Charm and strange particles production at ZEUS

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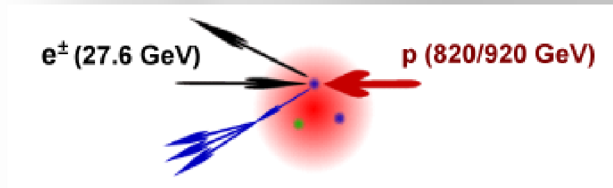
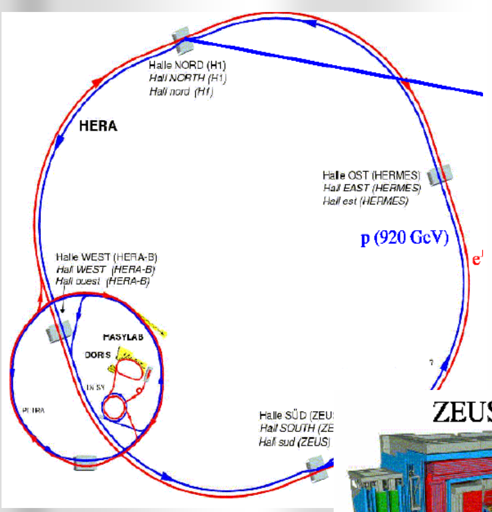
Outline

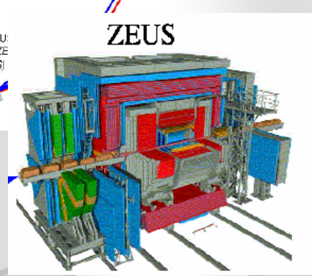
- ZEUS detector at the HERA
- Excited charm and charm-strange mesons
- Inclusive K0sK0s resonance production
- Summary

ZEUS detector at the HERA



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





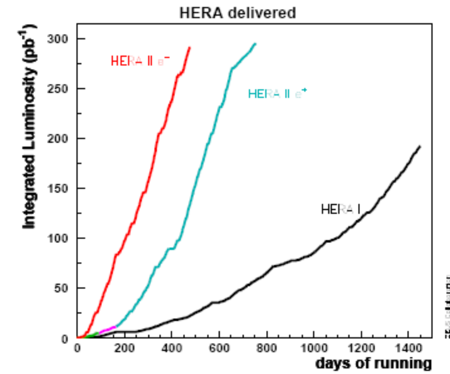
Complete 4π detector

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 GeV	$\Leftarrow p$ 820 – 920 GeV
	HERA I	**HERA II**
	1995-2000	**2003-2007**
$\sqrt{s}$	318 **(300)**	318 **GeV**
$\mathcal{L}$	$1.5 \cdot 10^{31}$	$7 \cdot 10^{31}\, cm^{-2}\, s^{-1}$
$\mathcal{L}_{int}$	~ 120	$\sim 370\, pb^{-1}$

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 $D_1(2420)^{o,\pm}$ and $D_2^*(2460)^{o,\pm}$
- Charm-strange excited mesons $D_{s1}(2536)^\pm$ and $D_{s2}(2573)^\pm$
- Recently, Supported Heavy Quark Effective Theory (HQET) predictions $D^{o*}(2400)^{o,\pm}$ and $D_1(2430)^o$
- 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* $D' \to D\pi\pi$ *and* $D^{*\prime} \to D^*\pi\pi$, *~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!

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:

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

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

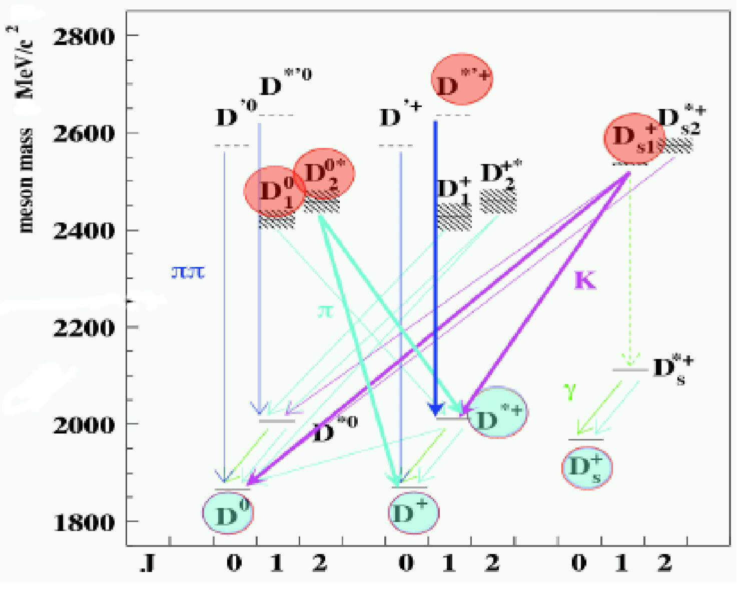
$D_2^*(2460)^0 \to D^{\pm}\pi^\mp$

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

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

Search for radially excited states:

