Radiation hardness of the ZEUS MVD frontend chip
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Chapter 7

Strangeness production

At HERA very precise measurements of the structure functions of the proton have been made. The contributions of some quark types have also been measured. Measurement of the strangeness distributions in the proton is difficult since the strange quark is very light. Strange particles are thus not only produced in the hard-scattering process but also copiously in the fragmentation that follows.

Here it was chosen to measure $K^0_s$ in charged current events. In these events a struck $s$ quark will be transformed into a $c$ quark, which has a high probability to form a $D$-meson. This meson has a large inclusive branching ratio ($\sim 25\%$) to $K^0_s$. The $K^0_s$ channel was also chosen since it has a relatively large $c\tau$ value. Hence, it will produce secondary vertices and will therefore be one of the first particles to be looked for with the MVD.

The $K^0_s$ is reconstructed by determining the invariant mass of two tracks under the assumption that both tracks are pions. With different mass assignment, this method also allows the reconstruction of $\phi$ and $\Lambda$. $K^{*\pm}$-mesons can be found by combining a reconstructed $K^0_s$ with a charged track assuming it is a pion. Results on the production of these particles will also be shown.

7.1 Studying the strange sea in the proton

Naively the proton consists of three valence quarks, two $u$ quarks and one $d$, connected via gluons. However, the quarks can radiate extra gluons and the gluons can split into two other gluons or a quark-antiquark pair. The (anti-)quarks produced this way are referred to as sea quarks. They can be of all types and exist only for a short time, $\Delta \tau \sim \frac{\hbar}{m_q}$. Therefore, the sea will mainly exist of the light quarks $u, d, s$ (and their antiquarks).

The strange quark content of the sea can be extracted by combining results from neutral current scattering and charged current scattering on nuclear targets[35]. The strangeness distribution has for instance been obtained by combining data from muon-iron scattering.
measured by the NMC collaboration[36] and neutrino-nucleon scattering measured by the CCFR collaboration[37].

Using isospin symmetry, the structure function $F_2$ in muon-nucleon scattering can be expressed as

$$F_2^{\mu N} = \frac{1}{2} \left( F_2^{\mu p} + F_2^{\mu n} \right) = \frac{5}{18} \left[ u + \bar{u} + d + \bar{d} + \frac{2}{5} (s + \bar{s}) \right]$$  \hspace{1cm} (7.1)

Averaging $W_2$ in both neutrino and antineutrino scattering yields

$$\frac{1}{2} \left( W_2^{\nu N} + W_2^{\bar{\nu} N} \right) = x (u + \bar{u} + d + \bar{d} + s + \bar{s})$$  \hspace{1cm} (7.2)

The strangeness distribution is then obtained as

$$\frac{1}{2} x \left| s(x) + \bar{s}(x) \right| = \frac{5}{12} \left( W_2^{\nu N} + W_2^{\bar{\nu} N} \right) - 3F_2^{\mu N}$$  \hspace{1cm} (7.3)

This is only valid for values of $Q^2$ where $\gamma$ exchange dominates in muon-nucleon scattering.

A different way to extract the strangeness distribution is to use neutrino scattering events in which a charmed particle is produced. Charmed particles are hardly produced in fragmentation, due to the large mass of the charm quark, hence the $W^\pm$ must have coupled to a strange (anti-)quark in the sea. This method has been used by the CCFR collaboration. After reanalysis of the data, both methods show good agreement of the strange quark distributions.

In the analysis of the strangeness distribution it is commonly assumed that the momentum distributions of the $s$ and $\bar{s}$ are the same. But this does not have to be the case[38]. For $q\bar{q}$ pairs that arise directly from gluon splitting the quark and antiquark distributions have to be the same. But only the net strangeness number of the proton has to be zero. When there is intrinsic strangeness in the proton, the $s$ and $\bar{s}$ can move freely through the proton. The proton can then fluctuate in a meson-baryon pair. To keep it together both velocities have to be the same. Hence, when the proton fluctuates into a $K^+(u\bar{s})\Lambda(uds)$ pair, the momentum of the $s$ must be larger than that of the $\bar{s}$ since the mass of the $\Lambda$ is larger than the mass of the $K^+$. The presence of this intrinsic strangeness can be confirmed or excluded by measuring the helicity distributions for $\Lambda$ and $\bar{\Lambda}$.

