



Excited Charm and $K_0^*K_0^*$ Resonance Production at ZEUS

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For the ZEUS Collaboration



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Outline

- Main detectors for heavy hadron spectroscopy and ZEUS experiment;
- Motivation;
- Inclusive $K^0_s K^0_s$ resonance production;
- Excited charm and charm-strange mesons;
- Conclusions;

Main detectors for heavy hadron spectroscopy:

- **B-factories: Belle and BaBar;**

$e^+e^- \rightarrow Y(4S), \sqrt{s} \sim 10.6 \text{ GeV}$, Charm particles from B-mesons.

- **Charm factories CLEO-c and BES-II;**

$e^+e^- \rightarrow J/\psi, \psi(2S), \psi(3770)$, $\sqrt{s} \sim 3.8\text{-}4.8 \text{ GeV}$

- **Tevatron: CDF and DØ;**

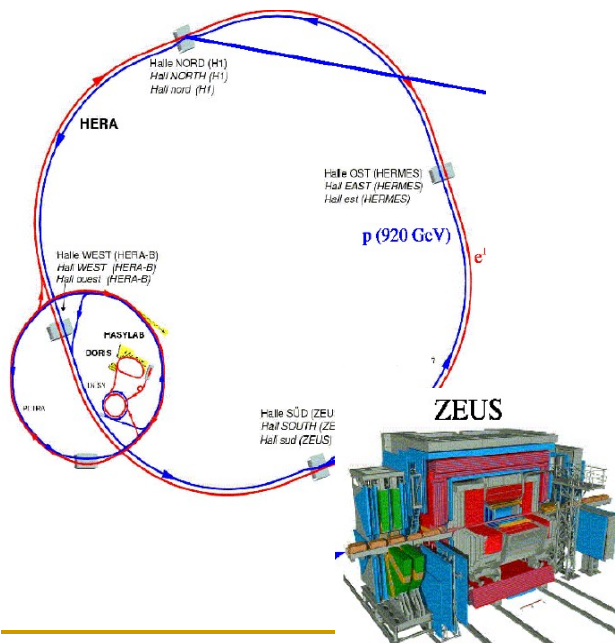
$pp \rightarrow b\text{-baryons}$, $\sqrt{s} \sim 1.96 \text{ TeV}$

- **HERA: ZEUS and H1;**

ep collider, $\sqrt{s} \sim 0.318 \text{ GeV}$

ZEUS detector at the HERA

- ZEUS: 56 universities and laboratories, 18 countries
- HERA – until 2007 was the only ep collider in the world
- HERA II (2002-2007): upgraded detectors, longitudinally polarised e^\pm beams



Complete 4π detector

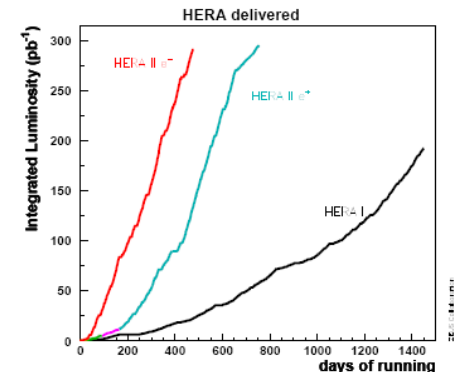
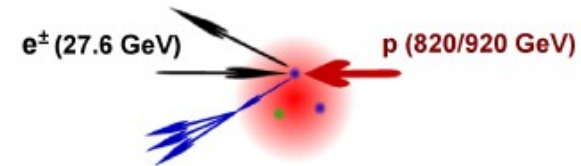
Tracking:

- central tracking detector
 - Silicon μ -Vtx
- (operate in a B field of 1.43 T)

Calorimeters:

- Uranium-scintillator (CAL)
- Instrumented-iron (BAC)

Muon chambers



$$e \Rightarrow 27.6 \text{ GeV} \quad \Leftarrow p \quad 820 - 920 \text{ GeV}$$

HERA I HERA II

1995-2000 2003-2007

\sqrt{s}	318 (300) GeV	318 GeV
\mathcal{L}	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31} \text{ cm}^{-2} \text{ s}^{-1}$
\mathcal{L}_{int}	~ 120	$\sim 370 \text{ pb}^{-1}$

Motivation

- heavy hadron spectroscopy - **Quark Models based on QCD** - describe strong interactions;
- test of QCD: prediction masses, widths, transitions and decays;
- inconsistency with model predictions: new kinds of particles and new phenomena

Motivation *for study excited charm and charm strange production*

Heavy-quark spectroscopy has recently undergone a renaissance with the discovery of several new states:

- ❖ Non-strange excited charm mesons $D_1(2420)^{\circ,\pm}$ and $D_2^*(2460)^{\circ,\pm}$
- ❖ Charm-strange excited mesons $D_{s1}(2536)^{\pm}$ and $D_{s2}(2573)^{\pm}$
- ❖ Recently, Supported Heavy Quark Effective Theory (HQET) predictions $D^{\circ*}(2400)^{\circ,\pm}$ and $D_1(2430)^{\circ}$
- ❖ Recent discovery charm-strange $D_{s0}^*(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$
- ❖ *Predicted: broad non-strange charged excited charm meson with $JP=1+$ has not yet been observed.*
- ❖ *Predicted: radially excited charm $D' \rightarrow D\pi\pi$ and $D^{*'} \rightarrow D^*\pi\pi$, ~ 2.6 GeV. Narrow resonance at 2637 MeV with $D^{*\pm} \pi^+ \pi^-$ reported by DELPHI, however OPAL – no evidence.*

The properties of these states challenge the theoretical description of heavy-quark resonances. Further measurement of excited charm and charm-strange mesons are important!

