Strangeness, Charm and Beauty Production at HERA

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on behalf of the ZEUS and H1 Collaborations

OUTLINE

Introduction
Strangeness production
Charm production
Beauty production
Summary

PHIPSI Workshop, Oct 13-17, Beijing, China
The HERA Collider

✓ two large multipurpose experiments: H1 and ZEUS
✓ running ended mid 2007 after about 2500 days of activity and ~500 pb⁻¹ of integrated luminosity per experiment

The HERA Kinematics

e p

ep c.m. energy: \( s = (P+k)^2 \)
\( \gamma^* p \) c.m. energy: \( W = (P+q)^2 \)

exchanged momentum squared (photon virtuality) \( Q^2 = -q^2 = -(k-k')^2 \)

\( Q^2 \approx 0 \text{ GeV}^2 \) → photoproduction
\( Q^2 > 1 \text{ GeV}^2 \) → electroproduction (DIS)
Strangeness Production at HERA

- $K_S$
- $\Lambda$, $\bar{\Lambda}$
- $K^*(892)$
- $\phi$
- Inclusive $K_S K_S$ resonance
**K_S Production**

**HERA I data:** 1999-2000, 50pb⁻¹  
2<Q²<100 GeV²  
0.1<y<0.6

- σ_{vis}(ep → eK_S X)=21.18 ± 0.09 ^{+1.19}_{-1.23} nb
- CDM λ_s =0.3 for Q², η and p_T
- MEPS λ_s =0.2 for Q²
- shape of η and low p_T show difficulties

**K_S differential cross section in laboratory frame**
$\Lambda, \bar{\Lambda}$ Production

HERA I data: 1999-2000, 50pb$^{-1}$
$2<Q^2<100$ GeV$^2$
$0.1<y<0.6$

- $\sigma_{\text{vis}}(ep \rightarrow \Lambda X) = 3.96 \pm 0.06^{+0.23}_{-0.24}$ nb
- $\sigma_{\text{vis}}(ep \rightarrow \bar{\Lambda} X) = 3.94 \pm 0.07^{+0.23}_{-0.24}$ nb
- CDM $\lambda_s = 0.3$ for $Q^2$
- shape of $\eta$ and low $p_T$ show difficulties

H1 differential cross section in laboratory frame
**K* and φ production**

HERA I data: 2000, 37 pb⁻¹
- Q² < 0.01 GeV²
- 0.5 < pₜ (K*₀, φ) < 7 GeV

HERA II data: 2005-2007, 302 pb⁻¹
- 5 < Q² < 100 GeV²
- 0.1 < yₑX < 0.6
- 0.5 < pₜ (K*±) < 7 GeV

Clear K*₀, K*± and φ are observed

\[ \sigma_{\text{vis}} (ep \rightarrow K^0X) = 6260 \pm 350 \pm 860 \text{ nb} \]
\[ \sigma_{\text{vis}} (ep \rightarrow \phi X) = 2400 \pm 180 \pm 340 \text{ nb} \]
\[ \sigma_{\text{vis}} (ep \rightarrow K^{*\pm}X) = 7.36 \pm 0.09 \pm 0.9 \text{ nb} \]
Inclusive $K_SK_S$ resonance

- HERA I + HERA II data: $\sim 500\text{pb}^{-1}$
  - dominated by photoproduction 90%, while 10% by DIS
  - clear KS signal $\sim 1260000$
  - signal region: $481 < M(\pi^+\pi^-) < 515 \text{MeV}$

Three clear enhancements, $f_2(1270)/a_2(1320)$, $f_2(1525)$ and $f_0(1710)$, were observed.

The mass and width of $f_2(1270)/a_2(1320)$, $f_2(1525)$ and $f_0(1710)$ are compatible with PDG value.