$D^{*\prime}(2640)^\pm \to D^{*\pm}\pi^+\pi^-$ (DELPHI) $\quad J^P = 1^-$?



ZEUS HERA I 1995 - 2000 ($126\ pb^{-1}$) DIS + PHP

Eur.Phys.J C60,25(2009)

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

$$D_1(2420)^o \rightarrow D^{*+} \pi^-$$

$$D_2{}^*(2460)^o \rightarrow D^{*+} \pi^- , D^+ \pi^-$$

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:

$D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (K^- \pi^+) \pi_s^+$

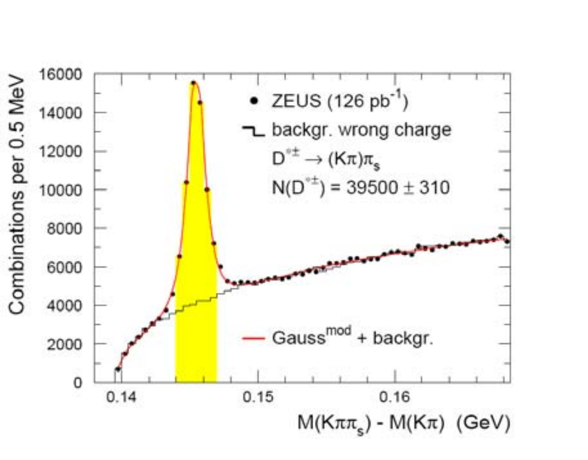
ΔM=M(Kππ)-M(Kπ), ***Signal: 39500***

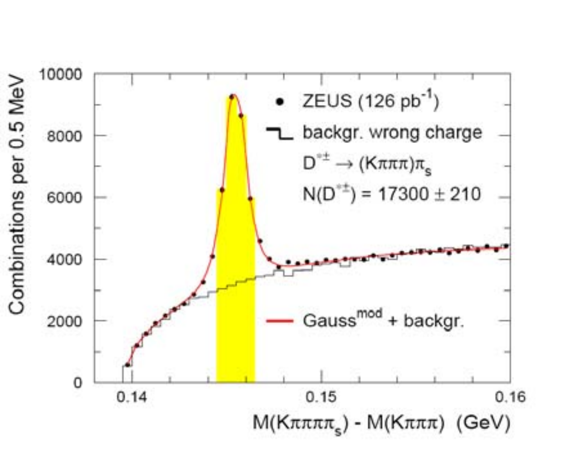
$D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (K^- \pi^+ \pi^+ \pi^-) \pi_s^+$

ΔM=M(Kππππs)-M(Kπππ), ***Signal: 17300***

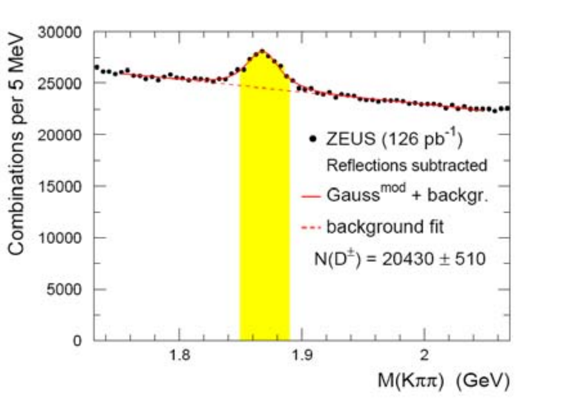
Background-wrong charge combination.

