Production of the excited charm mesons $D_1$ and $D_2^*$ at HERA

NPB 866, 229 (2013)

Andrii Verbytskyi, Kyiv Institute for Nuclear Research, on behalf of the ZEUS collaboration

DIS2013, Marseille, France
April 22, 2013
Introduction
Zeus at Hera

**HERA:**
- Collider experiments: H1 and Zeus;
- $ep$ collisions at $E_{CMS} = 318$ GeV.

**ZEUS:** $\sim 0.5$ fb$^{-1}$ collected data,
- $130$ pb$^{-1}$ between 1992 and 2000 (HERA-I);
- $370$ pb$^{-1}$ between 2003 and 2007 (HERA-II).
Heavy quarks at HERA

Boson-gluon fusion:

The goal is to obtain:

- all possible excited charm meson masses, widths and angular distributions;
- branching ratios;
- charm quark fragmentation fractions.

Up to $\sim 5 \times 10^9$ $c$-quarks: enough for ground and excited charm analysis.
Excited charm meson spectrum

Reconstructed states:
- $c\bar{u}$: $D_1^0(2420), D_2^{*0}(2460)$
- $c\bar{d}$: $D_1^{*+}(2420), D_2^{*+}(2460)$

The states were reconstructed in their decays to $D^0$, $D^{*+}$, $D^+$ ("ground" states) and pions.
Ground state reconstruction
Almost **90000** $D^{*+}$ candidates! Candidates from the mass window $(0.144 - 0.147$ GeV) are taken for the excited charm mesons analysis.
$D^+$ and $D^0$ reconstruction

\[ D^+ \rightarrow K^- \pi^+ \pi^+ \]
\[ D^0 \rightarrow K^- \pi^+ \]

ZEUSS

Combinations per 2 MeV

- ZEUS (373pb$^{-1}$)
  - Gauss$^{\text{mod.}+\text{bg.}}$
  - background

\[ N(D^*) = 39283 \pm 452 \]
\[ S(D^*) > 3 \]

MVD allows to use lifetime tagging of displaced vertices.
Neutral excited states
$D^{*+}\pi_\alpha^-$ and $D^+\pi_\alpha^-$ mass spectra and fit

The mass distributions $M(D^{*+}\pi_\alpha)$ and $M(D^+\pi_\alpha)$. The solid curves are the result of a simultaneous fit to the sum of:

- background contribution;
- $D_2^0$ and $D_1^0$ relativistic Breit-Wigner $\otimes$ resolution;
- $D(2430)^0$ and $D(2400)^0$ wide states relativistic Breit-Wigner $\otimes$ resolution.
$D^{*+}\pi_\alpha^-$ mass spectra in $\cos\alpha$ bins

The splitting into four bins helps to separate $D_1^0$, $D_2^{*0}$. Distribution in $\alpha$, the angle between $\pi_\alpha$ and $D^0$ in $D^{*+}$ CMS, is predicted to be

$$\frac{d\Gamma}{d\cos\alpha} \propto 1 + h \cos^2 \alpha,$$

where $h$ is a helicity parameter.
## Neutral states spectroscopy results

|                | HERA-II$^1$(this)        | HERA-I$^2$        | PDG$^3$   |
|----------------|------------------------|------------------|-----------|
| $M(D_1^0)$, MeV | 2423.1 ± 1.5$^{+0.4}_{-1.0}$ | 2420.5 ± 2.1 ± 0.9 | 2421.3 ± 0.6 |
| $\Gamma(D_1^0)$, MeV | 38.8 ± 5.0$^{+1.9}_{-5.4}$ | 53.2 ± 7.2$^{+3.3}_{-4.9}$ | 27.1 ± 2.7 |
| $h(D_1^0)$     | 7.8$^{+6.7+4.6}_{-2.7-1.8}$ | 5.9$^{+3.0+2.4}_{-1.7-1.0}$ |            |
| $M(D_2^{*0})$, MeV | 2462.5 ± 2.4$^{+1.3}_{-1.1}$ | 2469.1 ± 3.7$^{+1.2}_{-1.3}$ | 2462.6 ± 0.7 |
| $\Gamma(D_2^{*0})$, MeV | 46.6 ± 8.1$^{+5.9}_{-3.8}$ | 43 fixed         | 49.0 ± 1.4 |
| $h(D_2^{*0})$  | −1 fixed               | −1 fixed         |            |

---

$^1$H. Abramowicz et al. ZEUS Collaboration, *Production of the excited charm mesons $D_1$ and $D_2^{*}$ at HERA*, Nucl. Phys. B 866, 229-254, (2013).

$^2$S. Chekanov et al. ZEUS Collaboration, *Production of excited charm and charm-strange mesons at HERA*, Eur. Phys. J. C 60, 25, (2009).

$^3$J. Beringer et al., Particle Data Group Collaboration, *Review of Particle Physics (RPP)*, Phys. Rev. D 86 (2012) 010001.
Indication of $S$- and $D$-wave mixing

For mixed $S/D$-wave decay with the relative phase of $S$- and $D$-wave amplitudes $\phi$ and the fraction of $S$-wave $r = \frac{\Gamma_S}{\Gamma_S + \Gamma_D}$:

$$h = \frac{3(1-r-2\sqrt{2r(1-r)}\cos\phi)}{1+r+2\sqrt{2r(1-r)}\cos\phi}.$$
Charged excited states
$D^0\pi^+$ mass spectrum and fit

The solid curve is the result of a fit to the sum of:

- background contribution;
- $D_2^{*+}$ relativistic Breit-Wigner $\otimes$ resolution;
- $D_1^+$ and $D_2^{*+}$ feed-downs$^a$

$^a$Feed-downs, the peaking structures appearing in case of incomplete (e.g. missing $\pi^0$) reconstruction, are also used for measurements.

