Strange particle production at HERA

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- Motivation
- Inclusive strange particle production
- Bose - Einstein correlations
- Pentaquarks
- Summary
Inclusive Deep Inelastic Scattering at HERA: $e p \rightarrow e' X$

Kinematics of DIS

$s$: e-p c.m. energy, $\sqrt{S} \approx 300 - 318$ GeV

$Q^2 = -q^2$, 4-momentum transfer squared

$x$: fraction of p momentum carried by quark

$y$: inelasticity parameter

$W$: $\gamma p$ c.m. energy

$Q^2 \sim 0$: photoproduction

Multihadron (including strange particles) description:

Analytical QCD + LPHD hypothesis approach
Monte Carlo QCD based models: ARIADNE + JETSET / PYTHIA HERWIG

Data:

- identified separate hadrons and resonances
- multihadron production

Soft processes can be studied in:

- photoproduction
- hadronisation
Strange particle studies in DIS

- Strange hadron production in particularly baryons - not well understood
- Universal strange particle fragmentation?
  - ratio baryon to meson production
  - baryon and antibaryon production difference
- Comparison with other particle interaction processes
- Is the strangeness suppression factor different in e⁺e⁻ and ep interactions?
- If the space-time characteristics of emission source are different for strange particles?
- Does radius of emission volume depend on hadron mass?
Strange particle production

Strange quark production: possible mechanisms

- Flavour excitation - hard scattering of sea quark
- Gluon-splitting
- Boson - gluon fusion
- Heavy quark decay

Next step: fragmentation to hadrons - non perturbative process
Fragmentation models

ARIADNE plus JETSET

- QCD parton cascade: Color Dipol Model
- Lund string fragmentation

Strangeness suppression factor:
\[ \lambda_S = \frac{P(s)}{P(u)} ; \quad P(u) = P(d) \]

HERWIG

- Parton shower
- Production and decay colour singlet clusters
Neutral strange particles

- Differential cross sections
- Baryon to antibaryon production asymmetry
- Baryon to meson ratio

**ZEUS**

Reasonable description of x-sections by ARIADNE

- No baryon antibaryon asymmetry
- Rise of baryon to meson ratio for decreasing $x$
- ARIADNE underestimates low $x$ region

- No baryon anti-baryon asymmetry
- Small access in baryon to meson ratio over the ARIADNE at small $Q^2$
Cross sections: $p_T$ and $\eta$ dependence – Lab frame

- ARIADNE overestimates $K_S^0$ rate for small $p_t$
  - ratio baryon / meson underestimated in MC
- No significant baryon - antibaryon asymmetry
- ARIADNE overestimates $K_S^0$ production
- No baryon - antibaryon asymmetry
- Baryon to meson ratio: some rise in forward (proton fragmentation) region?
Strange particles - Breit frame fragmentation studies

Breit frame

Target \[ P_Z > 0 \] \[ P_Z \rightarrow Q \] \[ P_Z < 0 \]

Separates struck quark (current hemisphere) and proton remnant (target hemisphere)

Fragmentation studies based on scaled momentum distribution \[ x_p = \frac{2p}{Q} \]

Current region is analogous to single hemisphere of e^+e^- annihilation

Studies: comparison \[ x_p \] distributions for \[ \Lambda, \bar{\Lambda} \] and \[ K_S^0 \] with different MC - Ariadne (CDM) - for different \[ \lambda_S \] and HERWIG

For current region agreement with CDM is reasonable already for \[ \lambda_S = 0.2 \]

For target region CDM distribution closer to data for \[ \lambda_S = 0.3 \]

CDM is more sensitive for changes of \[ \lambda_S \]

Strangeness suppression related to gluon density in the proton remnant?

L. Zawiejski Strange particle production at HERA ISMD2005 August 10 2005
Breit frame - ratio $\Lambda / K^0_S$ measurements

In current region:

reasonable agreement with ARIADNE (CDM) Monte Carlo for $\lambda_S = 0.2$

different behaviour for HERWIG

In target region:

problem with description of the ratio as function of $p_T^{\text{Breit}}$ - an effect of reconstructed $\Lambda$ in Lab?

similar trend for $x_p$ dependence in data and ARIADNE MC - but smaller values

Larger value: $\lambda_S \approx 0.3$ is expected

More statistics is necessary
Bose-Einstein correlations in \( K^\pm \) and \( K^0_S K^0_S \) pairs

BE effect for pairs of identical bosons: symmetrization wave-function \( \rightarrow \) interference effect – enhancement in the bosons production with similar momenta.