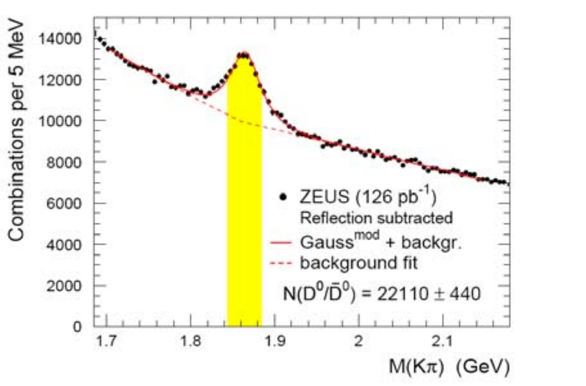
Yellow band - ranges used for excited charm mesons





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 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: *$D_1(2420)^o$ and $D_2^*(2460)^o$*

- *Decay channel* $\rightarrow$ ***D^{*+} π^-***

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

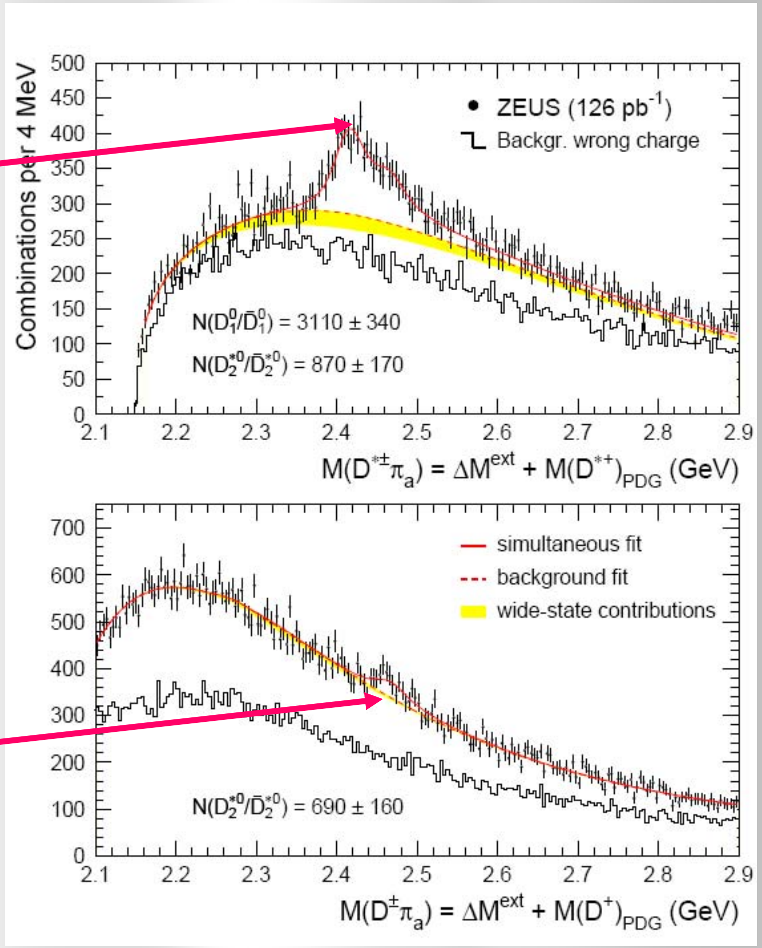
$\Delta M^{ext} + M(D^{*\pm})_{PDG}$ **(dots)**

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

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

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

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



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

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

D_1^o *and* $D_2{*}^o$ in four helicity bins

Used helicity angular distribution to extract *D₁(2420)ᵒ* and *D₂*(2460)ᵒ* 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

