

Pentaquarks in high-energy colliding experiments: perspectives from HERA

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Abstract. Several issues related to pentaquark searches relevant for current and future high-energy colliding experiments are discussed. We make an attempt to explain why pentaquark candidates are not seen by some experiments, and what makes the HERA experiments so special in such searches.

1 Introduction

Recently, many experimental groups made significant efforts to find new states which can be explained as consisting of five quarks. A number of experiments [1–8] including ZEUS [9] have reported narrow signals in the vicinity of 1530 MeV in the nK^+ and $K_S^0 p$ invariant-mass spectra. The signals were consistent with the exotic pentaquark baryon state $\Theta^+(1530)$ with quark content $uudd\bar{s}$ [10]. Several other experiments searched for this state with negative results [11–18]. Most recently, the Spring8 experiment strengthened positive evidence for $\Theta^+(1530)$ [19], while new preliminary data from the JLab laboratory indicated no signal [20]. ZEUS also reported negative searches for other pentaquark candidates [21–24].

At present, ZEUS is the only high-energy colliding experiment which observes the $\Theta^+(1530)$ candidate in the $K_S^0 p$ decay channel. The H1 experiment has evidence for the lightest charmed pentaquark state [25]. Several other colliding experiments, BaBar [16], ALEPH [14], Belle [17] and CDF [15] do not observe any of the pentaquarks. Although in some cases the results are still preliminary, it is evident that the statistics of such experiments for several known states exceed the statistics of those experiments which observe the pentaquarks. While non-observation of pentaquarks in e^+e^- collisions does not necessarily contradict to the observation of a signal predominantly produced in the forward region with a baryon in the beam or in the target, it is more difficult to explain why no pentaquarks are seen in $p\bar{p}$ collisions at Tevatron and for some other fixed-target experiments.

The aim of this article is not to give a detailed review of the present status of pentaquark searches, which can be found elsewhere [26–28], but to discuss the most intriguing problem: why the ZEUS experiment observes the $\Theta^+(1530)$ state in deep inelastic scattering (DIS) at medium Q^2 . The answer on this question may also explain

the negative searches at Tevatron, and perhaps, the negative results for some fixed-target experiments. We also will discuss several experimental issues which could be important for current and future pentaquark searches in high-energy experiments.

The existing experimental results are still rather controversial, therefore, it is difficult to discuss them without making any assumptions. We assume that the $\Theta^+(1530)$ state in the $K_S^0 p$ decay mode is indeed a pentaquark, but not a new Σ state with a strongly suppressed $\Lambda\pi$ decay mode. Secondly, at present, there is rather weak evidence for antipentaquarks: the ZEUS result [9] indicates that the peak at 1522 MeV is mainly driven by the $K_S^0 p$ decay mode rather than due to the $K_S^0 \bar{p}$ channel (although a structure at 1480 MeV, which is consistent with the PDG $\Sigma(1480)$ bump, is more pronounced for the $K_S^0 \bar{p}$ invariant mass). Since antipentaquarks can only be produced by pure quark fragmentation, the second observation avoids the contradiction with negative searches in e^+e^- annihilation experiments.

2 Possible production mechanism

We will start with the discussion of possible differences in the production mechanism of baryonic states in ep collisions at HERA and other experiments.

Probably, the most simple explanation of why pentaquarks have not been observed in e^+e^- experiments lays in the fact that these experiments do not have a net baryon number in the colliding beams. If one thinks in terms of the pentaquark explanation of the $\Theta^+(1530)$ signal, the production of this state in e^+e^- should be significantly suppressed since it requires five quarks to be glued together by the soft fragmentation mechanism – something which is difficult to explain using the conventional hadronisation mechanisms. This could explain the negative results in e^+e^- annihilation experiments.

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The situation is different when a baryonic state is present in either beam and/or in the target. In this case, the fragmentation mechanism is not as simple as in e^+e^- , and it is possible that the hadronic final state would have enhanced baryon production rate in comparison with the e^+e^- annihilation. If the presence of the net baryon number is indeed a necessary condition for formation of the $\Theta^+(1530)$ pentaquark, then one should explain the negative results of the CDF experiment [15].