**BE effect:**
- related to the space-time characteristic of the particle emission source
- gives information about hadronisation process
  - emission volume measured in different reactions: ee ep hh AA
  - radius dependence of the emission volume on the produced hadron mass

**Experimentally:** BE correlation function can be measured from two-particle distribution \( R \):

\[
R(Q_{12}) = \frac{P(Q_{12})}{P_{\text{ref}}(Q_{12})}
\]

as function of the 4-momenta difference of the two particles: \( Q_{12} = \sqrt{-(p_1 - p_2)^2} \)

- normalized density distribution of the number of identical boson-pairs in measured / reference sample (no BEC)

Standard parametrisation of \( R \): **Goldhaber parametrisation:**

\[
R(Q_{12}) \propto (1 + \lambda \exp(-r^2Q_{12}^2))
\]

(assuming spherical emitting source)

**extraction from fit to data:**
- \( r \) - radius of the emitting source
- \( \lambda \) - strength of the effect - degree of incoherence
  (0 – fully coherent, 1 fully incoherent)
Use double ratio method with mixed sample pairs of Kaons from different events

\[
R(Q_{12}) = \frac{P(Q_{12})_{\text{data}}}{P(Q_{12})_{\text{MCnoBEC}}} = \frac{P(Q_{12})_{\text{data}}}{P_{\text{mix data}}(Q_{12})} = \frac{P(Q_{12})_{\text{MC}}}{P_{\text{mix MCnoBEC}}(Q_{12})}
\]

\[
\lambda = 0.31 \pm 0.06 + 0.09 - 0.06 \text{ (syst.)}
\]

\[
r = 0.57 \pm 0.09 \text{ (stat.)} + 0.15 - 0.06 \text{ (syst.)}
\]

Similar to previous ZEUS result for charged pions:

\[
r_\pi = 0.666 \pm 0.009 \text{ (stat.)} + 0.022 - 0.036 \text{ (syst.)}
\]

Smaller \( \lambda \) in comparison to \( e^+e^- \to \) data populate mostly proton remnant fragmentation region

Strong signal of \( \phi^0(1020) \) resonance in data -> it is possible that at least one kaon in pairs coming from \( \phi^0 \)
BEC - $K_S^0K_S^0$ pairs

**BE effect clearly visible**

$r = 0.61 \pm 0.08 + 0.07 - 0.08$ (syst.)

$\lambda = 1.16 \pm 0.29 + 0.28 - 0.08$ (syst.)

$r$ value for $K_S^0$ in good agreement with $K^\pm$

large $\lambda \rightarrow$ low $Q_{12}$ affected

mainly by $f^0(980)$ resonance which not well described by simulation.

Agreement with $e^+e^-$ (LEP) for radius

$\lambda$ value larger than for ALEPH and DELPHI

and more similar to OPAL

Influence of $f^0(980)$:

removed by ALEPH and DELPHI
Dependence of BEC radius on hadron mass

Experimental indication:

\[ r(m_\pi) > r(m_K) > r(m_p) > r(m_\Lambda) \]

Theory \(^{123}\):

- LUND model does not predict such dependence of \( r(m) \)
- Heisenberg uncertainty relations and QCD via virial theorem can describe such mass dependence

But the situation is not so clear:

\( r \) values for pions and kaons are not so different and the effect comes from heavier particles → more precise measurements from different processes are necessary

HERA results on protons and \( \Lambda \) will be available soon

QCD allows for 5–quarks hadronic states. These exotic states so-called pentaquarks with $4\,q + \bar{q}$ can be produce as bound "stable" (colourless) particles.

Support from Theory - an example:
Chiral quark soliton model → antidecuplet pentaquarks

D. Diakonov et al. (Z. Phys. A.359 (1997) 305) : lightest member: narrow ($\Gamma < 15 \text{ MeV}$) exotic state
This so-called $\Theta^+$ pentaquark has mass $\approx 1530 \text{ MeV}$ and includes an anti-strange quark $uudd\bar{s}$
Possible decays: $\Theta^+ (1530) \rightarrow K^+ n$ or $K^0 p$

Other possible 5-quarks states:
• two strange quarks like $\Xi_{3/2}^- (ddss\bar{u})$ and $\Xi_{3/2}^0$ decaying into $\Xi$ and charged pions

Search for pentaquarks in high energy ep collisions by ZEUS / H1
Strange pentaquark $\Theta^+$ - DIS / photoproduction studies