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

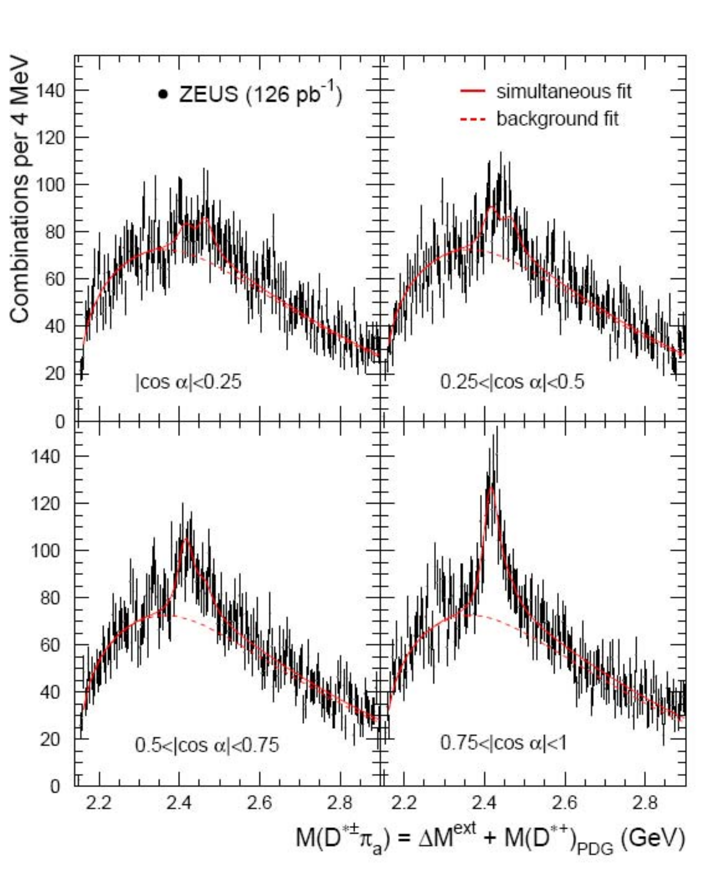
$$M(D_2^{*0}) = 2469.1 \pm 3.7(\text{stat.})^{+1.2}_{-1.3}(\text{syst.}) \pm 0.2(\text{PDG})\ \text{MeV}.$$

Fitted masses agree with PDG

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

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

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

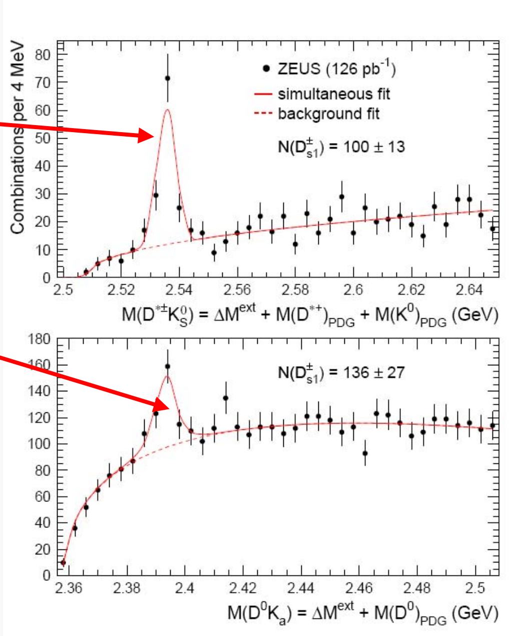


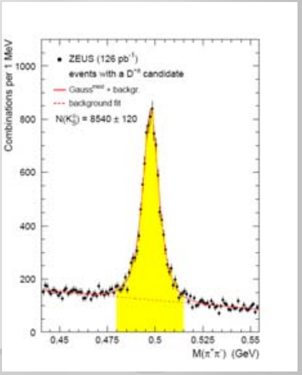
Excited charm mesons: D_{s1+}

- D_{s1+} –> $D*+$(*both decay channels*) with $K^o s$ –> π+ π-
- D_{s1+} –> ($D*^o$ with $K±$)
- To extract D_{s1+} yields and properties: fit using simultaneously values of M($D*^o$ $K±$) and M($D*+$ $K^o s$) in four helicity intervals
- ***Clear $D_{s1}(2536)+$ signals! Measured D_{s1+} mass in good agreement with the world average value!***

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

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





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

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

Barely consistent with pure 1^+ S-wave (h=0) → Significant S-D mixing

Branching ratios and fragmentation fractions

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

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

Assuming I-spin conservation for D_1^0, D_2^{*0} and $B_{D_{s1}^+\to D^{*+}K^0} + B_{D_{s1}^+\to D^{*0}K^+} = 1$ yields

