

Resonance Searches at HERA

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Inclusive production of $K_S^0 K_S^0$ 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") $\approx 120 \text{ pb}^{-1}$ and during 2003 - 2007 ("HERA II") $\approx 370 \text{ pb}^{-1}$. Two kinematic regions have been explored: Deep inelastic scattering (DIS) with photon virtuality $Q^2 > 1 \text{ GeV}^2$, where the scattered electron is visible in the main detector and photoproduction (PHP) with $< Q^2 > \approx 3 \cdot 10^{-4} \text{ GeV}^2$, where the virtual photon radiated from the incoming electron is quasi-real. The sample is dominated by PHP events.

2 Glueball search in the $K_S^0 K_S^0$ 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 $K_S^0 K_S^0$ 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 $\gamma\gamma \rightarrow K_S^0 K_S^0$. 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] $K_S^0 K_S^0$ spectra had no $f_2(1270)/a_2(1320)$ signal and a sizable $f_2'(1525)$ enhancement. The result was interpreted 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 $K_S^0 K_S^0$ 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 $e^\pm p \rightarrow K_S^0 K_S^0 + X$ 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_S^0 mesons were identified via their decay mode $K_S^0 \rightarrow \pi^+ \pi^-$. A clean K_S^0 signal was seen for events with $\geq 2 K_S^0$ candidates. The number of $K_S^0 K_S^0$ pairs found in the K_S^0 mass range $481 < M(\pi^+ \pi^-) < 515 \text{ MeV}$ is $\approx 672,000$.

Figure 1 shows the $K_S^0 K_S^0$ mass distribution reconstructed by combining two K_S^0 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.

Two types of fit, as performed for the reaction $\gamma\gamma \rightarrow K_S^0 K_S^0$ 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] $BW(R) = \frac{M_R \sqrt{\Gamma_R}}{M_R^2 - m^2 - i M_R \Gamma_R}$. 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 $m(K_S^0 K_S^0)$ 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

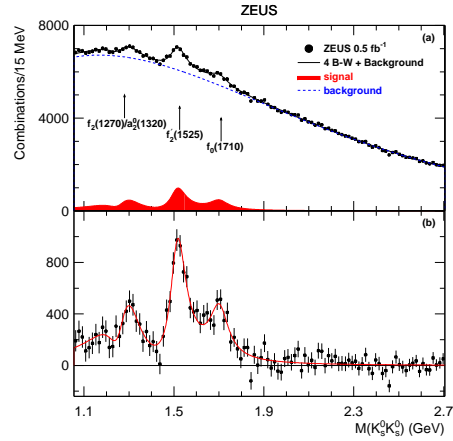


Figure 1: (a) The $K_S^0 K_S^0$ distribution (dots). Solid line is the coherent fit (see text); background function is given by the dashed line. (b) Background-subtracted $K_S^0 K_S^0$ distribution (dots); solid line is the fit result.

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 $\chi^2/ndf = 162/97$.

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 $\Theta^+ = uud\bar{s}$ pentaquark state predicted by Diakonov et al.[6]. If a strange pentaquark exists, charmed pentaquarks, $\Theta_c^0 = uud\bar{c}$, 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

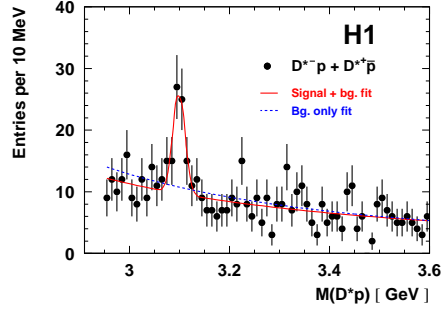


Figure 2: $M(D^{*\pm}p^\mp)$ from H1 DIS HERA I, compared with fit results where both signal and background components are included and where only background is included.