$e^\pm p \rightarrow e^\pm \Theta^+ X \rightarrow e^\pm K^0_S p X$

$K^0_S p$ decay mode: well reconstructed $K^0_S$ and proton

**ZEUS**

- 121 pb$^{-1}$

**H1**

- 71 pb$^{-1}$

$K^0_S$ reconstruction:
- $K^0_S \rightarrow \pi^+\pi^-$ using secondary vertex
- $p_t(K^0_S) > 0.3 \text{ GeV} , |\eta(K^0_S)| < 1.5$
- remove Dalitz $e^+e^-$ pairs and $\Lambda$'s

Proton reconstruction:
- tracks from primary vertex
- $dE/dx$ identification:
  - ZEUS - band method and
cuts: $dE/dx > 1.15 , p < 1.5 \text{ GeV}$
  - H1 - likelihood method - $dE/dx$ -
momentum can be $> 1.5 \text{ GeV}$

Mass resolution for $K^0_S p$:
- ZEUS - 2.4 MeV
- H1 - 5 MeV

An example: band method
Positive results for $\Theta^+$

<table>
<thead>
<tr>
<th>Group</th>
<th>Reaction</th>
<th>Mass</th>
<th>Width</th>
<th>$\sigma$ s</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEPS</td>
<td>$\gamma C \rightarrow K^+K^- X$</td>
<td>1540 +10</td>
<td>&lt; 25</td>
<td>4.6</td>
</tr>
<tr>
<td>DIANA</td>
<td>$K^+Xe \rightarrow K^0p X$</td>
<td>1539 + 2</td>
<td>&lt; 9</td>
<td>4.4</td>
</tr>
<tr>
<td>CLAS</td>
<td>$\gamma d \rightarrow K^+K^0p(n)$</td>
<td>1542 +5</td>
<td>&lt; 21</td>
<td>5.2</td>
</tr>
<tr>
<td>SAPHIR</td>
<td>$\gamma p \rightarrow K^+K^0(n)$</td>
<td>1540 +6</td>
<td>&lt; 25</td>
<td>4.8</td>
</tr>
<tr>
<td>ITEP</td>
<td>$\nu A \rightarrow K^0p X$</td>
<td>1533 +5</td>
<td>&lt; 20</td>
<td>6.7</td>
</tr>
<tr>
<td>CLAS</td>
<td>$\gamma p \rightarrow \pi^+K^-K^+(n)$</td>
<td>1555 +10</td>
<td>&lt; 26</td>
<td>7.8</td>
</tr>
<tr>
<td>HERMES</td>
<td>$e^+d \rightarrow K^0p X$</td>
<td>1528 +3</td>
<td>13 +9</td>
<td>~5</td>
</tr>
<tr>
<td>ZEUS</td>
<td>$e^+p \rightarrow e'K^0p X$</td>
<td>1522 +3</td>
<td>8+4 (5)</td>
<td>~5</td>
</tr>
<tr>
<td>SVD</td>
<td>$pA \rightarrow K^0pX$</td>
<td>1526 +3</td>
<td>&lt; 10</td>
<td>5.5</td>
</tr>
<tr>
<td>COSY</td>
<td>$pp \rightarrow K^0p\Sigma^-$</td>
<td>1530 +5</td>
<td>&lt; 18</td>
<td>4-6</td>
</tr>
</tbody>
</table>

But also negative results from many experiments:

- BES, Belle, BaBar, HERA-B, CDF, PHENIX, SPHINX, HyperCP, CLAS, H1

new results - final conclusion? - important for understanding physics of strong inter.
DIS: $Q^2 > 20 \, \text{GeV}^2$

- evidence for narrow peak near $1522 \, \text{MeV}$ (4.6 $\sigma$ signal)
- with $\Gamma = 8 \pm 4 \, \text{MeV}$


**Photoproduction:** $\Theta^+$ is absent $\rightarrow$

- significant combinatorial background and multiplicity can lead to small ratio $S/B$

For DIS this ratio was 10 times larger

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Fit: Double-Gaussian + background function

Use $\Lambda_c^+ \rightarrow K^0_s \, p$ peak (2285) for photoproduction and DIS to calculate signal to background ratio

**place for $\Theta^+$**
**$\Theta^+$ production properties: $\Theta^+$ and $\Lambda(1520)$**

Negative result from $e^+e^-$ may indicate that ZEUS signal is related to proton fragmentation

Check: studies in different pseudorapidity regions: forward and rear, comparison of $K^0_S p$ signal with reconstructed $\Lambda(1520)$ from u,d,s fragmentation

$\Lambda(1520) \rightarrow K^\pm p p$

Region with significant proton remnant fragmentation

Region dominated by pure fragmentation

$\Theta^+$ - produced mostly at forward rapidity hemisphere $\eta_{LAB} > 0$ and $Q^2 > 20$ GeV$^2$ - $\Lambda(1520)$ behaviour is different

Does the production of $\Theta^+$ involve the diquark fragmentation mechanism?  