fragmentation functions and strangeness suppression of excited D mesons

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

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

$\Rightarrow$ Frag. fractions for excited D mesons in ep and e^+e^- consistent

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

$$D^{*\prime +} \to D^{*+} \pi^{+} \pi^{-}$$

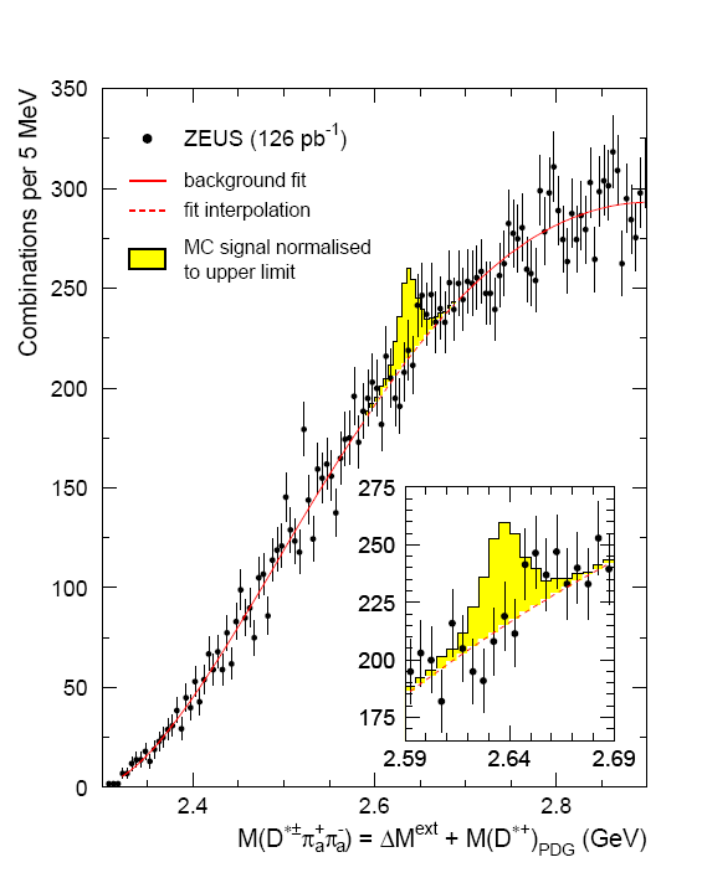
- combining each selected D^{*+} candidate with two additional tracks with opposite charges.
- No radially excited $D^{*\prime}(2640)^{\pm}$ charm meson observed.

Upper limit:

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

OPAL result: < 0.9%

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



Motivation *for study K0sK0s 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:

  $f_0(980)$, $f_0(1370)$, $f_0(1500)$, $f_0(1710)$

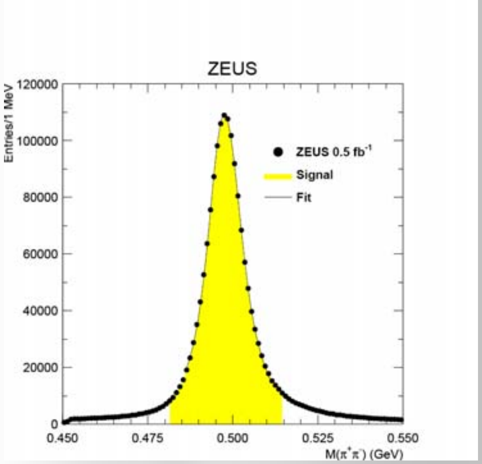
  only two can fit into the $q\bar{q}$ nonent
- Lattice calculations predict that the lightest glueball has $J^{PC} = 0^{++}$ and mass in range 1550 – 1750 MeV
- It can mix with $q\bar{q}$ (I = 0) states close in mass
- $f_0(1710)$ is considered to be a possible glueball candidate
- The $K_S^0K_S^0$ system can couple to $J^P = 0^+$ and 2^+

➔ $K_S^0K_S^0$ is a good place to search for the lightest 0^+ glueball

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

K0s mass distribution for events with ≥ two K0s candidates

- ZEUS data 1996- 2007
- Signal window for M(*K*0s*K*0s) analysis: 481 ≤M(π+π-) ≤515 MeV
- No. of *K*0s candidates in signal window ~ 1,258,400
- Clean *K*0s signal; background ~8%



Cuts:

- pT(K0s)>0.25 GeV
- 2D Collinearity angle <0.12 rad; (angle in *xy*-plane between *K*0s momentum vector and vector defined by interaction point and decay vertex)
- |Zvtx| <50;

$M(K_S^0 K_S^0)$ = 497.49 MeV consistent with PDG

σ = 4.1 MeV consistent with detector resolution

K0sK0s mass spectrum (incoherent fit)