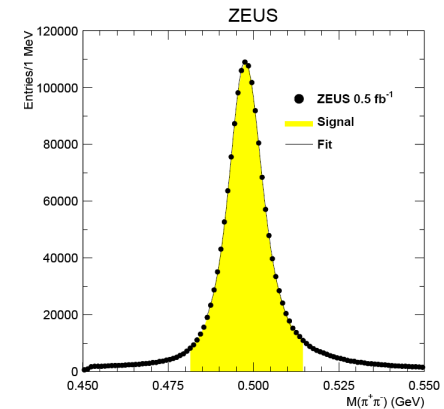
Motivation *for study $K_S^0 K_S^0$ resonance production*

- The SM allows glueballs (gg), hybrids ($q\bar{q}g$) and mixed states
 - The scalar meson sector ($J^P=0^+$) has too many established $I = 0$ states:
 $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$
only two can fit into the $q\bar{q}$ nonet
 - Lattice calculations predict that the lightest glueball has $J^{PC} = 0^{++}$ and mass in range 1550 – 1750 MeV
 - It can mix with $q\bar{q}$ ($I = 0$) states close in mass
 - $f_0(1710)$ is considered to be a possible glueball candidate
 - The $K_S^0 K_S^0$ system can couple to $J^P = 0^+$ and 2^+
- $K_S^0 K_S^0$ is a good place to search for the lightest 0^+ glueball

Phys. Rev. Lett. 101, 112003 (2008)

K0s mass distribution for events with \geq two K0s candidates

- ZEUS data 1996- 2007
- Signal window for $M(K0sK0s)$ analysis: $481 \leq M(\pi^+\pi^-) \leq 515$ MeV
- No. of $K0s$ candidates in signal window $\sim 1,258,400$
- Clean $K0s$ signal; background $\sim 8\%$



Cuts:

- $p_T(K0s) > 0.25$ GeV
- 2D Collinearity angle < 0.12 rad; (angle in xy -plane between $K0s$ momentum vector and vector defined by interaction point and decay vertex)
- $|Z_{vtx}| < 50$;

$M(K_S^0 K_S^0) = 497.49$ MeV
consistent with PDG
 $\sigma = 4.1$ MeV consistent with
detector resolution

K⁰_sK⁰_s mass spectrum (incoherent fit)

Fit (as in L3) to background plus incoherent sum of 3 modified RBW resonance, 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

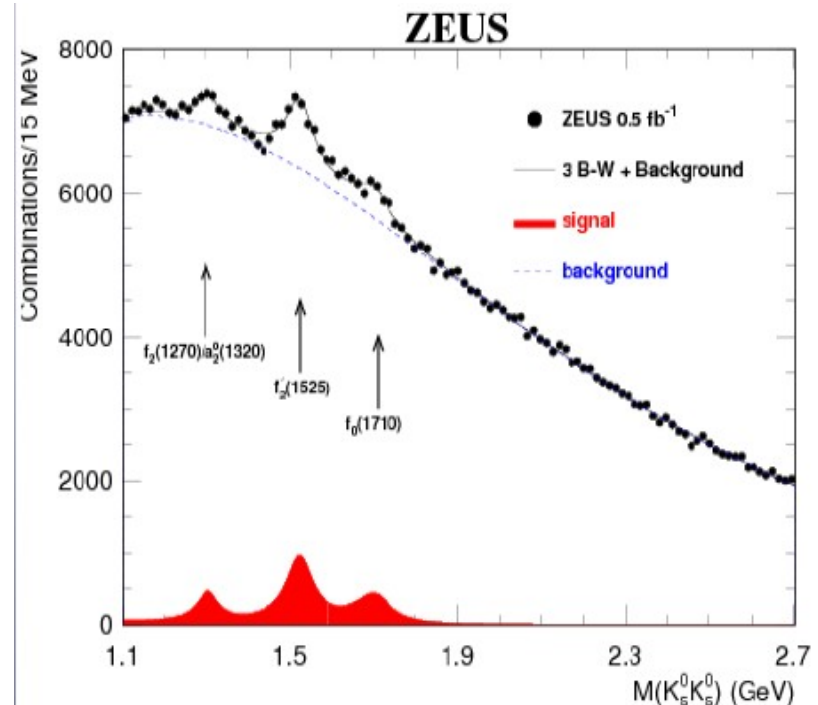
$f_2(1270)/a_2(1320)$, $f_2'(1525)$, $f_0(1710)$

C_R = Amplitude of resonance R

M_R = Mass of resonance R

Γ_R = Variable width of resonance R

$m = K_S^0 K_S^0$ invariant mass



$\chi^2/ndf = 96/95$

Bad fit without $f_0(1710) \Rightarrow f_0(1710)$ required

Dip between f_2/a_2 and f_2' not reproduced

K_S⁰K_S⁰ mass spectrum (coherent fit)

- K_S⁰K_S⁰ invariant-mass distribution was reconstructed by combining two K_S⁰ candidates selected in the mass window;

M, Γ of all resonances – free parameters in the fit.

