Two $D^{*\pm} \to D^0\pi_S^{\pm}$ decay channels were used with $D^0 \to K^{\mp}\pi^{\pm}$ and $D^0 \to K^{\mp}\pi^{\pm}\pi^{+}\pi^{-}$. The Θ_c^0 search was performed in the kinematic range $|\eta(D^*)| < 1.6$ and $p_T(D^*) > 1.35(2.8)$ GeV and with ΔM values between 0.144 - 0.147 (0.1445 - 0.1465) GeV for the $K\pi\pi$ ($K\pi\pi\pi\pi$) channel. In these bands ≈ 62000 D^*'s were obtained after subtracting wrong-charge combinations with charge ± 2 for the D^0 candidate and ± 1 for the D^* candidate. Selecting DIS events with $Q^2 > 1$ GeV^2 yielded smaller, but cleaner D^* signals with ≈ 13500 D^*'s.

Protons were selected with momentum $P(p) > 0.15$ GeV. To reduce the pion and kaon background, a parameterisation of the expected dE/dx as a function of P/m was obtained using tagged protons from Λ decays and tagged pions from K_S^0 decays. The χ^2 probability of the proton hypothesis was required to be above 0.15.

Figure 3 shows the $M(D^{*\pm}p^{\mp})$ distributions for the $D^0 \to K\pi$ (left) and $D^0 \to K\pi\pi\pi$ (right) channels for the full (up) and the DIS (down) samples. No narrow signal is seen in any of the distributions. 95% C.L. upper limits on the fraction of D^* mesons originating from Θ_c^0 decays, $R(\Theta_c^0 \to D^*p/D^*)$, were calculated in a signal window $3.07 < M(D^*p) < 3.13$ GeV for the $K\pi\pi$ and $K\pi\pi\pi\pi$ channels. The $M(D^*p)$ distributions were fitted to the form $x^a e^{-bx+cx^2}$, where $x = M(D^*p) - M(D^*) - m_p(PDG)$. The number of reconstructed Θ_c^0 baryons was estimated by subtracting the background function from the observed number of events in the signal window, yielding $R(\Theta_c^0 \to D^*p/D^*) < 0.23\%$ and $< 0.35\%$ for the full and DIS combined two channels. A visible rate of 1% for this fraction is excluded by 9 s.d. (5 s.d.) for the full (DIS) combined sample. The acceptance-corrected rates are, respectively, 0.37% and 0.51%. The 95% C.L. upper limit on the fraction of charm quarks fragmenting to Θ_c^0 times the branching ratio $\Theta_c^0 \to D^*p$ for the combined two channels is $f(c \to \Theta_c^0) \cdot B_{\Theta_c^0 \to D^*p} < 0.16\%$ ($< 0.19\%$) for the full (DIS) sample.

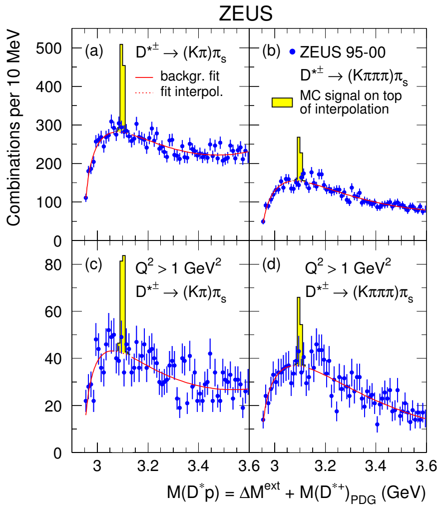

Figure 3: $M(D^{*\pm}p^{\mp})$ from ZEUS HERA I. Solid curves are fits to a background function. Shaded historgams are MC Θ_c^0 signals, normalised to $\Theta_c^0/D^* = 1\%$, on top of the background fit.

In a HERA II DIS data sample that is ≈ 4 times larger than the HERA I sample, H1 does not see any significant peak at 3.1 GeV (Fig.4). A preliminary 95% C.L. for the ratio of D^*p to D^* is 0.1%.