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

$$F(m) = C_R \frac{M_R \Gamma_R}{\left(M_R^2 - m^2\right)^2 + M_R^2 \Gamma_R^2}$$

representing the peaks

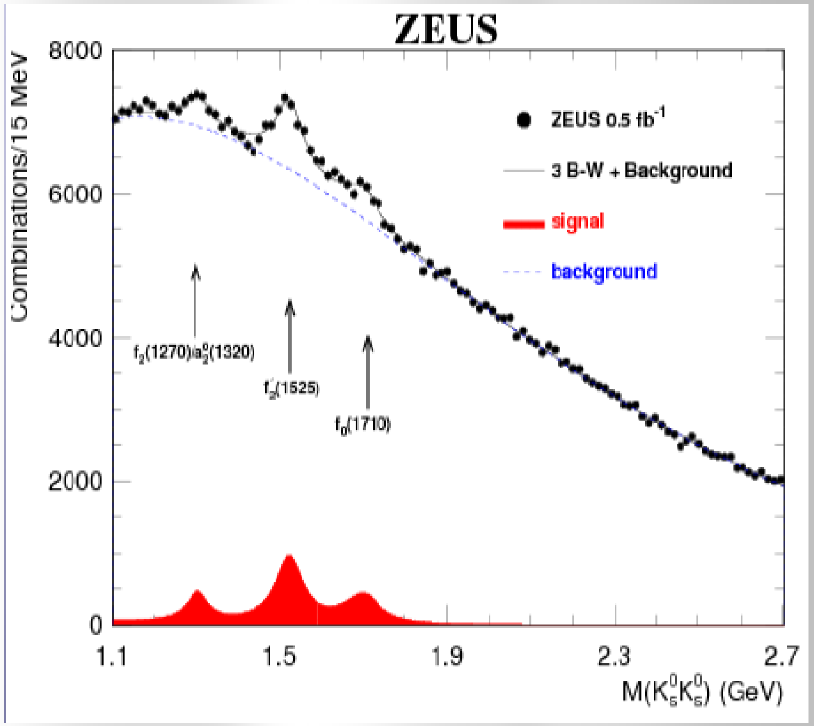
$f_2(1270)/a_2(1320)$, $f_2'(1525)$, $f_0(1710)$

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

K0sK0s mass spectrum (coherent fit)

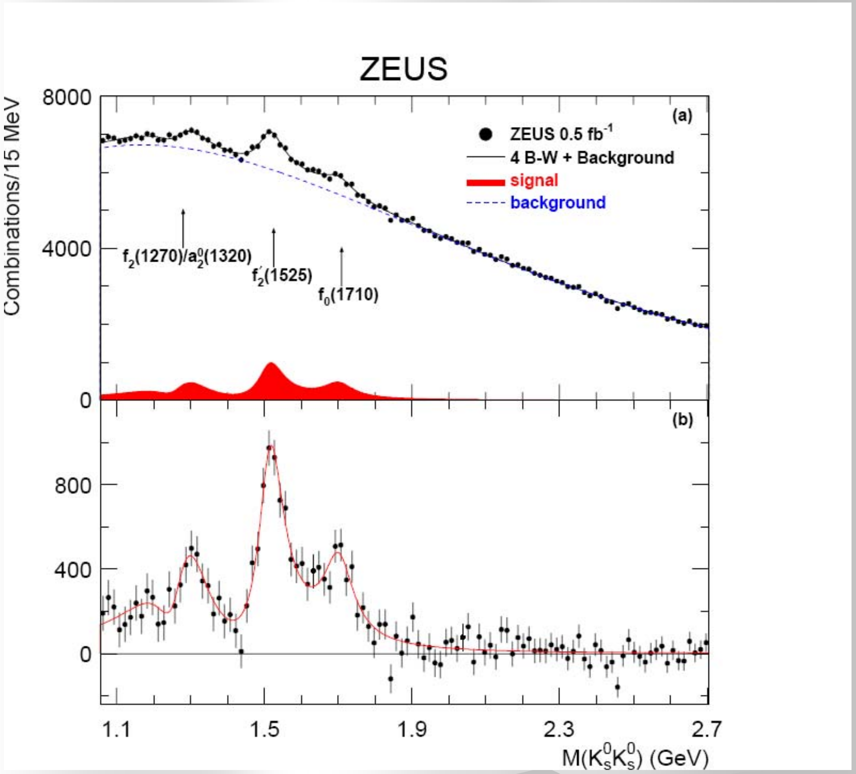
- K0sK0s invariant-mass distribution was reconstructed by combining two K0s candidates selected in the mass window;