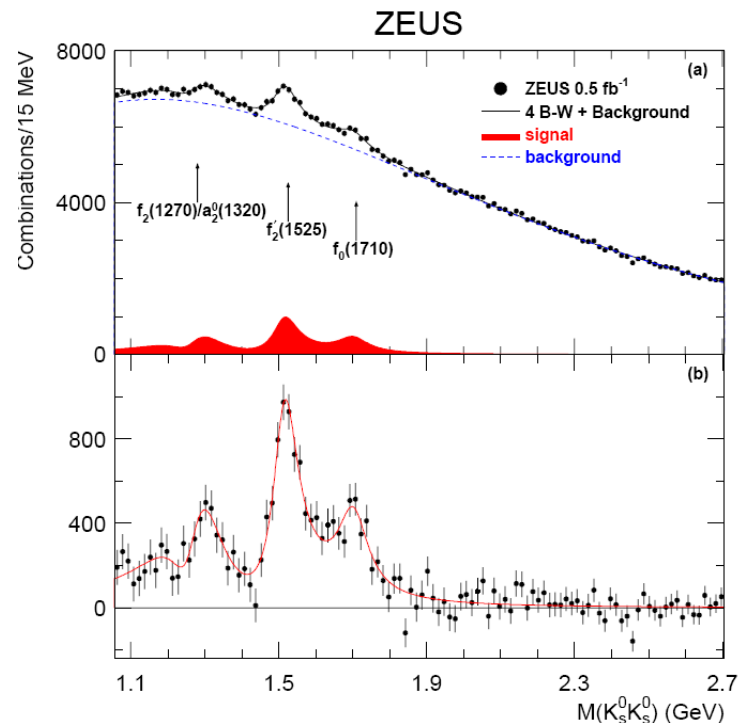
Bottom plot background subtracted $M(K_S^0 K_S^0)$ spectrum with fitted BW functions.

Good fit $\chi^2/\text{ndf} = 86/97$.

Peak around 1.3 GeV suppressed due to destructive interference between $f_2(1270)$ and $a_2(1320)$.
Dip between $f_2(1270)/a_2(1320)$ and $f_2'(1525)$ is well reproduced.

No. of fitted $f_0(1710)$ events:
 $4058 \pm 820 \sim 5\sigma$ significance

⁷ Fit without $f_0(1710)$ strongly disfavoured $\chi^2/\text{ndf} = 162/97$



Results

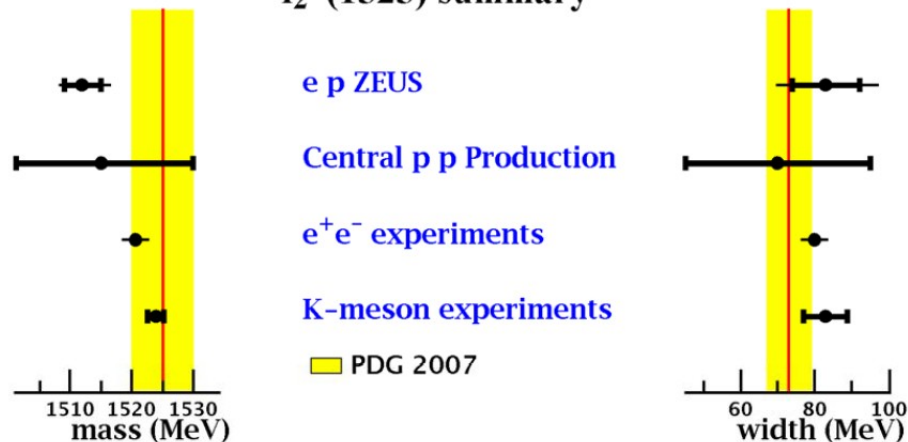
Fit	No interference		Interference		PDG 2007 Values	
χ^2/ndf	96/95		86/97			
in MeV	Mass	Width	Mass	Width	Mass	Width
$f_2(1270)$	1304 ± 6	61 ± 11	1268 ± 10	176 ± 17	1275.4 ± 1.1	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$			1257 ± 9	114 ± 14	1318.3 ± 0.6	107 ± 5
$f_2'(1525)$	$1523 \pm 3^{+2}_{-8}$	$71 \pm 5^{+17}_{-2}$	$1512 \pm 3^{+1.4}_{-0.5}$	$83 \pm 9^{+5}_{-4}$	1525 ± 5	73^{+6}_{-5}
$f_0(1710)$	$1692 \pm 6^{+9}_{-3}$	$125 \pm 12^{+19}_{-32}$	$1701 \pm 5^{+5}_{-3}$	$100 \pm 24^{+7}_{-22}$	1724 ± 7	137 ± 8

For fit with interference:

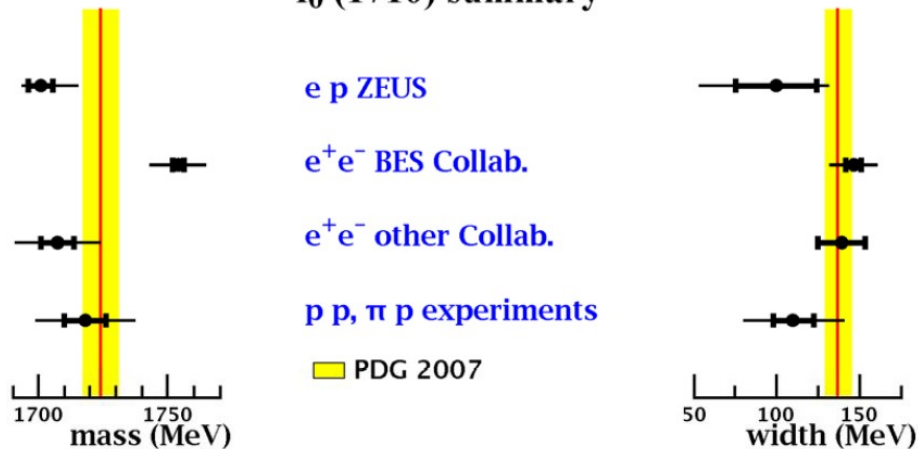
- $a_2(1320)$ mass below PDG value. Similar shift, attributed to destructive $f_2(1270)/a_2(1320)$ interference, seen by Faiman *et al.*
- Widths of all observed resonances close to PDG values
- $f_2'(1525)$, $f_0(1710)$ masses below PDG; uncertainties compatible with PDG
- One of the best $f_0(1710)$ reported signals: 4058 ± 820 events ~ 5 s.d.

