Recent Results from H1

evidence for an anti-charmed baryon state

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on behalf of the H1 collaboration

Outline:

• Deep inelastic scattering at HERA
• Charm production
• Search for an anti-charmed baryon state
• Signal checks and significance estimate
• Summary
The HERA accelerator

$E_e = 27.6 \text{ GeV}$

$E_p = 920 \ (820) \text{ GeV}$

ep collisions at $\sqrt{s} \approx 300-320 \text{ GeV}$

DESY
Hamburg
Germany
Deep-inelastic scattering (DIS) kinematics

- **DIS kinematics:**
  - pairs of Lorentz invariants:
    - 4-momentum transfer squared: $Q^2 = -q^2$
    - Bjorken scaling variable: momentum fraction of proton carried by quark $x = Q^2/(2qP)$
    - inelasticity $y = qP/kP$
    - mass of the hadronic system $W^2 = (P + q)^2$

- **Kinematic regimes:**
  - $Q^2 > 1 \text{GeV}^2$: DIS scattered e in detector
  - $Q^2 < 1 \text{GeV}^2$: Photoproduction, $\gamma p$ scattered e in beampipe

- $E_e = 27.6 \text{ GeV}$
- $E_p = 920 \ (820) \text{ GeV}$
- $\sqrt{s} \approx 300-320 \text{ GeV}$
Physics at HERA

Main aim:
structure of the proton and
precision tests of
strong interactions (QCD)

properties of QCD:
• scaling violations
• asymptotic freedom

→ Nobel prize 2004
“for the discovery of asymptotic
freedom in the theory of strong
interactions”
D.J. Gross, H.D. Politzer, F. Wilczek
Charm Production at HERA

heavy quark mass:
charm no constituent of the proton in our kinematic range

→ copius production from gluon in the proton

charm production is dominated by Boson Gluon Fusion (BGF) in LO:
\[ \gamma g \rightarrow cc \text{ (bb)} \]
Charm Production at HERA (II)

Charm contribution to total cross section

ratio of structure functions: $F_2^{\text{cc}}/F_2$
large, going up to $\sim 30\%$

HERA is a charm factory
Pentaquark searches

Search inspired by evidence for exotic narrow resonances in K+n
= candidates for strange pentaquark state $\theta^+$

**Why not charm?**

Assume: $\theta^+$ produced by fragmentation from vacuum
- features of QCD vacuum are universal
- QCD is flavour blind
expect similar properties as for $\theta^+$ for a charmed pentaquark

look for exotic baryonic charm resonance
e.g. combine charm meson with baryons
e.g. D* with protons
H1 detector at HERA

Central drift chamber CJC rec. of D*, protons

backward electromagnetic calorimeter SpaCal rec. of scattered e

D*p event in DIS
D* signal

Golden decay channel:

\[ \text{D}^*+ \rightarrow \text{D}^0 \; \pi^+_s \rightarrow \text{K}^- \; \pi^+ \; \pi^+_s \; (+ \text{c.c.}) \]

low branching ratio, but clean signal

\[ \text{M(D}^*) - \text{M(D}^0) = 145.4 \text{ GeV} \]

Q-value: 5 MeV

- apply “mass difference method”:
  \[ \Delta \text{M(D}^*) = \text{M(K} \; \pi \; \pi_s) - \text{M(K}\pi) \]

- Estimate combinatorial bgr (non charm):
  replace \( \text{D}^0 \rightarrow \text{K}^- \; \pi^+ \)
  by 2 same charge tracks

“wrong charge D”:

fake \( \text{D}^0 \; (K^+ \; \pi^+/ K^- \; \pi^-) + \pi_s \)

DIS events:

- 96-00 data, Lumi 75 pb\(^{-1}\)
- scattered electron in calorimeter
- \( 1 < Q^2 < 100 \; \text{GeV}^2, \; 0.05 < y < 0.7 \)
Proton selection

Particle identification via energy loss dE/dx

Resolution for minimal ionizing particles ~8%

most probable dE/dx: phenomenological parameterisation (Bethe Bloch)
combining $D^*$ mesons and protons

3400 $D^*$ selected:

$\Delta M(D^*)$ mass window: $\pm 2.5$ MeV

Now we have: reconstructed $D^*$ mesons and protons (from dE/dx)
what do we get if we combine them?
opposite sign D*p invariant mass distribution

Apply mass difference technique
\[ M(D^*p) = m(K\pi\pi\pi) - m(K\pi\pi) + M_{PDG}(D^*) \]

narrow resonance at
\[ M = 3099 \pm 3 \text{(stat.)} \pm 5 \text{ (syst.) MeV} \]

2 bgr contributions:

- **charm**: real D* with random track
  estimated with MC

- **non charm**: estimated by wrong charge D

charm and non-charm bgr:
- no enhancement in D* Monte Carlo
- no enhancement in wrong charge D

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

Signal visible in both charges D*-p and in D**+\bar{p} with similar strength and compatible mass

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

\[ M = 3102 \pm 3 \text{ MeV} \]

\[ M = 3096 \pm 6 \text{ MeV} \]

charm and non-charm bgr:
- no enhancement in D* Monte Carlo
- no enhancement in wrong charge D

Background well described by D* MC and “wrong charge D” from data
Signal visible also in like sign D* p?