4 Excited charm and charm-strange mesons

The large charm production at HERA allows to search for excited charm states. ZEUS studied the orbitally excited states $D_1(2420)^0 \to D^{*\pm}\pi^{\mp}$ ($J^P = 1^+$), $D_2^*(2460)^0 \to D^{*\pm}\pi^{\mp}, D^{\pm}\pi^{\mp}$

($J^P = 2^+$) and $D_{s1}(2536)^{\pm} \to D^{*\pm}K^0_S, D^{*0}K^{\pm}$ ($J^P = 1^+$) and searched for the radially excited state $D^{*'}(2640)^{\pm} \to D^{*\pm}\pi^+\pi^-$ ($J^P = 1^-$?) with a HERA I PHP + DIS sample[9].

A large sample of events has been collected with the ground state charm mesons $D^{*\pm}, D^0, D^{\pm}$. The number of $D^{*\pm}$ mesons was obtained by subtracting the wrong charge background. The number of $D^{\pm} \to K^{\mp}\pi^{\pm}\pi^{\pm}$ and $D^0(\bar{D}^0) \to K^{\mp}\pi^{\pm}$ was extracted from fits to a modified Gauss function, $Gauss^{mod} \sim exp(-0.5x^{1+\frac{1}{(1+0.5x)}})$, where $x = (M - M_D)/\sigma$, plus a background function. For the D^*, both D^0 decay modes to $K\pi$ and $K\pi\pi\pi$ were used.

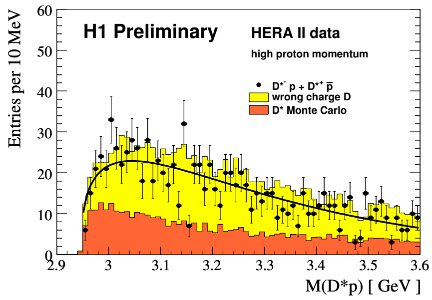

Figure 4: $M(D^{*\pm}p^{\mp})$ from H1 DIS HERA II. The solid line is a background parametrisation.

4.1 Excited charm mesons

To reconstruct the excited charm mesons, a $D^{*\pm}$ or $D^{\pm}$ candidate was combined with a pion of opposite charge, π_a. Figure 5 shows the "extended" mass difference distributions $M(D^{*\pm}\pi_a) - M(D^{*\pm}) + M(D^*)_{PDG}$ (upper plot) and $M(D^{\pm}\pi_a) - M(D^{\pm}) + M(D)_{PDG}$ (lower plot). A clear excess is seen in $M(D^{*\pm}\pi_a^{\mp})$ around the D_1^0/D_2^{*0} mass region. A small excess near the D_2^{*0} mass is seen in $M(D^{\pm}\pi_a^{\mp})$. No excess is seen for wrong charge combinations, where $D^*(D)$ and π_a have the same charge.

To distinguish between the D_1^0 and D_2^{*0}, the helicity angular distribution, parametrised as $dN/d\cos\alpha \approx 1 + h\cos^2\alpha$, was used. Here α is the angle between the π_a and π_S momenta in the D^* rest frame. The helicity parameter h is predicted [10] to be $3(-1)$ for pure D-wave D_1^0 (D_2^{*0}).

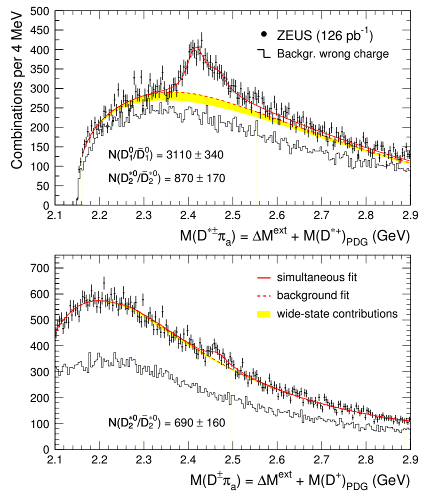

Figure 5: $M(D^{*\pm}\pi_a)$ and $M(D^{\pm}\pi_a)$ distributions. Solid curves are simultaneous fit; dashed curves are background; histograms are wrong-charge combinations.

