Evidence for a Narrow Exotic Anti-Charmed Baryon State

Karin Daum
H1 Collaboration

Heidelberg, May 17

Outline:
- The strange sector — A motivation
- The experimentalist’s view — Where and how to search?
- The $D^*p$ signal — Detailed investigation
- The $D^*p$ signal — Signal assessment
- Conclusion
The particle zoo

Hundreds of hadrons can be grouped into:

- Meson: Made of quark-antiquark pairs
- Baryon: Made of three quarks

QCD does not forbid larger configurations. Particle Data Group 1986 reviewing evidence for exotic baryons states:

“...The general prejudice against baryons not made of three quarks and the lack of any experimental activity in this area make it likely that it will be another 15 years before the issue is decided.

PDG dropped the discussion on exotic baryon searches after 1988.
Exotic baryons

Particles with $B=1$ and $S=1$ could not be made of 3 quarks!

Several theoretical predictions

Problem: $\Gamma \approx \mathcal{M}$

1997: DPP Soliton model
$\mathcal{M}(\Theta^+) \approx 1530$ MeV, $\Gamma \approx 15$ MeV
**PDG was right!**

2003: LEPS at Spring-8 first evidence for $\Theta^+$
$M = 1540 \pm 10$ MeV,
$\Gamma < 25$ MeV

Restarting the quest for exotic particles

*It took more than 15 years*
The strange pentaquark $\Theta^+$

<table>
<thead>
<tr>
<th>No.</th>
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<th>Channel</th>
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Masses not very consistent

$\chi^2 = 4.6/\text{NDF}$

Sign of $S$ not determined

Minimal quark content: uudds

$B=1 \ & \ S=1$

\[ \downarrow \]

\[ \text{Result: uudds} \]
### The strange pentaquark $\Theta^+$

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- $\chi^2 = 4.6/\text{NDF}$
- Masses not very consistent

Sign of $S$ not determined

$B=1$ & $S=1$

Minimal quark content: $uudds$

- $M(\Theta^+) - M(K) - M(n) = 100 \text{ MeV}$
- Small natural width
Experimentalist's simple-minded picture of the strange pentaquark

(Motivation for the search in the charm sector)

- $\Theta^+$ produced by fragmentation from the vacuum
- It does not matter how the strange antiquark of the $\Theta^+$ has been produced
- Its properties (mass, lifetime) may possibly result from features of the QCD vacuum
- These features of the QCD vacuum are universal
  Since QCD is flavour blind, similar properties are expected for the charmed analogue of the $\Theta^+$
Where to look for the charmed pentaquark?

We need

A charmed meson

+ 

An antibaryon
Where to look for the charmed pentaquark?

Common belief:
\[ \Theta_c \rightarrow \overline{D} \ p \]
(pseudo-scalar D meson)

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<tr>
<th>Charm fragmentation fractions</th>
<th>$f(c \rightarrow D^+)$</th>
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Vector mesons not suppressed
Where to look for the charmed pentaquark?

Common belief:
\[ \Theta_c \rightarrow \bar{D} p \]
(pseudo-scalar D meson)

Golden channel: \( D^+ \rightarrow K^- \pi^+ \pi^+ \)
Vector mesons not suppressed

Golden channel: \( D^{*+} \rightarrow D^0 \pi^+ \rightarrow K^- \pi^+ \pi^+ \)

Charmed baryon
Vector meson

Charm fragmentation fractions

| \( f(c \rightarrow D^+) \) | \( \gamma p \) | 0.248 ± 0.014 +0.004−0.008 |
| | DIS | 0.202 ± 0.020 +0.029−0.023 |
| | \( e^+ e^- \) | 0.232 ± 0.010 |

| \( f(c \rightarrow D^0) \) | \( \gamma p \) | 0.557 ± 0.019 +0.005−0.013 |
| | DIS | 0.658 ± 0.054 +0.117−0.086 |
| | \( e^+ e^- \) | 0.549 ± 0.023 |

| \( f(c \rightarrow D_s^+) \) | \( \gamma p \) | 0.107 ± 0.009 ±0.005 |
| | DIS | 0.156 ± 0.043 +0.036−0.050 |
| | \( e^+ e^- \) | 0.101 ± 0.009 |