$f_2(1525)$ and $f_0(1710)$: mass and width

$f_2(1525)$ summary



$f_0(1710)$ summary



Excited charm and charm-strange mesons

- Large charm production cross sections at HERA allow to search for excited charm states

Look for orbitally excited states:

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

$$D_2^*(2460)^0 \rightarrow D^{*\pm}\pi^\mp \quad J^P = 2^{++}$$

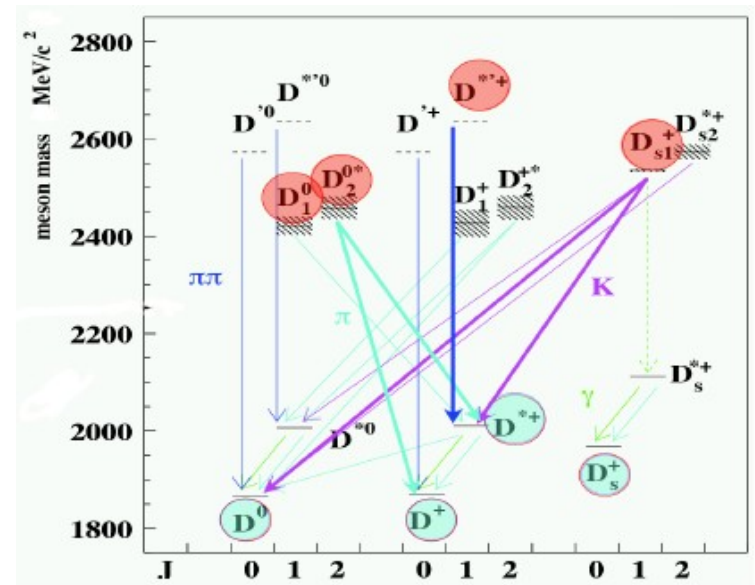
$$D_2^*(2460)^0 \rightarrow D^\pm\pi^\mp$$

$J^P = 1^+$ state cannot decay to $D\pi$

$$D_{s1}(2536)^\pm \rightarrow D^{*\pm}K_s^0, D^{*0}K^\pm \quad J^P = 1^+$$

Search for radially excited states:

$$D'^\pm(2640) \rightarrow D^{*\pm}\pi^+\pi^- \text{ (DELPHI)} \quad J^P = 1^- ? \quad \text{ZEUS HERA I 1995 - 2000 (126 pb}^{-1}\text{) DIS + PHP}$$



Eur.Phys.J C60,25(2009)

Study of the excited charm mesons $D_1(2420)^0$, $D_2^*(2460)^0$

$$D_1(2420)^0 \rightarrow D^* + \pi^-$$

$$D_2^*(2460)^0 \rightarrow D^* + \pi^-, D + \pi^-$$

combining each selected D^*+ (or D^+) candidate with an additional track, assumed to be a pion, with a charge opposite to that of the D^*+ (or D^+) candidate.

Reconstruction of lowest-mass charm mesons:

D^{*+}

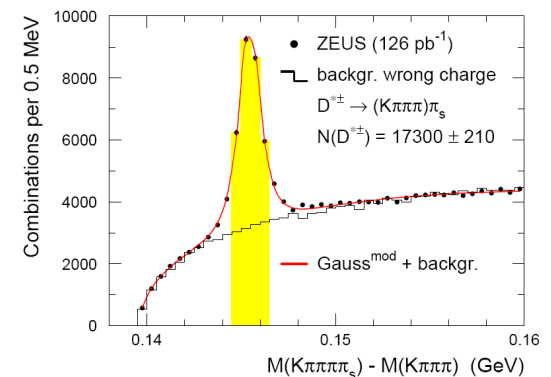
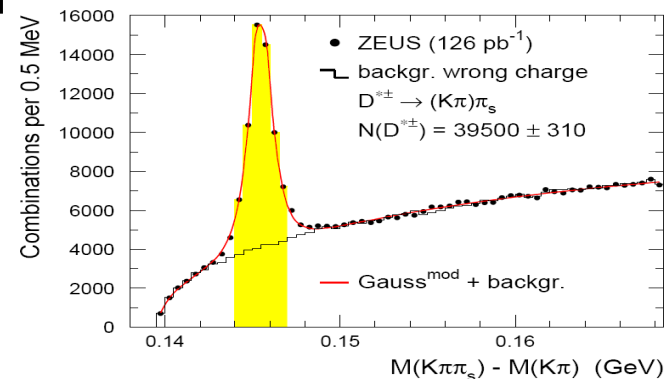
D^{*+} mesons were identified using the two decay channels:

$$D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+) \pi^+ \\ \Delta M = M(K\pi\pi) - M(K\pi), \quad \text{Signal: } 39500$$

$$D^{*+} \rightarrow D^0 \pi^+ \rightarrow (K^- \pi^+ \pi^+ \pi^-) \pi^+ \\ \Delta M = M(K\pi\pi\pi\pi) - M(K\pi\pi\pi), \quad \text{Signal: } 17300$$