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Width</th>
<th>PDG08</th>
<th>Mass</th>
<th>Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_2(1270)$</td>
<td>$1268\pm10$</td>
<td>$176\pm17$</td>
<td></td>
<td>$1275.4\pm1.1$</td>
<td>$185.2^{+3.1}_{-2.5}$</td>
</tr>
<tr>
<td>$a_2(1320)$</td>
<td>$1257\pm9$</td>
<td>$114\pm14$</td>
<td></td>
<td>$1318.3\pm0.6$</td>
<td>$107\pm5$</td>
</tr>
<tr>
<td>$f_2(1525)$</td>
<td>$1512\pm3^{+1.4}_{-1.5}$</td>
<td>$83\pm9^{+5}_{-4}$</td>
<td></td>
<td>$1525\pm5$</td>
<td>$73^{+6}_{-5}$</td>
</tr>
<tr>
<td>$f_0(1710)$</td>
<td>$1701\pm5^{+9}_{-2}$</td>
<td>$100\pm24^{+7}_{-22}$</td>
<td></td>
<td>$1724\pm7$</td>
<td>$137\pm8$</td>
</tr>
</tbody>
</table>
Charm Production at HERA

- D* in photoproduction
- Excited charm and charm-strange production
D* in Photoproduction

- HERA II data: 93pb⁻¹
- Kinematic range
  - $Q^2 < 2$ GeV²
  - $100 < W < 285$ GeV²
  - $p_t(D^*) > 1.8$ GeV
  - $|\eta(D^*)| < 1.5$

Differential cross sections as functions of $p_t(D^*)$ and $\eta(D^*)$

- Data in reasonable agreement with NLO predictions (FMNR and GMVFNS)
- GMVFNS too steep in $p_t$, slightly different shape in $\eta$
Excited charm and charm-strange mesons production

the large charm production cross sections at HERA also offers a unique place to study excited charm and charm-strange mesons

\[ D_1(2420)^0 \rightarrow D^{*+}\pi^- \quad J^P=1^+ \]
\[ D^*_2(2460)^0 \rightarrow D^{*+}\pi^-, D^+\pi^- \quad J^P=2^+ \]
\[ D_s(2536)^+ \rightarrow D^{**}K_S, D^0K^+ \quad J^P=1^+ \]
\[ D^*(2640)^+ \rightarrow D^{*+}\pi^+\pi^- \quad J^P=?? \]

- HERA I data: 126 pb\(^{-1}\)
- DIS and photoproduction
Excited charm and charm-strange mesons production

**Excited charm mesons**

\[ D^0_1 \rightarrow D^{*0}_2 \rightarrow D^* \pi \]

\[ N(D^0_1/D^{*0}_2) = 3110 \pm 340 \]

\[ N(D^0_1/D^{*0}_2) = 870 \pm 170 \]

difficult to separate \( D^0_1 \) and \( D^{*0}_2 \)

**Excited charm strange mesons**

\[ D^+_{s1} \rightarrow D^{*+} K^0_s \]

\[ N(D^+_{s1}) = 100 \pm 13 \]

\[ D^{*0}_{s2} \rightarrow D^0 \pi \]

\[ N(D^{*0}_{s2}) = 690 \pm 160 \]

\[ D^0_1 \rightarrow D^0 K^\pm \]

\[ N(D^0_1) = 136 \pm 27 \]

due to spin parity conservation \( D^0_1 \) can NOT decay in this mode
Excited charm and charm-strange mesons production

<table>
<thead>
<tr>
<th></th>
<th>$f(c \rightarrow D_1^0)(%)$</th>
<th>$f(c \rightarrow D_2^0)(%)$</th>
<th>$f(c \rightarrow D_{s1}^+)(%)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZEUS</td>
<td>$3.5 \pm 0.4^{+0.4}_{-0.6}$</td>
<td>$3.8 \pm 0.7^{+0.5}_{-0.6}$</td>
<td>$1.11 \pm 0.16^{+0.08}_{-0.10}$</td>
</tr>
<tr>
<td>OPAL</td>
<td>$2.1 \pm 0.7 \pm 0.3$</td>
<td>$5.2 \pm 2.2 \pm 1.3$</td>
<td>$1.6 \pm 0.4 \pm 0.3$</td>
</tr>
<tr>
<td>ALEPH</td>
<td></td>
<td></td>
<td>$0.94 \pm 0.22 \pm 0.07$</td>
</tr>
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</table>

- the HERA rates are in reasonable agreement with those measured in others ($e^+e^-$) experiments
  