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 χ^2/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±820 ~ 5σ significance
Fit without $f_0(1710)$ strongly disfavoured χ^2/ndf = 162/97



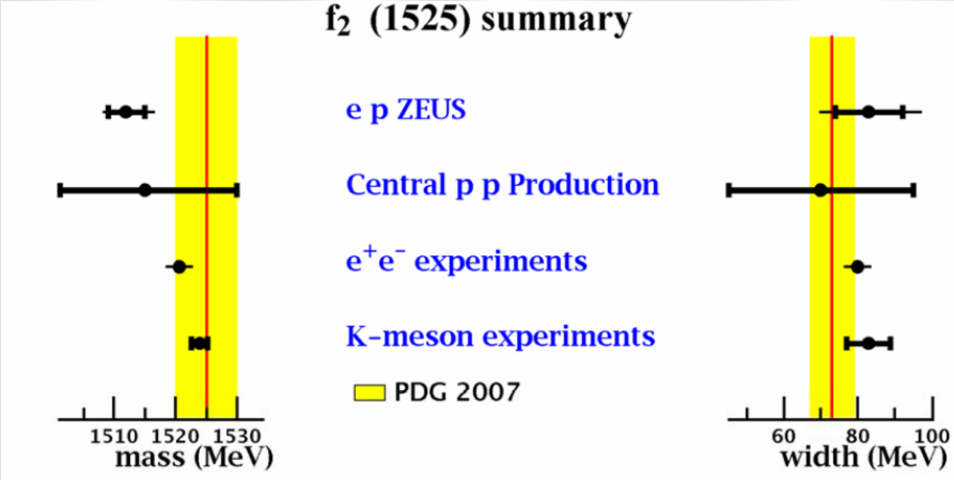
Results

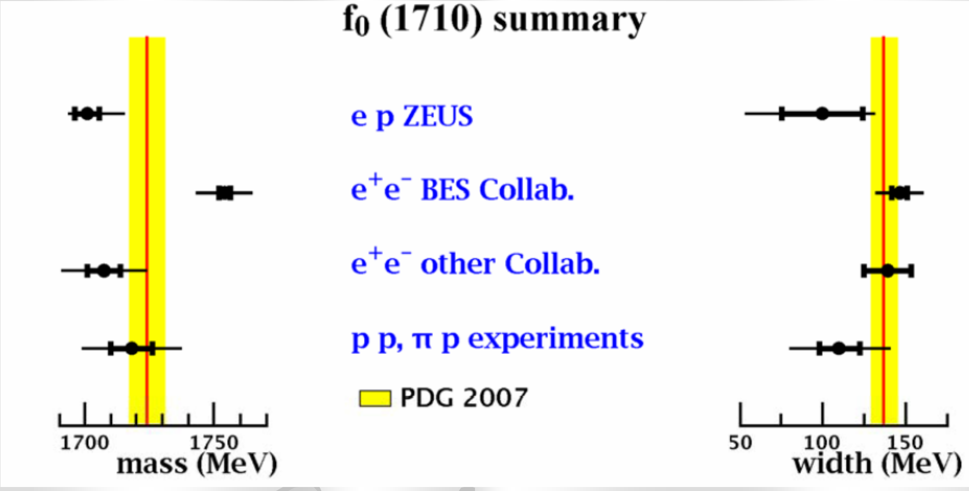
Fit	No interference		Interference		PDG 2007 Values	
χ^2/ndf	96/95		86/97			
in MeV	Mass	Width	Mass	Width	Mass	Width
$f_2(1270)$	1304 ± 6	61 ± 11	1268 ± 10	176 ± 17	1275.4 ± 1.1	$185.2^{+3.1}_{-2.5}$
$a_2^0(1320)$			1257 ± 9	114 ± 14	1318.3 ± 0.6	107 ± 5
$f_2'(1525)$	$1523 \pm 3^{+2}_{-8}$	$71 \pm 5^{+17}_{-2}$	$1512 \pm 3^{+1.4}_{-0.5}$	$83 \pm 9^{+5}_{-4}$	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 *f0*(1710): mass and width





Summary

- Sizeable production of the excited charm and charm-strange mesons was observed in *ep* interactions.
- 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
- measured D_1^0 helicity parameter h=5.9 consistent with prediction for pure *D*-wave.
- 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 hadronising into D_1^0, D_2^{*0} or D_{s1}^+ are consistent with obtained in e+e-, agreement with charm fragmentation universality;
- No radially excited $D^{*\prime}(2640)^{\pm}$ meson was observed.