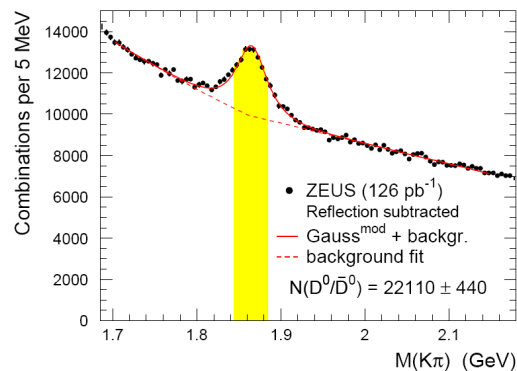
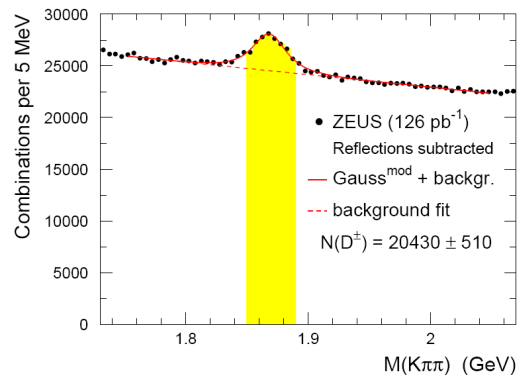
Background-wrong charge combination.

Yellow band - ranges used for excited charm mesons



Reconstruction of lowest-mass charm mesons:

D⁺ and D⁰



$$D^+ \rightarrow K^- \pi^+ \pi^+.$$

Width (D⁺)=12.9 MeV;
(*detector resolution*)

Guts:

$$p_T(D) > 2.8 \text{ GeV}$$

$$|\eta(D)| < 1.6$$

Yellow band corresponds to ranges used for excited charm mesons

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

Width (D⁰)=17.4 MeV;

Excited charm mesons: $D_1(2420)^0$ and

$D_2^*(2460)^0$

- Decay channel $\rightarrow D^* + \pi^-$

A clear enhancement in the range where contributions from $D_1(2420)^0$ and $D_2^*(2460)^0$ mesons are expected.

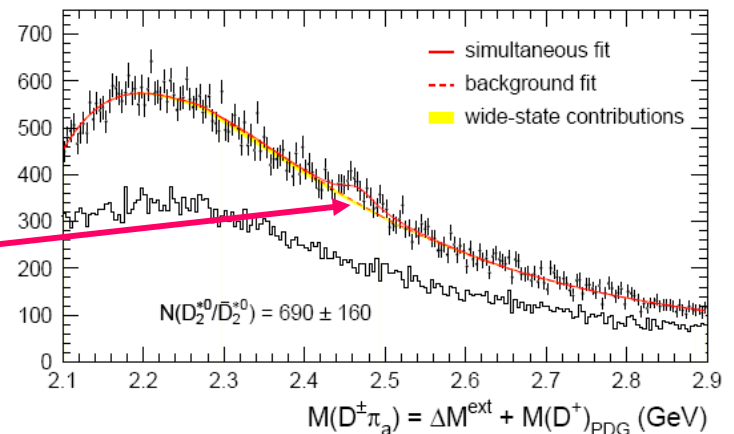
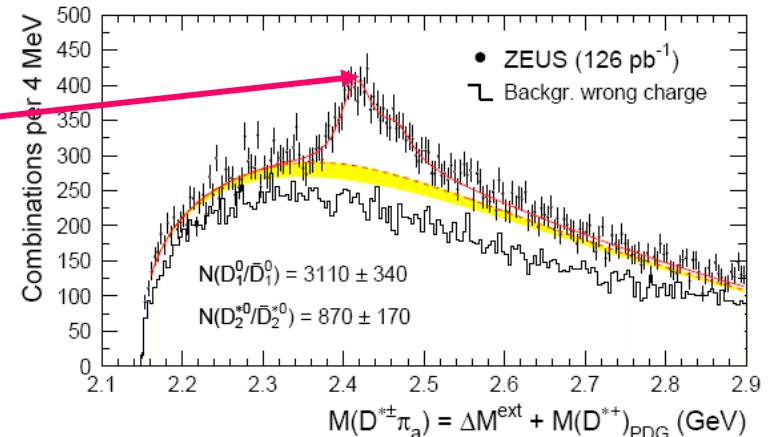
$$\Delta M^{ext} + M(D^{*\pm})_{PDG} \text{ (dots)}$$

$$\Delta M^{ext} = M(K\pi\pi_s\pi_e) - M(K\pi\pi_s)$$

$$p_T(D^{*\pm}) > 1.35 \text{ GeV}, |\eta(D^{*\pm})| < 1.6$$

$$\Delta M^{ext} = M(K\pi\pi\pi\pi_s\pi_e) - M(K\pi\pi\pi\pi_s)$$

$$p_T(D^{*\pm}) > 2.80 \text{ GeV}, |\eta(D^{*\pm})| < 1.6$$



- Decay channel $\rightarrow D + \pi^-$

A small excess around the nominal mass of the D_2^* meson.