Figure 6 shows the $D^{*\pm}\pi_a$ "extended" mass difference in 4 helicity $|\cos\alpha|$ intervals. The D_1^0 contribution increases with $|\cos\alpha|$ and dominates for $|\cos\alpha| > 0.75$. A simultaneous fit was performed to the 4 helicity regions of Fig.6 and to the $M(D\pi)$ distribution of Fig.5. The data is described well with 15 free parameters (signal yields, masses, D_1^0 width and helicity). The fitted masses agree with PDG. The fitted D_1^0 width is $53.2 \pm 7.2(stat.)^{+3.3}_{-4.9}(syst.)$ MeV compared to 20.4 ± 1.7 MeV of PDG. The fitted D_1^0 helicity ($5.9^{+3.0}_{-1.7}(stat.)^{+2.4}_{-1.0}(syst.)$) is consistent with a pure D-wave.

4.2 Excited charm strange mesons

To reconstruct the $D_{s1}^{\pm} \rightarrow D^{*\pm}K_S^0$ decays, a $D_{s1}^{\pm}$ candidate was formed by combining a D^* candidate with a reconstructed K_S^0 of the same event. Figure 7 (upper plot) shows the "extended" mass difference distribution $M(D^{*\pm}K_S^0) - M(D^{*\pm}) + M(D^*)_{PDG} + M(K^0)_{PDG}$. A clear $D_{s1}(2536)^{\pm}$ signal is seen. The decay mode $D_{s1}^{\pm} \rightarrow D^{*0}K^{\pm}$ is reconstructed from the "extended" mass difference $M(D^0K_a) - M(D^0) + M(D^0)_{PDG}$. A nice $D_{s1}^{\pm}$ signal is seen (Figure 7 lower plot) at a mass shifted down by ≈ 142 MeV from the $D_{s1}^{\pm}$ mass. The signal is a feed-down from $D_{s1}^{\pm} \rightarrow D^{*0}K^{\pm}$ with $D^{*0} \rightarrow D^0\pi^0, D^0\gamma$. An unbinned likelihood fit was performed using simultaneously values of $M(D^0K_a)$, $M(D^{*\pm}K_S^0)$ and $\cos\alpha$ for the $D^{*\pm}K_S^0$ combinations. Yields and widths of both signals and the $D_{s1}^{\pm}$ mass and helicity parameter were free parameters of the fit. The fitted D_{s1} helicity parameter is $h(D_{s1}^{\pm}) = -0.74^{+0.23}_{-0.17}(stat.)^{+0.06}_{-0.05}(syst.)$. It is inconsistent with a pure $J^P = 1^+$ D-wave and is barely consistent with a pure $J^P = 1^+$ S-wave, indicating a significant $S - D$ mixing.

The helicity angular distribution form of a 1^+ state for any D- and S-wave mixing is: $dN/d\cos\alpha \approx r + (1-r)(1+3\cos^2\alpha)/2 + \sqrt{2r(1-r)}\cos\phi(1-3\cos^2\alpha)$, where $r = \Gamma_S/(\Gamma_S+\Gamma_D)$, $\Gamma_{S/D}$ is the S/D wave partial width and ϕ is relative phase between the 2 amplitudes, $\cos\phi = \frac{(3-h)/(3+h)-r}{2\sqrt{2r(1-r)}}$. Figure 8 shows a range, restricted by the measured $h(D_{s1}^{\pm})$ value and its uncertainties, in a plot of $\cos\phi$ versus r. The measurement suggests a significant contribution of both D- and S-wave amplitudes to the $D_{s1}(2536)^{\pm} \rightarrow D^{*\pm}K_S^0$ decay. The ZEUS range agrees nicely with the BELLE result and roughly with the CLEO measurement.

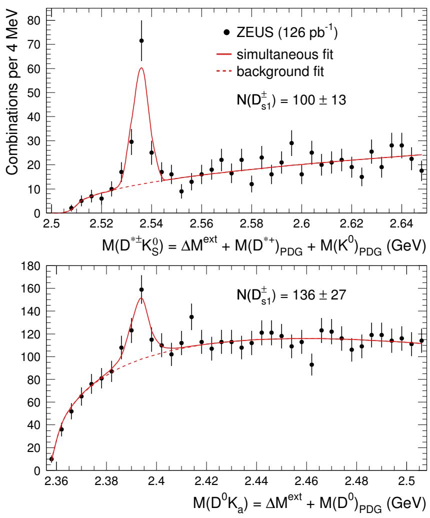

Figure 7: $M(D^{*\pm}K_S^0)$ and $M(D^0K^{\pm})$ distributions. Solid curves are simultaneous fit; dashed curves are background.