It should be emphasised that the $\Theta^+(1530)$ state was observed in DIS at the exchanged photon virtuality $Q^2 > 20 \text{ GeV}^2$ [9], while no signal was reported in photoproduction ($Q^2 \simeq 0$). The photoproduction events are dominated by the boson-gluon fusion (BGF) mechanism, $\gamma^*g \rightarrow q\bar{q}$, which makes the ep collisions to be very similar to $p\bar{p}$. Thus the negative result from Tevatron is not in contradiction with non-observation of the $\Theta^+(1530)$ state in photoproduction at HERA.

Note that the photoproduction data selected by ZEUS are trigger-biased mainly by the detection of high E_T jets. Therefore, such data are enriched with the BGF-type of events. In contrast, DIS data are free from such bias as they were collected by triggering the scattered electron, with a minimum bias on the hadronic final state.

What makes the HERA data so special with respect to exotic baryon searches? In ep collisions, a significant fraction of events contain a leading baryon carrying a large fraction of the incoming proton momentum [29–32]. There are several models describing the leading baryon production. One type of models is based on the QCD building blocks, quarks and gluons, and explains such baryons as the result of the hadronisation of the spectators from the incoming proton. In the second type of models, the leading baryons can be explained by the exchange of virtual particles. Finally, such baryons could originate from decays of low-mass proton resonances in diffractive interactions.

Recently, both H1 [30] and ZEUS [31] reported a rise in the leading-baryon yield with increase of Q^2 from the photoproduction regime to DIS. This could be explained by absorptive effects. If one assumes that a similar effect could also contribute to the exotic-baryon production, this may explain why ZEUS does not see the $\Theta^+(1530)$ signal for photoproduction and low Q^2 DIS. This could be a good guess, if one proves that the most central fragmentation region, corresponding to the pseudorapidity range $|\eta| < 1.5$ used for ZEUS pentaquark searches, can also be populated with baryons after fragmentation of the nucleon remnant (but, of course, with a significantly smaller probability than that for the most forward η region accessed by the leading-baryon calorimeters installed by ZEUS and H1).

To verify this assumption, Monte Carlo (MC) studies were performed using the following models: PYTHIA6.2 [33], HERWIG 6.5 [34], ARIADNE 4.12 [35] and LEPTO 6.5 [36]. The physics calculations were performed with the module “baryons_DIS.rmc” of the RunMC package [37]. The MC models do not contain the simulation of the leading-baryon effects due to the exchange of virtual particles, but rather they attempt to describe the effect as-

suming that the nucleon remnant is a diquark composed of the valence quarks as spectators. While PYTHIA, ARIADNE and LEPTO use the LUND model to describe the hadronisation by stretching a colour triplet string between the struck quark and the diquark¹, the HERWIG model uses the cluster model to hadronise such diquarks. In case of LEPTO, the soft-colour interaction model is used to simulate the rapidity-gaps events.

At this point, we are not interested in how realistic such models are in the description of the production rate of the leading baryons which carry a large fraction of the incoming proton energy [30,31]. The main question is whether they can predict events which have an enhanced production rate of the conventional baryons, compared to that of antibaryons for the central fragmentation region where the $\Theta^+(1530)$ state was seen by ZEUS.

Figure 1 shows the hadron-antihadron asymmetry separately for mesons and baryons as functions of p_T and η in the laboratory frame. The pseudorapidity was defined as $\eta = -\ln(\tan \frac{\theta}{2})$, where the polar angle, θ , is measured with respect to the proton beam direction (i.e. positive η corresponds to the proton beam direction). The Monte Carlo simulations were performed with ARIADNE for $Q^2 > 10 \text{ GeV}^2$ and $Q^2 > 1000 \text{ GeV}^2$. The simulations were done for the proton ($E_p = 920 \text{ GeV}$) and the electron ($E_e = 27.5 \text{ GeV}$) colliding beams. The asymmetry was defined as $r(h) = N(h)/N(\bar{h})$, where $N(h)$ ($N(\bar{h})$) is the number of counted hadrons (antihadrons) and $h = m, b$, where m and b denote mesons and baryons, respectively. The minimum transverse momentum for hadrons was set to 150 MeV as for the experimental searches [9].

It is interesting to observe that the ratios shown in Fig. 1 are above unity, i.e. they indicate the asymmetry. This is not a surprise since the hadronic final state is affected by the presence of the valence quarks from the incoming proton with the total electric charge +1. A similar effect is also expected for all types of hadrons (mesons and baryons) in the current jet [38], and it was found to be stronger with increase of Q^2 . The most interesting feature of Fig. 1 is that the asymmetry is larger for baryons than for mesons, and this tendency increases at low p_T and positive η . This could be an indication of the presence of the proton debris after the fragmentation process.