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 $D^{*\pm} \rightarrow D^0\pi_S^\pm$ decay channels were used with $D^0 \rightarrow K^\mp\pi^\pm$ and $D^0 \rightarrow K^\mp\pi^\pm\pi^+\pi^-$. 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 $Q^2 > 1$ GeV² 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 $D^0 \rightarrow K\pi$ (left) and $D^0 \rightarrow K\pi\pi\pi$ (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, $R(\Theta_c^0 \rightarrow D^*p/D^*)$, 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 $R(\Theta_c^0 \rightarrow D^*p/D^*) < 0.23\%$ 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 $\Theta_c^0 \rightarrow D^*p$ for the combined two channels is $f(c \rightarrow \Theta_c^0) \cdot B_{\Theta_c^0 \rightarrow D^*p} < 0.16\%$ ($< 0.19\%$) for the full (DIS) sample.

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 $D_1(2420)^0 \rightarrow D^{*\pm}\pi^\mp$ ($J^P = 1^+$), $D_2^*(2460)^0 \rightarrow D^{*\pm}\pi^\mp, D^\pm\pi^\mp$

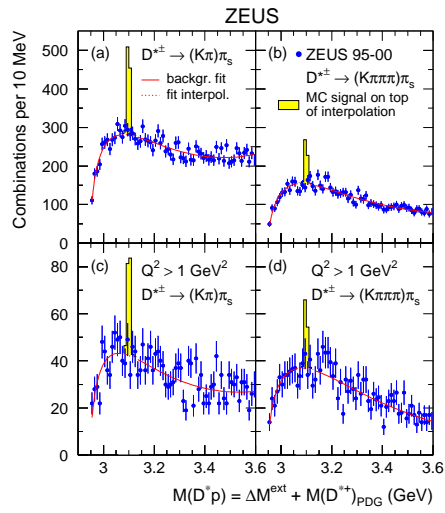


Figure 3: $M(D^{*\pm}p^\mp)$ from ZEUS HERA I. Solid curves are fits to a background function. Shaded histograms are MC Θ_c^0 signals, normalised to $\Theta_c^0/D^* = 1\%$, on top of the background fit.

($J^P = 2^+$) and $D_{s1}(2536)^\pm \rightarrow D^{*\pm} K_S^0, D^{*0} K^\pm$ ($J^P = 1^+$) and searched for the radially excited state $D^{*'}(2640)^\pm \rightarrow D^{*\pm} \pi^+ \pi^-$ ($J^P = 1^-$?) 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 $D^\pm \rightarrow K^\mp \pi^\pm \pi^\pm$ and $D^0(\bar{D}^0) \rightarrow K^\mp \pi^\pm$ was extracted from fits to a modified Gauss function, $Gauss^{mod} \sim \exp(-0.5x^{1+(1+0.5x)})$, 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.

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 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.

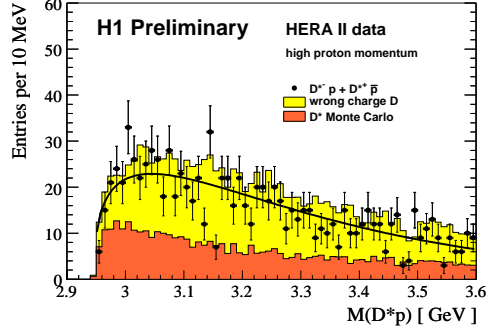


Figure 4: $M(D^{*\pm}p^\mp)$ from H1 DIS HERA II. The solid line is a background parametrisation.

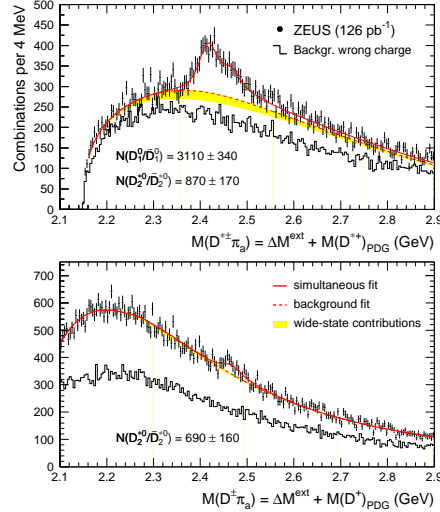


Figure 5: $M(D^{*\pm}\pi_a)$ and $M(D^\pm\pi_a)$ distributions. Solid curves are simultaneous fit; dashed curves are background; histograms are wrong-charge combinations.

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 $M(D^0 K_a) - M(D^0) + M(D^0)_{PDG}$. 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 $M(D^0 K_a)$, $M(D^{*\pm} K_S^0)$ 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.