D_1^0 and D_2^{*0} in four helicity bins

Used helicity angular distribution to extract
 $D_1(2420)^0$ and $D_2^{*}(2460)^0$ yields and properties
 h -helicity parameter ($h=3$ for pure D-wave)

$$dN/d\cos\alpha \approx 1 + h\cos^2\alpha$$

Simultaneous
 fit including all
 contributions

final state	$D^{*+}\pi_a$	$D^+\pi_a$
Signal yields		
$N(D_1^0)$	3110 ± 340	
$N(D_2^{*0})$	870 ± 170	690 ± 160

$$M(D_1^0) = 2420.5 \pm 2.1(\text{stat.}) \pm 0.9(\text{syst.}) \pm 0.2(\text{PDG}) \text{ MeV},$$

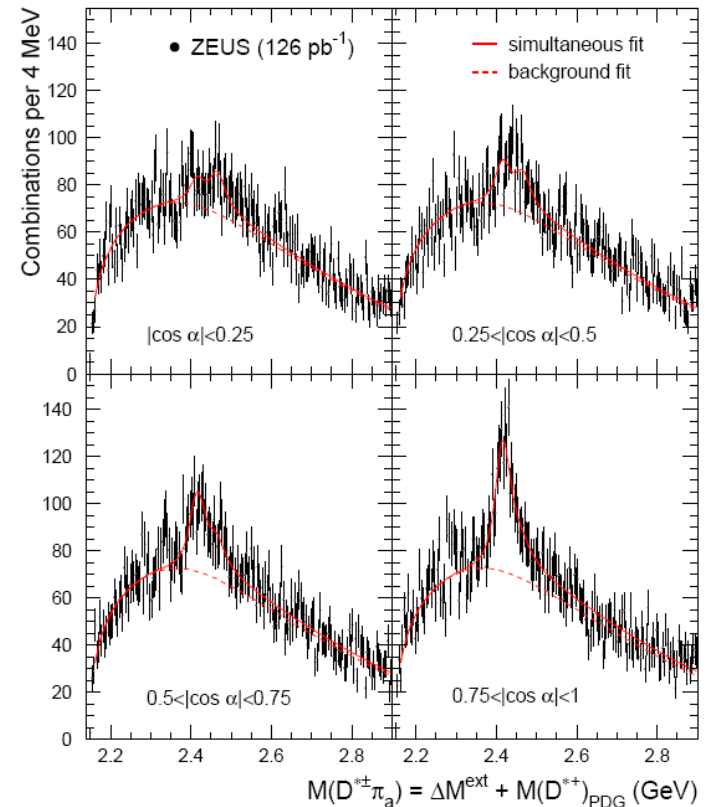
$$M(D_2^{*0}) = 2469.1 \pm 3.7(\text{stat.})^{+1.2}_{-1.3}(\text{syst.}) \pm 0.2(\text{PDG}) \text{ MeV}.$$

Fitted masses agree with PDG

$$\Gamma(D_1^0) = 53.2 \pm 7.2^{+3.3}_{-4.9} \text{ MeV} (\text{PDG} : 20.4 \pm 1.7 \text{ MeV})$$

$$h(D_1^0) = 5.9^{+3.0}_{-1.7}(\text{stat.})^{+2.4}_{-1.0}(\text{syst.}) \quad (\text{CLEO: } 2.74^{+1.40}_{-0.93})$$

Roughly consistent with pure D-wave ($h=3$)

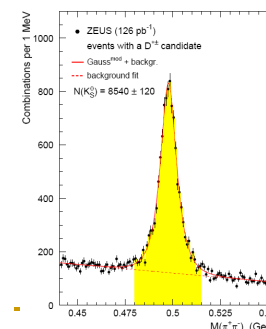
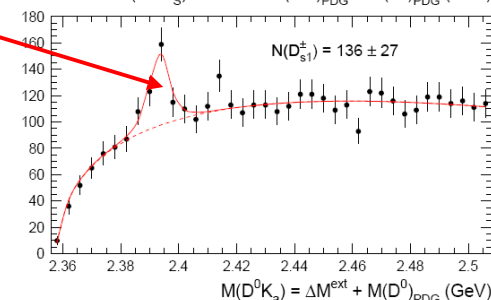
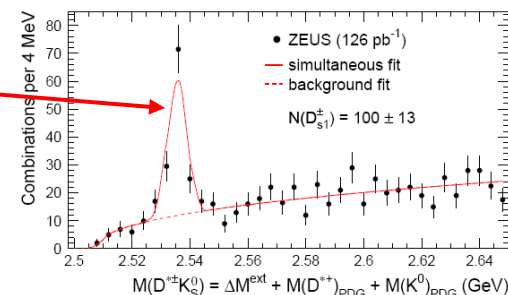


Excited charm mesons: D_{s1}^+

- $D_{s1}^+ \rightarrow D^{*+}(\text{both decay channels})$ with $K_S^0 \rightarrow \pi^+ \pi^-$
- $D_{s1}^+ \rightarrow (D^{*0} \text{ with } K^\pm)$
- To extract D_{s1}^+ yields and properties: fit using simultaneously values of $M(D^{*0} K^\pm)$ and $M(D^{*+} K_S^0)$ in four helicity intervals
- *Clear $D_{s1}(2536)^+$ signals! Measured D_{s1}^+ mass in good agreement with the world average value!*

$$M(D_{s1}^+) = 2535.57_{-0.41}^{+0.44}(\text{stat.}) \pm 0.10(\text{syst.}) \pm 0.17(\text{PDG}) \text{ MeV}$$

final state	$D^{*+} K_S^0$	$D^{*0} K_a$
Signal yields		
$N(D_{s1}^+)$	100 ± 13	136 ± 27



Fitted D_{s1} helicity parameter: $h(D_{s1}) = -0.74_{-0.17}^{+0.23}(\text{stat.})_{-0.05}^{+0.06}(\text{syst.})$

Inconsistent with pure 1^+ D-wave ($h=3$)