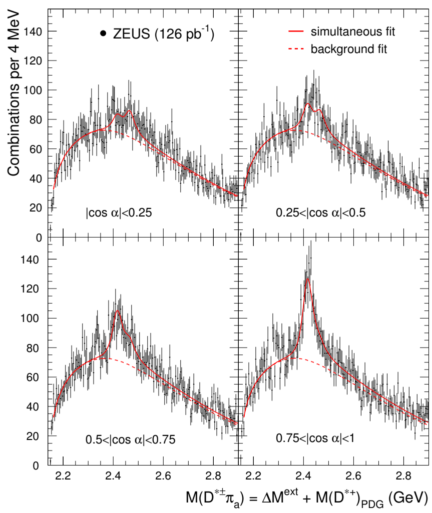

Figure 6: $M(D^{*\pm}\pi_a)$ distributions in 4 helicity intervals.

5 Branching ratios and fragmentation fractions

Using the ZEUS measured fractions $f(c \to D^{*+})$ and $f(c \to D^{+})$[11], the following decay rate ratios were derived: $\frac{B_{D_2^{*0} \to D^+\pi^-}}{B_{D_2^{*0} \to D^{*+}\pi^-}} = 2.8 \pm 0.8^{+0.5}_{-0.6}$ (PDG: 2.3±0.6); $\frac{B_{D_{s1}^+ \to D^{*0}K^+}}{B_{D_{s1}^+ \to D^{*+}K^0}} = 2.3 \pm 0.6 \pm 0.3$ (PDG: 1.27 ± 0.21).

Assuming isospin conservation for D_1^0 and D_2^{*0} and $B_{D_{s1}^+ \to D^{*+}K^0} + B_{D_{s1}^+ \to D^{*0}K^+} = 1$ yields a strangeness suppression of excited D mesons $f(c \to D_{s1}^+)/f(c \to D_1^0) = 0.31 \pm 0.06(stat.)^{+0.05}_{-0.04}(syst.)$.

In Table 2 the ZEUS fragmentation fractions of the excited charm mesons are compared with e^+e^- values. The results are consistent within errors.

DELPHI saw a narrow peak in $D^{*\pm}\pi^+\pi^-$ at 2637 MeV [12] and attributed it to a radially excited $D^{*'\pm}$. No signal was seen in ZEUS and a 95% C.L. upper limit of $f(c \to D^{*'\pm}) \cdot B_{D^{*'\pm} \to D^{*+}\pi^+\pi^-} < 0.4\%$ was set, compared to the weaker limit of OPAL (0.9%) [13].

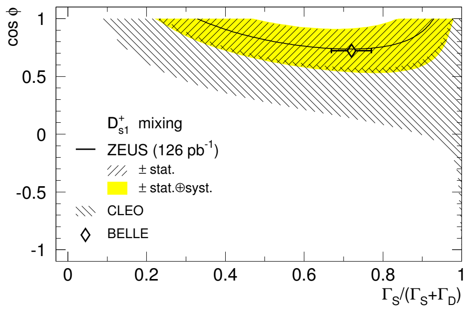

Figure 8: $\cos\phi$ vs. $\Gamma_S/(\Gamma_S + \Gamma_D)$ for $D_{s1}^+ \to D^{*+}K_S^0$ decay.

	$f(c \to D_1^0)[\%]$	$f(c \to D_2^{*0})[\%]$	$f(c \to D_{s1}^+)[\%]$
ZEUS	$3.5 \pm 0.4^{+0.4}_{-0.6}$	$3.8 \pm 0.7^{+0.5}_{-0.6}$	$1.11 \pm 0.16^{+0.08}_{-0.10}$
OPAL	2.1 ± 0.8	5.2 ± 2.6	$1.6 \pm 0.4 \pm 0.3$
ALEPH			$0.94 \pm 0.22 \pm 0.07$

Table 2: *The fractions of c quarks hadronising into* D_1^0, D_2^{*0} *and* D_{s1}^+ *mesons.*

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