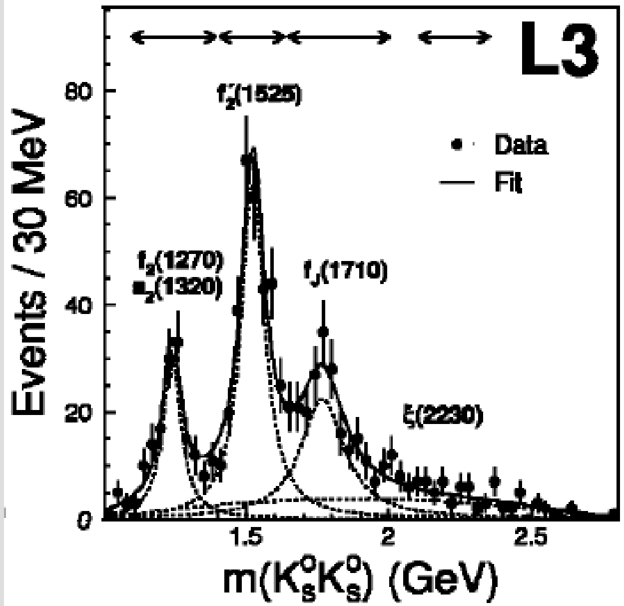
Summary(2)

- Observed three enhancements corresponding to $f_2(1270)/a_2(1320)$, $f_2'(1525)$ and $f_0(1710)$;
- $f_0(1710)$ with 5σ significance, has mass consistent with glueball candidate.
- No state observed heavier than f_0;
- Masses and widths of $f_2'(1525)$ and $f_0(1710)$ consistent with PDG;

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

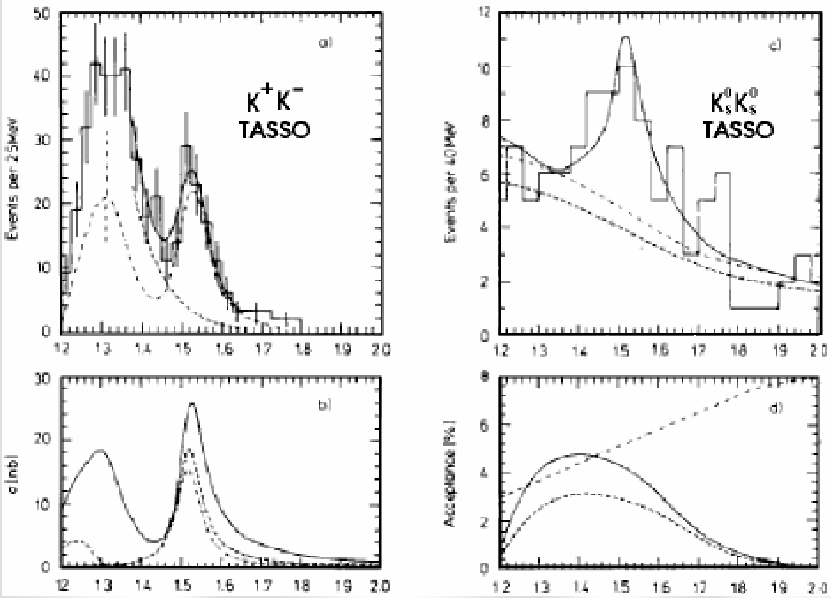
Maximum likelihood fit with 3 BW Functions plus 2nd order polynomial

$f_2'(1525)$ 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* $\gamma\gamma \rightarrow K^+K^-$, $K0sK0s$

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

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

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

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($K_S{}^0K_S{}^0$) spectra for an electromagnetic production process assuming SU(3) symmetry is H.J. Lipkin, private communication

$$F(m)=a\left[5\cdot\mathrm{BW}\left(f_2(1270)\right)-3\cdot\mathrm{BW}\left(a_2(1320)\right)+2\cdot\mathrm{BW}\left(f_2(1525)\right)\right]^2$$

$$+b\left[\mathrm{BW}\left(f_0(1710)\right)\right]^2+c\cdot\mathrm{background}$$

a, b, c are free parameters

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