$N(D_2^{*+}) = 737 \pm 164$
$N(D_2^{*+})_{FD} = 634 \pm 223$
$N(D_1^+)_{FD} = 759 \pm 183$
$S(D^0) > 0$
Charged states spectroscopy results

|                       | HERA-II (this)      | PDG          |
|-----------------------|---------------------|--------------|
| $M(D_1^+)$, MeV       | $2421.9 \pm 4.7^{+3.4}_{-1.2}$ | $2423.4 \pm 3.1$ |
| $\Gamma(D_1^+)$, MeV | 25 fixed            | 25 ± 6       |
| $h(D_1^+)$            | 3 fixed             |              |
| $M(D_2^{*+})$, MeV    | $2460.6 \pm 4.4^{+3.6}_{-0.8}$ | $2464.4 \pm 1.9$ |
| $\Gamma(D_2^{*+})$, MeV | 37 fixed          | 37 ± 6       |
| $h(D_2^{*+})$         | $-1$ fixed          |              |

- Only few previous results on $D_1^+$ (BABAR and CLEO);
- Good agreement with PDG.
Fragmentation fractions and branching ratios
Fragmentation fractions for excited charm mesons

Fragmentation fraction:

\[ f(c \rightarrow D) = \frac{N(D)}{N(c)}. \]

Also:

\[ f(c \rightarrow D^{**}) = \frac{N(D^{**})}{N(c)} = \frac{N(D^{**})}{N(D)} f(c \rightarrow D). \]

Extra assumptions on branching ratios, e.g. on sum of charged modes:

\[ \mathcal{B}_{D_{2}^{*0} \rightarrow D^{+}\pi^{-}} + \mathcal{B}_{D_{2}^{*0} \rightarrow D^{*+}\pi^{-}} = \frac{2}{3}. \]
Fragmentation fractions

|                         | $f(c \to D_1^0)$ | $f(c \to D_2^{*0})$ | $f(c \to D_1^+)$ | $f(c \to D_2^{*+})$ |
|-------------------------|------------------|----------------------|------------------|----------------------|
| **HERA-II**             | $2.9 \pm 0.5^{+0.5}_{-0.5}$ | $3.9 \pm 0.9^{+0.8}_{-0.6}$ | $4.6 \pm 1.8^{+2.0}_{-0.3}$ | $3.2 \pm 0.8^{+0.5}_{-0.2}$ |
| **HERA-I**              | $3.5 \pm 0.4^{+0.4}_{-0.6}$ | $3.8 \pm 0.7^{+0.5}_{-0.6}$ |                  |                      |
| **OPAL$^3$**            | $2.1 \pm 0.7 \pm 0.3$ | $5.2 \pm 2.2 \pm 1.3$ |                  |                      |

- **ZEUS** measurements of fragmentation fractions are the most precise and supports fragmentation universality;
- First measurements of $f(c \to D_1^+)$ and $f(c \to D_2^{*+})$.

---

$^3$K. Ackerstaff et al., Production of P wave charm and charm - strange mesons in hadronic $Z^0$ decays, Z. Phys. C 76 (1997) 425
### Branching ratios

|                  | $\mathcal{B}_{D_2^{*0} \rightarrow D^+ \pi^-}$ | $\mathcal{B}_{D_2^{*+} \rightarrow D^0 \pi^+}$ |
|------------------|-----------------------------------------------|-----------------------------------------------|
| **HERA-II**      | $1.4 \pm 0.3^{+0.3}_{-0.3}$                  | $1.1 \pm 0.4^{+0.3}_{-0.2}$                  |
| **HERA-I**       | $2.8 \pm 0.8^{+0.5}_{-0.6}$                  |                                               |
| **PDG**          | $1.56 \pm 0.16$                              | $1.9 \pm 1.1 \pm 0.3$                       |
| **Model A**      | $2.280 \pm 0.007$                            | $2.266 \pm 0.015$                            |
| **Model B**      | $2.3 \ldots 3.0$                             |                                               |

---

4. P. Colangelo et. al., New meson spectroscopy with open charm and beauty, Phys. Rev. D 86 (2012) 054024
5. A. F. Falk and M. E. Peskin, Production, decay, and polarization of excited heavy hadrons, Phys. Rev. D 49 (1994) 3320 and others
Conclusions

The following quantities were measured using HERA-II data:

- masses of $D_1$ and $D_2^*$ states;
- widths of neutral states;
- the fractions of $c$-quarks hadronising into $D_1$ and $D_2^*$ (including one of the first measurements of the $D_1^+$);
- ratios of branching fractions of the two decay modes of the $D_2^{*0}$ and $D_2^{*\pm}$ states;
- helicity parameter of $D_1^0$, which favours mixing of $S$- and $D$-waves in its decays to $D^{*\pm}\pi^\mp$. 
Backup: 2D projected decay length significance

\[ l_{\text{proj.}xy} = \vec{P}_{xy}(\vec{r}_{\text{prim.}xy} - \vec{r}_{\text{sec.}xy}), \]

\[ S = \frac{l_{\text{proj.}xy}}{\sigma(l_{\text{proj.}xy})} \]
What are the feed-downs?

Feed-downs are peaking structures that appear in incomplete reconstruction.

The main condition for the feed-down appearance is an extremely restricted kinematic space for the missing particle.

The reconstructed invariant-mass signal will be shifted from the nominal value and slightly distorted.

A special procedure has been developed to measure the mass parameters from the feed-down signals.