### 7.1.1 Strangeness suppression

Strangeness production in fragmentation in $e^+e^-$ is well described by string fragmentation[39]. In this model, the probability to produce a quark-antiquark pair is proportional to $exp \left(-\pi m_q^2/\kappa\right)$, where $m_q$ is the quark mass and $\kappa$ the string tension. Assuming that the probability for quarks to form a hadron is proportional to $exp \left(-E_{\text{bind}}/T\right)$, with the
Chapter 7. Strangeness production

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<td>G.T. Jones et al. [47]</td>
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<tr>
<td>$p\bar{p}$</td>
<td>$0.40\pm0.05$</td>
<td>CDF [48]</td>
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Table 7.1: Overview of measured values for the strangeness suppression factor.

The binding energy $E_{\text{bind}} = M_h - \sum_i m_{q_i}$ and effective temperature $T$, hadron production can be expressed as

$$N = C (2J + 1) \gamma_s^{N_s} e^{-\frac{E_{\text{bind}}}{T}}$$ \hspace{1cm} (7.4)$$

where $C$ is a normalisation constant, $J$ the spin, $N_s$ the number of strange quarks in the hadron and $\gamma_s = \exp(-\pi (m_s^2 - m_Q^2)/\kappa)$ the strangeness suppression factor. This model\[40\] describes the light flavoured hadron production at LEP well.

Fitting the production rates of various mesons, it is found that the mass of the $s$ quark is larger than the mass of the $u$ and the $d$. Using this model the quark pair production rates may be estimated as $u : d : s : c = 1 : 1 : \frac{4}{3} : 10^{-11}$. In Monte Carlo models the reduced production of strangeness with respect to up or down is controlled by a variety of parameters like the strangeness suppression factor and a correction factor to get the ratio of vector and pseudo-scalar particles correct. The strangeness suppression factor has been measured in many experiments and in many ways, e.g. by measuring the ratios $\frac{K_s^0}{\rho^0+\omega}$, $\frac{K^{*+}}{\rho^0+\omega}$, $\frac{2\phi}{K^{0*}}$, $\frac{2\phi}{K^{*0}}$ or $\frac{K^+}{\pi^+}$ at high momentum. The values measured at LEP are usually close to 0.3. A compilation can be found in [40]. However, at HERA mostly lower values are obtained; typically 0.2 for $K_s^0$ and even lower when using $\Lambda$. In neutrino-scattering and in $p\bar{p}$-collisions values between 0.2 and 0.4 have been found indicating that the description using a strangeness suppression factor is not very accurate outside of $e^+e^-$, see table 7.1.

7.1.2 Studying the strange sea at HERA

Studying the strange sea at HERA is relatively difficult. Strange particles can be produced in various ways, see figure 7.2. A strange quark can be produced in boson-gluon fusion, it can be struck directly in the proton sea or originate from a gluon that is radiated by a struck quark. Furthermore, since the strange quark is such a light quark, strange particles are easily produced in hadronization or in decays. Therefore, it is very hard to distinguish strange particles that have an $s$-quark originating from the hard interaction.
One way, in neutral current scattering, is to study strange particles in the Breit frame\[49\]. The Breit frame is a Lorentz frame where the virtual photon is space-like and the incoming (massless) quark is scattered on a “brick wall”, see figure 7.1. The maximum momentum a scattered quark can have in this frame is (by definition) $Q/2$. The important variables describing particle production are the scaled momentum fraction, $x_p \equiv 2P_{tot,b}/Q$, and the transverse momentum, $P_{T,b}$. When an interaction between the virtual photon and a quark in the proton occurs, like in figure 7.2(b), the hadron that includes the struck quark will thus be found mostly in the region of large $x_p$ and low $P_{T,b}$. This will be discussed in more detail in section 8.3.2.