Barely consistent with pure 1^+ S-wave ($h=0$) \rightarrow **Significant S-D mixing**

Branching ratios and fragmentation fractions

$$\frac{B_{D_2^{*0} \rightarrow D^+ \pi^-}}{B_{D_2^{*0} \rightarrow D^{*+} \pi^-}} = 2.8 \pm 0.8(\text{stat.})_{-0.6}^{+0.5}(\text{syst.}) \quad 2.3 \pm 0.6 \text{ (PDG)}$$

$$\frac{B_{D_{s1}^+ \rightarrow D^{*0} K^+}}{B_{D_{s1}^+ \rightarrow D^{*+} K^0}} = 2.3 \pm 0.6(\text{stat.}) \pm 0.3(\text{syst.}) \quad 1.27 \pm 0.21 \text{ (PDG)}$$

Assuming I-spin conservation for D_1^0, D_2^{*0} and $B_{D_{s1}^+ \rightarrow D^{*+} K^0} + B_{D_{s1}^+ \rightarrow D^{*0} K^+} = 1$ yields fragmentation functions and strangeness suppression of excited D mesons

$$f(c \rightarrow D_{s1}^+)/f(c \rightarrow D_1^0) = 0.31 \pm 0.06_{-0.04}^{+0.05}$$

	$f(c \rightarrow D_1^0)[\%]$	$f(c \rightarrow D_2^{*0})[\%]$	$f(c \rightarrow D_{s1}^+)[\%]$
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			$0.94 \pm 0.22 \pm 0.07$

⇒ Frag. fractions for excited D mesons in ep and e^+e^- consistent

Search for radially excited charm meson $D^{*'}(2640)_{\pm}$

$$D^{*'}_{+} \rightarrow D^{*+} \pi^{+} \pi^{-}$$

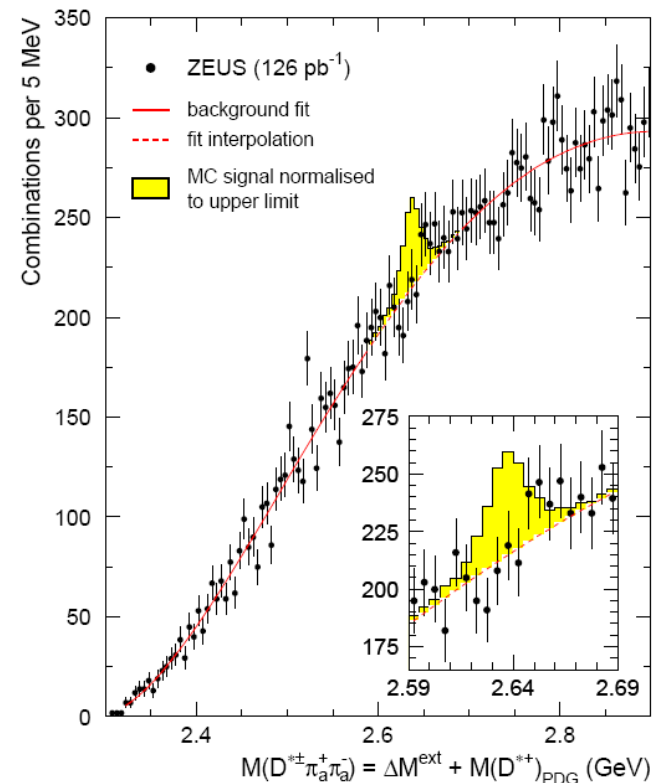
- combining each selected D^{*+} candidate with two additional tracks with opposite charges.
- No radially excited $D^{*'}(2640)_{\pm}$ charm meson observed.

Upper limit:

$$f(c \rightarrow D^{*+}) \cdot \mathcal{B}_{D^{*+} \rightarrow D^{*+} \pi^{+} \pi^{-}} < 0.4\% \quad (95\% \text{ C.L.}).$$

OPAL result: $< 0.9\%$

$D^{*'}_{\pm}$ signal window - theoretical predictions
 solid curve - fit background,
 shaded histogram - Monte Carlo $D^{*'}_{\pm}$ signal,
 normalised to upper limit on top of the fit.



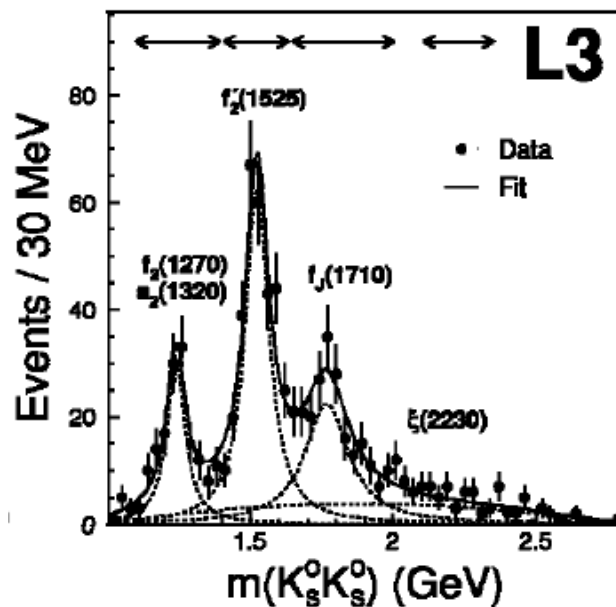
Conclusions

- Observed three enhancements corresponding to $f_2(1270)/a_2(1320)$, $f_2'(1525)$ and $f_0(1710)$;
- Masses and widths of $f_2'(1525)$ and $f_0(1710)$ consistent with PDG;
- No state observed heavier than f_0 ;
- Sizeable production of the excited charm and charm-strange mesons was observed.
- Measured masses of the D_1^0 , D_2^{*0} and D_{s1}^+ in reasonable agreement with the world average values. D_1^0 width 53.2 MeV above PDG 20.4 MeV and helicity parameter $h=5.9$ consistent with prediction for pure D -wave.
- measured D_{s1}^+ helicity parameter $h = -0.74$, inconsistent with prediction for a pure D - or S - waves. Suggests significant contributions of both waves.
- Ratios of dominant branching fractions are in agreement with the world average values.
- Fraction of c quarks into D_1^0 , D_2^{*0} or D_{s1}^+ are consistent with obtained in e^+e^- ;
- No radially excited $D^{*'}(2640)^\pm$ meson was observed.