| \( f(c \rightarrow \Lambda_c^+) \) | \( \gamma p \) | 0.076 ± 0.020 +0.017−0.001 |
| | \( e^+ e^- \) | 0.076 ± 0.007 |

| \( f(c \rightarrow D^{++}) \) | \( \gamma p \) | 0.233 ± 0.009 +0.003−0.005 |
| | DIS | 0.263 ± 0.019 +0.031−0.042 |
| | \( e^+ e^- \) | 0.235 ± 0.007 |

But what is experimentally feasible?
Experimental Considerations

**D$^+$ pseudoscalar meson**

- **without lifetime tag**
- **with lifetime tag**

D$^+$: huge background or low yield

D$^*$ profits from small Q-value in D$^*$ decay

**D$^*$ vector meson**

D$^*$ → D$^0\pi$ → (K$\pi\pi$) $\pi$

D$^*$ experimentally much easier

Let's try this!

Mass difference technique  \( \Delta M(D^{*\pm}) = m(K^{\mp\pi^\pm\pi}) - m(K^{\mp\pi^\mp}) \)
H1 experiment at HERA

HERA storage ring at DESY

Electrons 27.6 GeV

Protons 920 GeV

H1 Detector
The H1 experiment at HERA

- **Liquid Ar Calorimeter**
- **“Spaghetti” Calorimeter**
- **Central Jet Chambers**

**Drift chambers, acceptance:** $150^\circ < \theta < 165^\circ$

Yields simultaneously charge and timing information

$B = 1.15 \ T \rightarrow$ measure transverse momentum of charged particles

→ Tracking, Particle ID via dE/dx
**HERA kinematics**

\[
E = 27.6 \text{ GeV}, \quad E_p = 920 \text{ GeV}
\]

**Kinematic variables**

- \( Q^2 \): 4-momentum transfer squared
- \( x \): Bjorken \( x \)
- \( y \): Electron inelasticity
- \( W \): Mass of the hadronic system

2 kinematic regimes:

- \( Q^2 \approx 0 \text{ GeV}^2 \): Photoproduction
- \( Q^2 > 1 \text{ GeV}^2 \): Electroproduction (DIS)
Both regimes equally well suited for the analysis?

Photoproduction (\(\gamma p\))

\[ \gamma p \]

\[ K^\pm \pi^\mp \]

\[ \text{wrong charge D} \]

\[ \text{Entries per 0.5 MeV} \]

\[ M(D^*) \ [\text{GeV}] \]

DIS much cleaner → base analysis on DIS → use \(\gamma p\) as cross check

\[ \Delta M_{D^*} \ [\text{GeV}] \]

1) Mass of same sign \(K^\pm \pi^\mp\) in \(m(D^0)\) window
First ingredient - the D* meson

- 1996 – 2000 Data $L_{int} = 75 pb^{-1}$
- DIS: $1 GeV^2 < Q^2 < 100 GeV^2$
  $0.05 < y_e < 0.7$
- $p_T (D^*) > 1.5 GeV$
- $-1.5 < \eta (D^*) < 1.$
- $p_T (K) + p_T (\pi) > 2 GeV.$
- Inelasticity $z(D^*) > 0.2$

Good Signal/Background

3400 D*’s in DIS to start with

D* signal region subsequently used
Second ingredient - the proton

- $dE/dx$ calibrated for 1996 to 2000 data
- Parameterization accurate to 3-5%
- 8% average resolution

Normalized likelihood based on: measured $dE/dx$ & expectations for $\pi$, $K$, $p$ and resolution:
$L(\pi)+L(K)+L(p) = 1$

Final proton selection: $(L(p)>0.1\&\&p(p)>2).or.L(p)>0.3$

Use $dE/dx$ for background suppression
The recipe for the $D^*-p$ search

- Looking for a **narrow state** near threshold
- Expected 4-particle mass resolution about 35 MeV not favourable for a narrow state → **use mass difference technique**: $m(D^*p) - m(D^*)$
- Cut on the **normalized proton likelihood** $L(p)$ for pion suppression
- Take a $D^*$ candidate add a track consistent with a proton and opposite charge of the $D^*$ using $m_p$ for its mass