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1. S. Chekanov, hep-ph/0502098
H1: \( Q^2 > 5 \text{ GeV}^2, \ 0.1 < y < 0.6 \)
ZEUS: \( 0.01 < y < 0.95 \)

Visible range:
\( p_T(K_S^0p) > 0.5 \text{ GeV}, \ |\eta(K_S^0p)| < 1.5 \)

No signal - upper limit on \( \sigma(\Theta) \) assuming quark fragmentation of \( \Theta^+ \)
In other analysis low-momentum protons (< 1.5 GeV as in ZEUS) were used - better proton purity.

Still negative result
- statistics lower than in ZEUS
- more data is needed

Upper limit on $\Theta^+$ cross section for $20 < Q^2 < 100$ GeV$^2$
- does not contradict to the ZEUS observation: $\sigma(\Theta^+) \sim 120$ pb for $Q^2 > 20$ GeV$^2$
ZEUS results:
search for $\Xi_{-3/2} (ddss\bar{u})$ decaying to $\Xi^-\pi^- (\Xi^-\pi^+)$

Na49 – observation:
narrow peak at $1862 \pm 2$ MeV
$\Gamma < 18$ MeV

Reconstrucion of candidate:
- $\Lambda$ (secondary vertex)
- tracks with small DCA from $\Lambda$
- $\Xi$ + pions from primary vertex

No evidence for NA49 pentaquark

Upper limit: $R = \Xi_{-3/2}^{-1(0)} / \Xi^0(1530) \sim 0.2 - 0.5$
Summary

Strange particles provide good test of hadronization models:

- HERWIG does not describe the shape of the measured cross sections
- ARIADNE provides better description of the data but fails for some kinematic regions:
  - underestimates the baryon-to-meson ratio at lower x and in the target region of the Breit frame
  - overestimates pseudorapidity distribution of $K^0_s$ in almost whole $\eta$ region
- For quark fragmentation region data suggests a smaller $\lambda_s$ value than for target region where Monte Carlo description is not good
- No significant baryon antibaryon asymmetry was found
- The radius of the particle emission volume for kaons is consistent with pions and with LEP
  - measurements for heavier particles are necessary to clarify the $r$ dependence on the hadron mass

Pentaquarks

- Search for signal of the exotic narrow state was positive for $\Theta^+$ strange pentaquark for ZEUS and negative for H1
- No evidence for heavy strange pentaquark was found by ZEUS

Hoping to solve this puzzle with help of high statistics expected for HERA II
Thank you
\[ \Theta_c^0 = uuddc \]

Searches in effective mass

\[ M(D^*-p) \text{ (+ c.c.) spectra} \]

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

DIS : \(1 < Q^2 < 100 \text{ GeV}^2\)

H1 data sample : 75 pb\(^{-1}\) proton candidate - likelihood method - dE/dx energy lost

Photoproduction : \(Q^2 \leq 1 \text{ GeV}^2\)

Narrow resonance seen in DIS and photoproduction events

Mass = 3099 ± 3 (stat) ± 5 (syst.), the measured Gaussian width : 12 ± 3 (stat.)

\( \Theta_c^0 - H1 : \) fragmentation investigations

Possible production of \( D^*p(3100) : \) photon-gluon fusion PGF process

Baryon to meson \( \sigma(D^*p) / \sigma(D^*) \) ratio:
- well described by RAPGAP MC as function of event kinematics \( (Q^2, W, \text{subsys. energy}) \)
- indication for suppression baryon production \( D^*p \) relative to \( D^* \) in central rapidity region

Fragmentation study: use the similar method as for charm fragmentation function: in \( \gamma^*p \) frame particles projected into plane perpendicular to \( \gamma^* \) direction; divide the event into 2 hemisphere defined by \( D^* \) direction and calculate in hemisphere the hadronisation variable
\[
x_{\text{obs}}(D^*p,D^*) = \frac{(E - p_z)(D^*p,D^*)}{\Sigma_{\text{hem}}(E-p_z)}
\]

An example:

Rise for decreasing \( x_{\text{obs}} \rightarrow \) meson \( D^* \) originating from \( D^*p(3100) \) softer than inclusive \( D^* \) expected for decay of real particle \( D^*p \)

The \( D^*p(3100) \) fragmentation function is rather hard - behaviour expected for charmed hadrons
No evidence for $\Theta_c^0$ was found in more than 60000 $D^*$ candidates also after application the H1 selection criteria.