  - No radial excited $D^*(2640)^+$ observed
  
  - Upper limit:
    $f(c \rightarrow D^*)B(D^* \rightarrow D^+\pi^+\pi^-)<0.4\%$
  
  - OPAL result : $<0.9\%$
  
  - MC signal normalized to the upper limit
Beauty Production at HERA

- Beauty in Dijet PhP using electrons
- Beauty in Dijet PhP using muons
- Beauty in PhP using inclusive secondary vertexing
Beauty in Dijet PhP using electrons

- HERA I data: 120 pb$^{-1}$
- Kinematic range
  - $Q^2<1$ GeV$^2$
  - Dijet events with $E_T>7(6)$ GeV
- Likelihood analysis used to separate $b\rightarrow e$ from $c\rightarrow e$ and uds

NLO QCD prediction describes the shape well
- HERA II data
- ZEUS: 124pb\(^{-1}\), H1: 171pb\(^{-1}\)
- Similar kinematic range
  - \(Q^2<1\) GeV\(^2\)
  - Dijet events with \(E_T>7(6)\) GeV

- Simultaneous fit of the impact parameter \(\delta\) and \(p_T^{rel}\)
  - allows to separate b from c, light flavor background
Beauty in Dijet PhP using muons

- Compatible with previous measurements
- NLO calculations provide reasonable good description of data
Beauty in PhP using inclusive secondary vertexing

- HERA II data: 128pb⁻¹
- Dijet events with \( p_T^{\text{jet}} > 7(6) \) GeV
- Decay length significance \( S = \frac{d}{\delta d} \)
- For large \( m_{\text{vtx}} \) dominated by beauty
  → with cuts on \( S \) and \( m_{\text{vtx}} \) an almost pure beauty sample can be obtained

Good agreement between data and MC

Beauty-enriched \( m_{\text{vtx}} \) and multiplicity distributions
Beauty in PhP using inclusive secondary vertexing

Good agreement between data and NLO QCD predictions

Differential cross-sections in $P_T^{\text{jet}}$ and $\eta^{\text{jet}}$

ZEUS (prel.) 128 pb$^{-1}$

PYTHIA x 1.12

NLO QCD $\otimes$ had

$\frac{d^2\sigma}{dP_T^{\text{jet}} d\eta^{\text{jet}}}$ (pb)
Cross sections for b production extrapolated using NLO calculations

- The results are consistent with previous measurements
- General good agreement with NLO QCD predictions
Summary

- Inclusive $K_S,\Lambda,K^*(892)$ and $\phi$ productions have been studied.
- Three clear enhancements, $f_2(1270)/a_2(1320)$, $f_2(1525)$, and $f_0(1710)$, clearly observed in inclusive $K_SK_S$ mass spectrum.
- The masses and widths are compatible with PDG values.

- $D^*$ production studied in photoproduction regime.
- Excited charm and charm-strangeness mesons were observed in ep collision.
- The fragmentation rates are compatible with those measured in other experiments.
- No radial excited $D^{*'}(2460)$ meson was observed.

- Beauty production measured using different experimental techniques.
- Good description achieved with NLO calculations in all measurements.
Many thanks for your attention!
Hadronization of $s$ from the proton sea

$\gamma^*s \rightarrow s$ (QPM) or $\gamma^*s \rightarrow sg$ process

- rate of the boson-gluon fusion (BGF) $\gamma^*s \rightarrow ssbar$

- hadronization process alone contributes to the strangeness production

- Allows the investigation of strong interactions in the perturbative and non-perturbative process
- strange hadron production is not known to be well described by MC models
- ssbar production parameterized by the strangeness suppression factor
D* in photoproduction

Double-differential cross sections

Good agreement between data and NLO predictions
Except for high pt, high η region
Inclusive $K_S K_S$ resonance


Motivations
- the Standard Model allows for the existence of color singlet glueball
- the $K_S K_S$ system is expected to couple to scalar and tensor glueball
- Lattice QCD predicates that the lightest glueball has $J^{PC}=0^{++}$ and lies in the mass region 1550 - 1750 MeV