↓

**Look what you get!**
D* + cc in DIS for 1996 - 2000

\[ M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG} \]

This is what we get!
D* p + cc in DIS for 1996 - 2000

\[ \mathcal{M}(D^* p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG} \]

1) Mass of same sign K^± \pi^± in m(D^0) window

2) Also no peak from CASCADE or Beauty MC

- Significant peak in opposite sign D*p
- No enhancement in wrong charge D
- No enhancement in D* MC (RAPGAP)

Background well described by D* MC and wrong charge D from data
Signal in both $D^{*-}p$ and in $D^{*+}\bar{p}$

$$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$$

$25.8 \pm 7.1$ Events  
$23.4 \pm 8.6$ Events

Signal of similar strength observed for both charge combinations at compatible $M(D^*p)$
**Typical Events**

HERA-I

HERA-II
Signal in like sign $D^{*+}p$?\[ M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG} \]

- No significant peak in like sign $D^*p$
- No enhancement in wrong charge $D$ \(^2\)
- No enhancement in $D^*$ MC (RAPGAP) \(^3\)

Reasonably described by $D^*$ MC and wrong charge $D$ from data

1) Charge conjugate always implied
2) Mass of same sign $K\pi$ in $m(D^0)$ window
3) Same results from CASCADE or Beauty MC
Signal region in $D^*-p$ richer in $D^*$?

1) Charge conjugate always implied

Clear band visible

Clear peak visible

$\Delta M(D^*) = m(K\pi\pi)p - m(K\pi\pi) + m(D^*)_{PDG}$

$M(D^*p) = m(K\pi\pi)p - m(K\pi\pi) + m(D^*)_{PDG}$
**Signal region in D^*-p**

**1) richer in D^*-?**

\[ \Delta M(D^*) \text{ [GeV]} \]

\[ M(D^* p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG} \]

1) Charge conjugate always implied
Signal region in $D^*p$ richer in $D^{*-}$?

Normalization to the width of the windows in $M(D^*p)$

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

1) Charge conjugate always implied
Is the $D^* - p^1)$ signal due to protons?

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

1) Charge conjugate always implied
Is the $D^*-p$ signal due to protons?

$M(D^*p) = 3.104 \pm 0.003$ GeV

$\langle L(p) \rangle = 0.92$

$M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG}$

1) Charge conjugate always implied

Use this region with $L(p) > 0.5$
Is the physics different in the signal region?

- Single particle momentum spectra are steeply falling → This feature is preserved in the combinatorial background of invariant mass analyses

- In decays particles are also emitted in the direction of flight → Particles from a decay should have a harder spectrum than the combinatorial background

Check the proton momentum!
Is the physics different in the signal region?

Fit slope with $\alpha \cdot \exp\{-\beta p(p)\}$

Look at the momentum of the proton candidate in the signal region and in the side bands w/o dE/dx cuts

The momentum spectrum of the particles in the signal region is harder than in the $M(D^*p)$ side bands

No $L(p)$ cuts!
Is the physics different in the signal region?

Fit slope with $\alpha \cdot \exp \{-\beta p(p)\}$

The momentum spectrum of the particles in the signal region is harder than in the $M(D^*p)$ side bands.
Signal at large \( p(p) \) more prominent?

Signal to background improves at larger proton momentum \( \rightarrow \) look at \( M(D^*p) \)
Signal to background improves at larger proton momentum → look at $M(D^*p)$

Signal at large $p(p)$ more prominent? YES!
**D*⁻p** in photoproduction

\[ M(D^*p) = 3.103 \pm 0.004 \text{ GeV} \]

Peak also observed in photoproduction

\[ M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*)_{PDG} \]

>95% of background due to non-charm

No enhancement in non-charm background

1) Charge conjugate always implied

Photoproduction more difficult due to large non-charm background

**independent confirmation of the signal**
Possible Background: \( \text{D}^*_1(2420)/\text{D}^*_2(2460) \rightarrow \text{D}^*\pi \) ?