Backup- *L3 e^+e^- LEP experiment in two-photon collisions*

Phys. Lett. B501, 173 (2001)

They see 3 distinct peaks over a low background and attribute them to $f_2(1270)/a_2(1320)$, $f_2'(1525)$ and $f_0(1710)$



Spectrum dominated by the formation of the $f_2'(1525)$ tensor meson

$f_0(1710)$ signal of ~ 4 s.d. is seen

Maximum likelihood fit with 3 BW

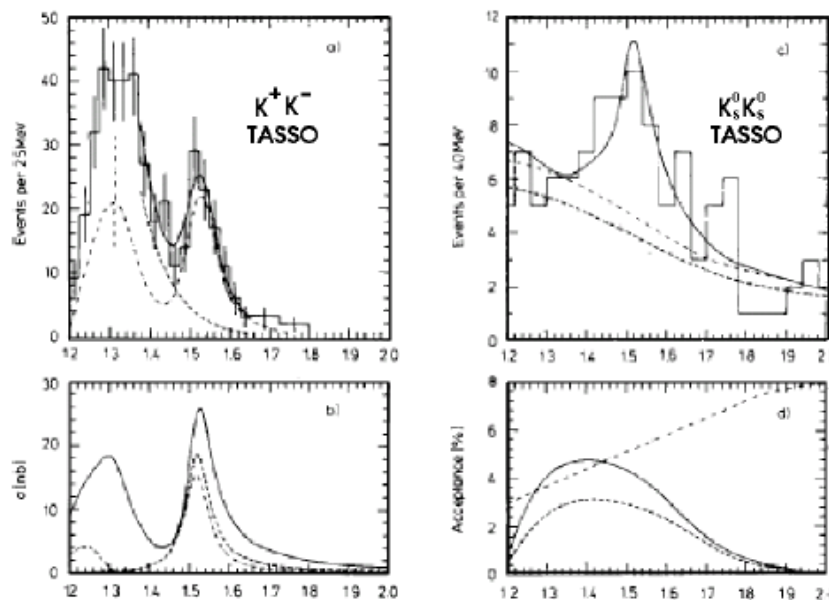
Functions plus 2nd order polynomial

$f_2'(1525)$ parameters consistent with PDG

	$f_2(1270)/a_2(1320)$	$f_2'(1525)$	$f_0(1710)$
Mass (MeV)	1239 ± 6	1523 ± 6	1767 ± 14
Width (MeV)	78 ± 19	100 ± 15	187 ± 60
Events	123 ± 22	331 ± 37	221 ± 55

Backup- TASSO $\gamma\gamma \rightarrow K^+K^-, K_S^0 K_S^0$

Phys. Lett.B121,216,1983



Results interpreted by interference effects between the 3 $J^P=2^+$

resonances $f_2(1270)$, $a_2(1320)$, $f_2'(1525)$

For the same spin-parity, production amplitude is sum of 3 coherent BW's

$$C_1 \cdot \text{BW}(f_2(1270)) \pm C_2 \cdot \text{BW}(a_2(1320)) + C_3 \cdot \text{BW}(f_2'(1525))$$

According to SU(3), sign of 2nd term is + for K^+K^- ; - for $K_S^0 K_S^0$

Faiman et al., Phys.Lett. B59, 269 (1975)

Backup- Coherent 2+ states

	$f_2(1270)$	$a_2(1320)$	$f'_2(1525)$
Isospin I	0	1	0
Quark content	$(u\bar{u} + d\bar{d})/\sqrt{2}$	$(u\bar{u} - d\bar{d})/\sqrt{2}$	$s\bar{s}$
Charge factor	$(\frac{2}{3} \cdot \frac{2}{3} + \frac{1}{3} \cdot \frac{1}{3})\frac{1}{2}$	$(\frac{2}{3} \cdot \frac{2}{3} - \frac{1}{3} \cdot \frac{1}{3})\frac{1}{2}$	$\frac{1}{3} \cdot \frac{1}{3}$
Amplitude ratio	$C_1 = 5$	$C_2 = -3$	$C_3 = 2$

→ The appropriate function to fit the $M(K_S^0 K_S^0)$ spectra for an electromagnetic production process assuming SU(3) symmetry is
H.J. Lipkin, private communication

$$F(m) = a \left[5 \cdot \text{BW}(f_2(1270)) - 3 \cdot \text{BW}(a_2(1320)) + 2 \cdot \text{BW}(f'_2(1525)) \right]^2 \\ + b \left[\text{BW}(f_0(1710)) \right]^2 + c \cdot \text{background}$$

a, b, c are free parameters

BW is a relativistic BW amplitude: $\text{BW}(R) = \frac{M_R \sqrt{\Gamma_R}}{M_R^2 - m^2 - iM_R \Gamma_R}$