HERA I + HERA II data: $\sim 500 \text{pb}^{-1}$
- dominated by photoproduction 90%, while 10% by DIS
- clear $K_S$ signal $\sim 1260000$
- signal region: $481 < M(\pi^+\pi^-) < 515$ MeV
No. of fitted $f_0(1710)$  
$4058 \pm 820 \sim 5\sigma$ significance

- peak around 1.3 GeV suppressed due to destructive interference between $f_2(1270)$ and $a_2(1320)$
- The dip between $f_2(1270)/a_2(1320)$ and $f_0(1500)$ is well reproduced
Charm Production at HERA

main process:

- direct $\gamma$
- boson gluon fusion

0.8 < $x_{\gamma}^{\text{obs}}$ < 1

other processes:

- resolved $\gamma$ processes
- 0 < $x_{\gamma}^{\text{obs}}$ < 0.8

key points:

- $m_Q$ (or $E_T^{\text{jet}}$ …) >> $\Lambda_{\text{QCD}}$
  ⇒ region of applicability of pQCD
- collinear vs. $k_T$ parton dynamics

photoproduction (PHP) regime ⇔ scattered electron is undetected ⇔ $Q^2 < 1 \text{ GeV}^2$
Heavy quark production at HERA

Dominant process: **boson-gluon fusion**

**Kinematic Variables:**

- \( Q^2 = -q^2 = (k-k')^2 \) \hspace{1cm} Neg. squared momentum transfer (virtuality of exchanged boson)
- \( s = (k+p)^2 \approx 4E_e E_p \) \hspace{1cm} CM Energy, at HERA \( \sqrt{s} = 318 \text{ GeV} \)
- \( x = Q^2 / 2p \cdot q \) \hspace{1cm} Bjorken scaling variable: momentum fraction of parton interacting with lepton in infinite momentum frame (QPM)
- \( y = p \cdot q / p \cdot k \) \hspace{1cm} Inelasticity: lepton momentum fraction transferred to boson in proton rest frame

**Kinematic Regimes:**

- Deep Inelastic Scattering (DIS): \( Q^2 > 1 \text{ GeV}^2 \)
- Photoproduction (PHP): \( Q^2 < 1 \text{ GeV}^2 \) (\( Q^2 \sim 10^{-3} \), quasi-real \( \gamma \))

**Why study heavy quark production at HERA?:**

- **Test of perturbative QCD** due to the hard scale given by the heavy quark mass.
- **Study of multi-scale problem:** often mass scales compete with other hard scales \( (p_T, Q^2...) \), additional theoretical uncertainties enter.
- **Better understanding of structure of the proton**
- Semileptonic decay: 
  \( ep \rightarrow e'bX \rightarrow e'jj + eX \)

- \( b \)-fraction extracted from likelihood fit using variables sensitive to \( e^- \) identification and semileptonic decays

Likelihood \( \mathcal{L}_{i,j} = \alpha_i(p_T, \eta) \cdot \mathcal{P}(dE/dx) \cdot \mathcal{P}(E_{ECAL}/E_{tot}) \cdot \mathcal{P}(E_{cal}/p_{trk}) \cdot \alpha_j(p_T, \eta) \cdot \mathcal{P}(\Delta(p_T, p_{trk})) \cdot \mathcal{P}(p_{rel}) \)
• Beauty with electron
Tagging semileptonic beauty decays

1) $p_T^{rel}$: $p_T$ of $\mu$ with respect to jet axis

2) impact parameter of $\mu$ (or h) with respect to primary vertex
   (H1: all, ZEUS: HERA II only)

3) $D^*\mu$ and $\mu\mu\mu$ correlations
Tagging Beauty with $\mu+$jets (I)

- Semileptonic decay:
  $$ ep \rightarrow e'bX \rightarrow \mu jjX $$

- Separate b from c and uds:
  - Large b mass $\rightarrow$ large muon $P_T^{rel}$
  - Large b lifetime $\rightarrow$ large muon impact param. $\delta$

$\rightarrow$ Simultaneous 2-dim $P_T^{rel}$ and $\delta$ fit
  (enhanced statistics and reduced syst.errors)
Inclusive secondary vertexing

Fit mirrored and subtracted decay length significance ($S^+ - S^-$) in bins of the secondary vertex mass