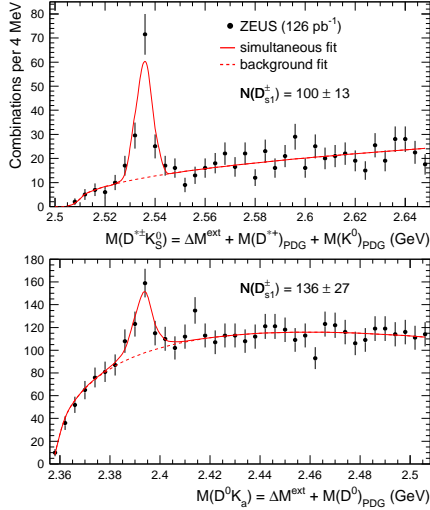


Figure 7: $M(D^{*\pm} K_S^0)$ and $M(D^0 K^{\pm})$ distributions. Solid curves are simultaneous fit; dashed curves are background.

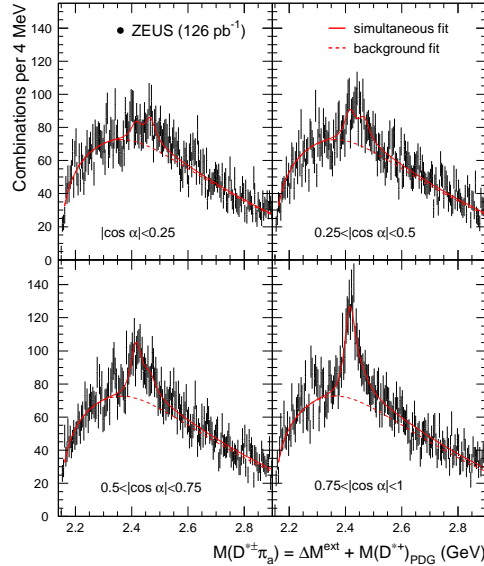


Figure 6: $M(D^{*\pm} \pi_a)$ distributions in 4 helicity intervals.

5 Branching ratios and fragmentation fractions

Using the ZEUS measured fractions $f(c \rightarrow D^{*+})$

and $f(c \rightarrow D^+)$ [11], the following decay

rate ratios were derived: $\frac{B_{D_2^{*0} \rightarrow D^+ \pi^-}}{B_{D_2^{*0} \rightarrow D^{*+} \pi^-}} =$

$$2.8 \pm 0.8_{-0.6}^{+0.5} \text{ (PDG: } 2.3 \pm 0.6); \frac{B_{D_{s1}^+ \rightarrow D^{*0} K^+}}{B_{D_{s1}^+ \rightarrow D^{*+} K^0}} =$$

$$2.3 \pm 0.6 \pm 0.3 \text{ (PDG: } 1.27 \pm 0.21).$$

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

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 $f(c \rightarrow D^{*\pm}) \cdot B_{D^{*\pm} \rightarrow D^+ \pi^+ \pi^-} < 0.4\%$ was set, compared to the weaker limit of OPAL (0.9%) [13].

	$f(c \rightarrow D_1^0)[\%]$	$f(c \rightarrow D_2^{*0})[\%]$	$f(c \rightarrow D_{s1}^+)[\%]$
ZEUS	$3.5 \pm 0.4_{-0.6}^{+0.4}$	$3.8 \pm 0.7_{-0.6}^{+0.5}$	$1.11 \pm 0.16_{-0.10}^{+0.08}$
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.

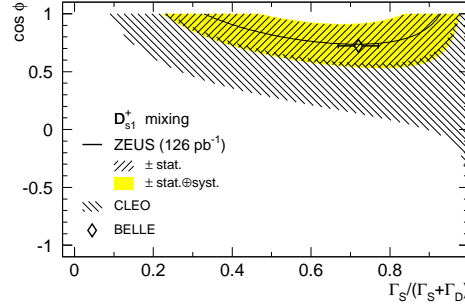


Figure 8: $\cos \phi$ vs. $\Gamma_S/(\Gamma_S + \Gamma_D)$ for $D_{s1}^+ \rightarrow D^{*+} K_S^0$ decay.

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