This has been shown to work for $\phi$ production \[50\]. In figure 7.3 the differential cross section for $\phi$ production is shown as a function of $x_p$. The measurement was performed in the kinematic region $10 < Q^2 < 100 \text{ GeV}^2$. For $x_p > 0.8$ the data overshoots the Monte Carlo without intrinsic strangeness, excluding the process shown in figure 7.2(b), significantly. Including this process in the Monte Carlo improves the correspondence in this region.

Intuitively, strangeness could be studied by looking for strange particles carrying a large fraction of the jet energy. But as can be seen in figure 7.4 (taken from \[51\] where the fragmentation function is presented at next-to-leading order) a particle containing the jet initiating strange quark only carries typically a very small fraction of the struck quarks momentum. The fraction of particles carrying more than 5% of the struck strange quark is $\int_{0.05}^{1} x D_{s}^{(K^{0}+\bar{K}^{0})} dx \approx 16\%$ at $Q^2 = 225 \text{ GeV}^2$. On the other hand, approximately 0.2% of the $K^{0}_{s}$'s will carry a momentum fraction larger than 0.75 of the struck quark.

Another way is analogous to the CCFR method. In charged current events, where a $W^{\pm}$-boson interacts with an $s$-quark, the outgoing quark will be a charm quark. The resulting charmed meson can be reconstructed in some cases. The standard method is to make use
of the small mass difference of only 145 MeV between the $D^*$ and the $D^0$ via the decay
\[
D^{*\pm} \rightarrow D^0\pi^\pm \rightarrow K^\pm\pi^+\pi^\pm \\
\rightarrow K_s^0\pi^+\pi^\pm \\
\rightarrow K^{*\pm}\pi^\pm \rightarrow K_s^0\pi^+\pi^\pm \\
\rightarrow K_s^0\phi\pi^\pm 
\]
However, this method has a small efficiency (of the order of 1%).

Of the strange particles, the $K_s^0$ is relatively straightforward to measure. It has a large lifetime and therefore many $K_s^0 \rightarrow \pi^+\pi^-$ will have a displaced vertex. The $\Lambda$ is found as a background in the $K_s^0$ sample. But $\Lambda$ and $K_s^0$ can be separated. However, the $K_s^0$ consists of a $s$ and a $\bar{d}$ quark. Thus even when the $K_s^0$ contains a struck quark, the contributions due to a struck $d$ and a struck $s$ are not separable. The $\phi$ meson does not have that problem, since it is a $s\bar{s}$ state. This also means that the probability to produce it in fragmentation is smaller since it is doubly suppressed. But since the $\phi$ decays at the primary vertex, there is a large background in the sample.

In this thesis an attempt is made to measure charm production in charged current events via $K_s^0$, $K^{*\pm}$ and $\phi$ reconstruction. Measuring the $K_s^0$ is also very interesting in the light of the new vertex detector as it provides a straightforward calibration method for reconstruction programs.

The inclusive cross section for charged current interactions is much smaller than for neutral current interactions. To increase the statistics, the cross sections for $K_s^0$, $\Lambda$, $\phi$ and $K^{*\pm}$ production are also measured in neutral current in the same kinematical region.

From the measured cross sections also values for the strangeness suppression factor and for the ratio of vector particles over vector plus pseudo-scalar particles ($V/(V+P)$) are obtained.

### 7.2 Data samples

The analysis is performed using the data of the 1998/1999 $e^-$ running period and the 1999/2000 $e^+$ running period. A Monte Carlo simulation is used to determine the $K_s^0$ finding efficiency and to cross check the results. The Monte Carlo events were simulated, including radiative effects, using HERACLES\cite{52} with the DJANGOH\cite{53} interface to ARIADNE\cite{54}. ARIADNE is used to simulate the hadronization using the color-dipole model. It uses the Lund string model of JETSET\cite{55}. The response of the ZEUS detector was simulated with a program based on GEANT\cite{56}.

An overview of the luminosities for the different samples is given in table 7.2. The systematic uncertainty in the luminosity is 1.8% for the $e^-$ data and 2.25% for $e^+$ data.
7.3. Event selection

The charged current event selection criteria are taken from the charged current total cross section analysis, for an extensive description see for the $e^-$ data [57] and for the $e^+$ data [58].