- Loose \( \text{D}^* \) cuts & pion selection

\[
N(\text{D}^*_1+\text{D}^*_2) = 276 \pm 70
\]

- \( \text{D}^* \) cuts of \( \text{D}^*p \) & pion selection

- \( \text{D}^* \) cuts of \( \text{D}^*p \) & proton selection

- Compatible with MC expectation

\[
\mathcal{M}(\text{D}^*\pi) = m(K\pi\pi) - m(K\pi\pi) + m(\text{D}^*) \quad _{\text{PDG}}
\]

No cut in \( \text{D}^*p \)
Possible Background: $D_1(2420)/D_2(2460) \to D^*\pi$?

No cut in $D^*p$

$N(D_1 + D_2) = 3.5$ in the $D^*p$ signal region from MC

$\mathcal{M}(D^*\pi) = m(K\pi\pi\pi) - m(K\pi\pi) + m(D^*)_{PDG}$

Corrected for combinatorics. Then expect 3.5 events from data

$\frac{N(D_1 + D_2)}{N(D^*)} = 8\%$
**Basics of kinematic tests**

**2-Body Decay**

\[ M^2 = (P_1 + P_2)^2 \]

\[ = (m_{D^*}^2 + m_X^2 + 2E_{D^*}E_X - 2\vec{p}_{D^*}\vec{p}_X) \]

\( M^2 \) independent of decay angle \( \cos\Theta^* \) only for correct mass assignment

---

**Monte Carlo!**
**Basics of kinematic tests**

**2-Body Decay**

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\( M^2 \) independent of decay angle \( \cos\Theta^* \) only for correct mass assignment
Basics of kinematic tests

2-Body Decay

\[ M^2 = (P_1 + P_2)^2 = (m_{D^*}^2 + m_X^2 + 2E_{D^*}E_X - 2 \vec{p}_{D^*} \vec{p}_X) \]

**Do we see a band like structure in the \( M(D^*p) - M(D^*X) \) plane in data? → Let’s have a look**
Signal due to $D^*\pi$?

Back to data!

Band in $D^*\pi$ clearly visible
Signal due to $D^*_\pi$?

Go to the $D^*p$ signal region

No indication for contributions from $D_1$ and $D_2$
Signal due to $D^*\pi$?

**NO!**

Go to the $D^*p$ signal region

Sign for $X \rightarrow D^*p$: available phase space in $D^*\pi$ completely used
Lots of further kinematic test

• Reflections from a possible signal in $D^*K$ mass distribution: ruled out
• Possible contributions from $D^{*0} \rightarrow D^0 \gamma$ with $\gamma$-conversion: ruled out
• Possible contributions from $D_{S1}/D_{S2} \rightarrow D^0 K$: ruled out
• Possible peak structures in all possible mass correlations with all possible mass hypotheses of the particles making the $D^*$ and the $D^*p$ system to search for real or fake resonances, e.g. $\Lambda$, $\Delta^0$, $\Delta^{++}$, $K^0_S$, $\phi$, $f_2$
  no enhancements found
• Possible peak structures in all possible mass correlations among the proton candidate the remaining charged particles of the event with all possible mass assignments to search for real or fake peaks.
  no enhancements found
Signal assessment

Stability of result against all sorts of variations checked

In total about 90 $D^*p$ in DIS+$\gamma p$

Masses & widths from fits are consistent

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<td>12±3</td>
<td>50.6 ±112</td>
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<td>$D^{*-}p$ (DIS)</td>
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<td>$D^{**}\bar{p}$ (DIS)</td>
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<td>3103±4</td>
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<td>43 ±14</td>
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Significance estimation

- Significance estimate based on the background only hypothesis $N_b = 51.7 \pm 2.7$
- Use of different background functions as well as the background model from data and MC
- Significance determined in a binning free method
  → Background fluctuation probability $4 \times 10^{-5} \text{(Poisson)} \equiv 5.4 \sigma \text{ (Gauss)}$
  Change in likelihood of fits: $62 \sigma$

$N_s + N_b = 95 D^*p$ cand. within $2\sigma$

$N_b = 45.0 \pm 2.8$ from background + signal Hypothesis (fit)
Conclusions

- **H1 has observed a narrow resonance in both** $D^*-p$ **and** $D^{*-}p$ **with**
  
  $M(D^*p) = 3099 \pm 3\text{ (stat.)} \pm 5\text{ (syst.)}\text{ MeV}$
  
  $\sigma = 12 \pm 3\text{(stat.)}\text{ MeV}$

- **The background fluctuation probability is smaller than** $4 \times 10^{-8}$.