Data consistent with background estimation.

No significant peak in like sign D* p.

Charmed and non-charmed bgr:
- No enhancement in D* Monte Carlo.
- No enhancement in wrong charge D.

Background well described by D* MC and “wrong charge D” from data.
Signal visible also in like sign D*p?

data consistent with background estimation

No significant peak in like sign D* p

No!

charm and non-charm bgr:
- no enhancement in D* Monte Carlo
- no enhancement in wrong charge D

Background well described by D* MC and “wrong charge D” from data
Signal faked by reconstruction problem?

Typical D* p candidates:

All signal events visually scanned – no anomalies
Signal faked by reconstruction problem?

Typical $D^*p$ candidates:

All signal events visually scanned – no anomalies \textbf{No!}
Does Resonance come from $D^*$?
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$\Delta M(D^*)$ in $D^*p$ – signal region and sidebands:

- $D^*p$ signal region is richer in $D^*$ than sidebands

Side band scaled to the width of the signal window in $M(D^*p)$ no further normalization!

$D^*p$ signal region is richer in $D^*$ than sidebands
Does Resonance come from D*?

\[ \Delta M(D^*) \text{ in } D^*p - \text{signal region and sidebands:} \]

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

\[ D^*p + D^{*+}\bar{p} \]

**H1**

- **D^*p Side bands**
- **D^*p signal region**

Side band scaled to the width of the signal window in \( M(D^*p) \) no further normalization!

D^*p signal region is richer in D* than sidebands \( \text{Yes!} \)
Does resonance come from protons?

Use well identified protons with
- $p(p) < 1.2$ GeV
- $dE/dx > 1.15$
- good $dE/dx$ particle identification

Signal is there for well identified protons

$M(D^*p) = 3104 \pm 3$ MeV
Does resonance come from protons?

Use well identified protons with:
- $p(p) < 1.2$ GeV
- $dE/dx > 1.15$
- good $dE/dx$ particle identification

$M(D^*p) = 3104 \pm 3$ MeV

Yes!

Signal is there for well identified protons
on and off resonance kinematics

- **single charged particles:**
  - momentum spectrum steeply falling!
    preserved in combinatorial bgr

- **Particles from decay:**
  - Lorentzboost
  - particles may be emitted in direction of flight

Harder momentum spectrum expected for particles from decay
on and off resonance kinematics

- Single charged particles:
  - Momentum spectrum steeply falling!
  - Preserved in combinatorial bgr

- Particles from decay:
  - Lorentzboost
  - Particles may be emitted in direction of flight

Harder momentum spectrum expected for particles from decay

Check assumption using D*:
- $\pi_S$ momentum spectrum harder for D* than for wrong charge D bgr!

How does it look for protons from D* p?

Example: $\pi_S$ from D* (looser selection)
on and off resonance kinematics

momentum distribution of proton candidates (no particle identification)

better S/B for higher momenta? D*+p combinations for p(p)>2GeV (no proton selection)

Proton momentum spectrum harder for signal region than for sidebands

prominent signal is visible

No dE/dx!
Independent confirmation? Photoproduction analysis

\[ \gamma p, Q^2 < 1 \text{GeV}^2 \]

- Total: 4900 D*
- D*p peak at the same mass in \( \gamma p \)
- larger bgr than in DIS
  non-charm bgr dominant (95%)
  well described by wrong charge D
- no enhancement in non-charm bgr

non-charm bgr dominant
no enhancement in wrong charge D

independent confirmation of the signal
Signal significance

**Signal+background fit:**
- Mass: \(3099 \pm 3\text{(stat)} \pm 5\text{(syst.)}\) MeV
- Width: \(12 \pm 3\) MeV
  (consistent with experimental resolution)

**Numbers of signal and background:**
- \(N_b = 45.0 \pm 2.8\)
  (within \(\pm 2\sigma = \pm 24\) MeV)
- \(N_s = 50.6 \pm 11.2\)
  (1.46 \(\pm 0.32\) % of D* yield, uncorrected in acceptance)

**Background fluctuation probability (52 \(\rightarrow\) 95):**
- \(4 \times 10^{-8}\) (Poisson)
- \(5.4\) \(\sigma\) (Gauss)