The main selection criteria are missing $P_T$ due to the neutrino escaping detection, absence of cosmic muons and absence of beam gas overlays. Furthermore, only events where the angle of the hadronic system w.r.t. the beam-axis, $\gamma$, is larger than 0.4 are accepted. If $\gamma$
is smaller than 0.4, the jet is produced in the very forward direction and there are hardly any reconstructed tracks in the event. In this case, the vertex is approximated using the timing of the calorimeter cells. Since the analysis presented here needs an accurately known vertex (based on tracks), this region is excluded.

Since the main selection criterium in charged current is missing transverse momentum, a large minimum value has to be set (∼15 GeV). Using equation (2.5) and (2.6),

\[ Q^2 (1 - y) = P^2_{T,e} \equiv P^2_{T,missing} \]  

Hence, the cut on missing transverse momentum translates into a minimum \( Q^2 \) of approximately 200 GeV\(^2\).

The neutral current selection criteria are taken from the high-\( Q^2 \) neutral current cross section analysis, for the \( e^+ \) data [24] and for \( e^- \) data [59]. The main selection criteria are cuts to select events with a reconstructed scattered lepton cluster in the calorimeter with a track pointing at it and only little energy around the cluster. The main component of the remaining background is produced by photoproduction. In photoproduction an almost
real photon is exchanged, thus $Q^2 \approx 0$. The electron leaves the detector undetected and the actual interaction is a photon-proton interaction. These events can be misidentified as deep inelastic scattering events when a particle is misidentified as the scattered electron. A useful variable to remove photoproduction in neutral current scattering is $E - p_z$ where $E$ is the sum of all energy deposits in the calorimeter and $p_z$ the projection of all energy deposits in $z$. Since the energy of the incoming proton is equal to the $z$-component of its momentum, $E - p_z$ is zero for the incoming proton. For the lepton which is moving in the $-z$ direction, $E - p_z = 27.5 = 55$ GeV. This quantity is conserved in the collision and a good variable to measure since escaping particles in the beampipe in the $+z$ direction have approximately equal $E$ and $p_z$. When the scattered lepton disappears through the beampipe in the $-z$-direction, the total $E - p_z$ value will be lower by approximately two times the scattered lepton energy. Hence, in photoproduction events the $E - p_z$ peaks at much lower values and can be suppressed by selecting events with $E - p_z$ between 38 and 65 GeV.

The number of events after event selection are shown in table 7.2. Except for the $e^-$ charged current, the correspondence between the data and Monte Carlo is good.

### 7.4 Summary

The strangeness distribution in the proton has been measured by combining data from muon-nucleon and neutrino-nucleon scattering at low $Q^2$ and by measurement of charm...
production in neutrino-nucleon scattering. The latter is equivalent to charged current events at HERA. From measurement of charm production in charged current events, $F_2^{s\bar{s}}$ can be extracted.

In neutral current, measurement of strange particle production itself does not allow to extract $F_2^{s\bar{s}}$, because strange particles are copiously produced in fragmentation and the particle containing the struck strange quark only carries a small fraction of the struck quark momentum. Only in the Breit frame, at large values of $x_p$, one becomes sensitive to intrinsic strangeness.

Strangeness production in fragmentation is in $e^+e^-$ well described by string fragmentation. In Monte Carlo programs, particle production in fragmentation is governed by many parameters of which the strangeness suppression factor is most important for strange particle production and $V/(V+P)$ determines the vector particle content. The obtained values in $ep$ or $p\bar{p}$ collisions are different from the values obtained in $e^+e^-$, indicating that strangeness production is not well understood.

In the next chapter an analysis of strangeness production at HERA is presented using neutral and charged current events and using $e^+$ and $e^-$ data. In addition to the cross sections for $K^0, \Lambda, \phi$ and $K^{*\pm}(892)$ production, the strangeness suppression factor and the ratio of vector and vector and pseudo-scalar particles are extracted.