- **The signal is also observed in an independent photoproduction sample**

- **The signal region is richer in $D^*$ mesons and show a harder momentum spectrum of the proton candidates**

- **No simple explanation for this resonance could be found.**
  
  $\Rightarrow$ *It is interpreted as an anti-charmed baryon decaying to $D^*-p$ and its charge conjugate.*

- **Its quantum numbers are** $C=-1$ **and** $B=1$. **The minimal quark content is** $uudd\bar{c}$. **It is a candidate for a charmed pentaquark state.*
The strange pentaquark $\Theta^+$

$O(10k)$ $K^0$

$O(1M)$ $K^0$

\[ Q^2 \text{ small} \]

\[ Q^2 \text{ large} \]

ZEUS

$K_S^0 p(p)$

Q$^2 > 20$ GeV$^2$

$\sqrt{ }$ / ndf = 35 / 44
peak = 1521.5 $\pm$ 1.5 MeV
width = 6.7 $\pm$ 1.6 MeV
events = 221 $\pm$ 48

Only at large Q$^2$

$M (\text{GeV})$

$M(\pi^+\pi^-p) [\text{GeV}]$

[Graphs and data plots related to the strange pentaquark $\Theta^+$ are shown.]
Checks

• **Meanwhile 4 independent analyses**
  (whoever looks for it, verifies it)

• **Using 4 independent codes for the central analyses**
  (final $D^*$ selection and proton selection)

• **Based on 3 independent $D^*$ pre-selections**

• **With 2 different methods** (mass difference technique / constrained fit)

• **Signal observed in DIS and photoproduction**

• **In independent running periods**

• **All events in the signal region scanned independently**
The very first look at D*-p

- Look for a narrow state near threshold
- Expected 4-particle mass resolution about 35 MeV → use mass difference: \( m(D^*p) - m(D^*) \) \(^1\)
- Cut on the normalized proton likelihood \( L(p) \) for pion suppression

\( \text{Take a } D^* \text{ candidate add a track consistent with a proton using } m_p \) 
\( D^* \text{ selection as used for } F_C \text{ 96/97 analysis } \& L(p) > 5\% \)

Narrow enhancement about 150 MeV above threshold: real or fake?
Does some acceptance effect fool us?

Proton efficiency

\[ M(D^*p) = m(K\pi\pi p) - m(K\pi\pi) + m(D^*) \] (PDG)

Good p efficiency

Smooth variation with \( M(D^*p) \)
Shape reflects opening of phase space
Lots of further kinematic test

- Reflections from a possible signal in $D^*K$ mass distribution:
- Possible contributions from $D^{*0} \rightarrow D^0 \gamma$ with $\gamma$-conversion:
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- Possible peak structures in all possible mass correlations among the proton candidate the remaining charged particles of the event with all possible mass assignments to search for real or fake peaks.
Lots of further kinematic test

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• Possible contributions from $D^{*0} \rightarrow D^0\gamma$ with $\gamma$-conversion: ruled out
• Possible contributions from $D_{S1}/D_{S2} \rightarrow D^0 K$: ruled out
• Possible peak structures in all possible mass correlations with all possible mass hypotheses of the particles making the $D^*$ and the $D^*p$ system to search for real or fake resonances, e.g. $\Lambda$, $\Delta^0$, $\Delta^{++}$, $K_S^0$, $\phi$, $f_2$: no enhancements found
• Possible peak structures in all possible mass correlations among the proton candidate the remaining charged particles of the event with all possible mass assignments to search for real or fake peaks: no enhancements found