**For significance estimate:**
- **bgr only hypothesis fit**
  - \(N_b = 51.7 \pm 2.7\)
  - Events in signal region: 95
Summary

- evidence for a neutral anti-charmed baryon state decaying to $D^*p$ in deep-inelastic scattering

- signal is due to $D^*$ and protons
- harder proton momentum spectrum observed in the signal region than in sidebands as expected for decay
- Independent confirmation of signal in photoproduction

- probability for signal due to background fluctuation:
  $4 \times 10^{-8}$ (Poisson) corresponding to $5.4 \sigma$ (Gauss)

- directly comparable experiment: ZEUS
  controversy between ZEUS and H1 not settled
Backup slides
## Details of fit

<table>
<thead>
<tr>
<th>Charges</th>
<th>M[MeV]</th>
<th>[MeV]</th>
<th>$N_S$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^<em>-p + D^{</em>+}\bar{p}$</td>
<td>3099 ± 3</td>
<td>12 ± 3</td>
<td>50.6 ± 11.2</td>
</tr>
<tr>
<td>$D^*-p$</td>
<td>3102 ± 3</td>
<td>9 ± 3</td>
<td>25.8 ± 7.1</td>
</tr>
<tr>
<td>$D^{*+}\bar{p}$</td>
<td>3096 ± 6</td>
<td>13 ± 6</td>
<td>23.4 ± 8.6</td>
</tr>
</tbody>
</table>
check events
• signal events scanned visually: no anomalies
• double entries?
  1.) Within +- 24 MeV around peak: 1 double entry
  2.) All M(D*p) < 3.6 GeV: 1.12 entries / event

signal from D*,p?
• backward D* analysis: signal region D* rich
• well identified protons (p<1.2, hard dE/dx): signal there
  average norm. likelihood in signal region <L_p>=0.92

physics in signal and bgr region?
• physics on/off resonance: proton spectrum harder on resonance

peak stable?
• signal present in subsamples (in Q^2, x, y, η, p_t, data taking period)
• variations of binning and selection: mass, width stable
• signal present in photoproduction
All Checks (II)

signal from bgr or from D*, protons?
• wrong charge D bgr instead of real D*: no peak
• D* sidebands instead of ΔM(D*) signal window: no peak
• K, π selected (via dE/dx) instead of protons (p-mass assigned): no peak
• Kπ combinations with masses above region where charm contributes: no peak

check reflections
• protons assigned K, π mass: no peak
• Invariant masses m(pK), m(pπ), m(pπs) and all other possible 2-particle masses: no res. structures
• reflections from D10, D20*: expected contribution (MC): 4 evts (±24MeV)
• Signal due to D*0→D0γ→D0 e+ e−? no (electrons misidentified as πs and proton)
D* signal in DIS and photoproduction

- DIS cleaner signal
- photoproduction: supporting evidence
Acceptance effects?

Proton efficiency

Smooth variation with $M(D^*p)$
Shape reflects opening of phase space

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

“Pion survival probability”

Good p efficiency
Reflections from decays to $D^{*}\pi$?

$D_1^0$, $D_2^{0*} \rightarrow D^{*}\pi$

loose $D^*$ cuts

$\pi$ selection

$D_1^0$, $D_2^{0*} \rightarrow D^{*}\pi$

$D^*$ cuts of $D^*p$

$\pi$ selection

$D^*$ cuts of $D^*p$

proton selection

$D_1$, $D_2$ window

Expect 3.5 decays ($D_1^0$, $D_2^{0*} \rightarrow D^{*}\pi$) in $D^*p$ signal
Reflections from decays to $D^*_\pi$?

$D_1^0, D_2^{0*} \rightarrow D^*_\pi$

Signal for $X \rightarrow D^*_p$: available phase space in $D^*_\pi$ completely used

Within $\pm 24$ MeV around $D^*_p$ signal: 4 events from $D_1^0, D_2^{0*}$ expected
Could signal be due to decay $D^{0*} \rightarrow D^0 \gamma$?

$D^{0*} \rightarrow D^0 \gamma \rightarrow D^0 e^+e^-$
- asymmetric in energy
- misidentified as proton and $\pi_s$?

No accumulation at small $m_{ee}$ in $D^*p$ signal region or elsewhere.
Non observation at ZEUS

D* decay channels:

\[ D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow K^- \pi^+ \pi_s^+ \quad (+ c.c.) \]
\[ D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow K^- \pi^+\pi^+\pi^- \pi_s^+ \quad (+ c.c.) \]

> 60000 D*

DIS (Q^2>1GeV^2) and photoproduction (Q^2<1GeV^2)
1995-2000 data, 127 pb^-1

No peak observed
results not compatible with H1

Upper limit on R(\(\theta_0^c \rightarrow D^*p/D^*\)) : 0.35%
(both channles, Q^2>1GeV^2)