Thus, occasionally, baryons can be kicked out of a proton by the fragmentation process to the central pseudorapidity region. The probability of such effect is small, but not negligible, especially at high Q^2 . As was discussed above, there are other mechanisms responsible for the leading-baryon production, and they may further contribute to the baryon-antibaryon asymmetry in the pseudorapidity region shown in Fig. 1.

To illustrate the presence of the net baryon number from the incoming beam better, one can calculate the double ratio, $r(b)/r(h)$. This double ratio has the advantage that the trivial effects related to leading hadrons in the current jet are removed, thus $r(b)/r(h)$ is more sensitive to the presence of the baryonic enhancement due to the

¹ For BGF, this picture is modified as tree quarks remain in colour octet after the gluon emission.

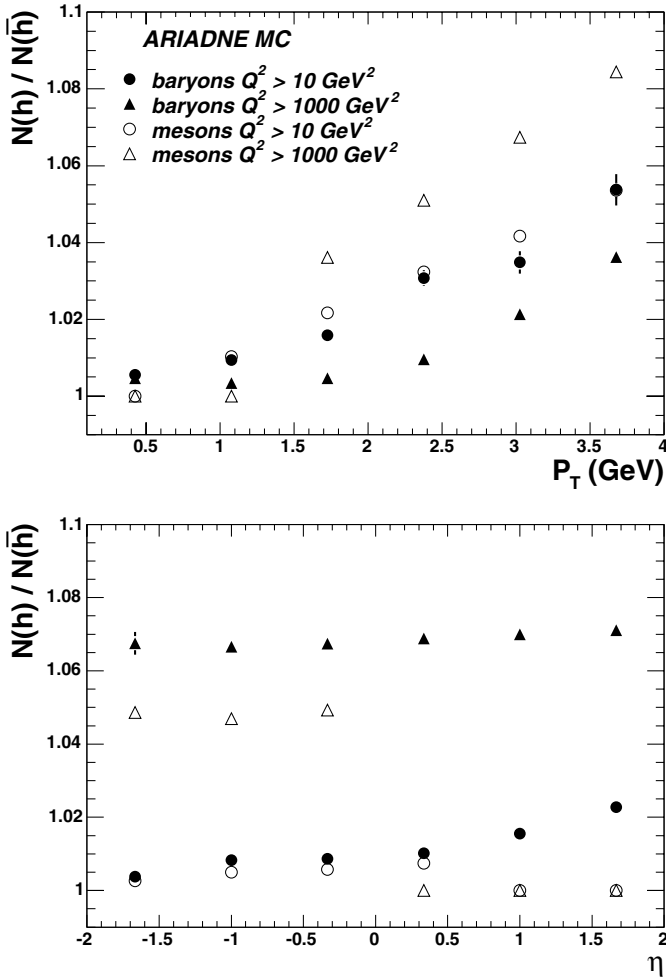


Fig. 1. The ratio of the total number of final-state hadrons to antihadrons, $N(h)/N(\bar{h})$, as functions of p_T and η in DIS. The ARIADNE Monte Carlo model is used. The ratios are shown for mesons and baryons separately for two regions in Q^2

proton-remnant fragmentation. Figure 2 illustrates such double ratios for ARIADNE, using the points shown in Fig. 1. The result shows a significant deviation from unity. The effect is at the level of 2% for $\eta \simeq 2$ at $Q^2 > 10 \text{ GeV}^2$. For $Q^2 > 1000 \text{ GeV}^2$, the double ratio can be as big as 7% for the same η region. The observed effect is mainly due to baryons produced at low p_T .

The same studies were also performed with LEPTO and HERWIG (not shown). For Figs. 1 and 2, the LEPTO model generated for $Q^2 > 10 \text{ GeV}^2$ with the soft colour interactions is somewhat above the ARIADNE model for $Q^2 > 10 \text{ GeV}^2$, but it is below the ARIADNE predictions for $Q^2 > 1000 \text{ GeV}^2$. HERWIG shows a stronger asymmetry than LEPTO for both the ratio and the double ratio, which is likely to be related to differences between the Lund and cluster hadronisation models. Thus the ratios shown in Figs. 1 and 2 have large model-dependent uncertainties.

Figures 3 and 4 show similar ratios for photoproduction events obtained using PYTHIA and HERWIG. Both

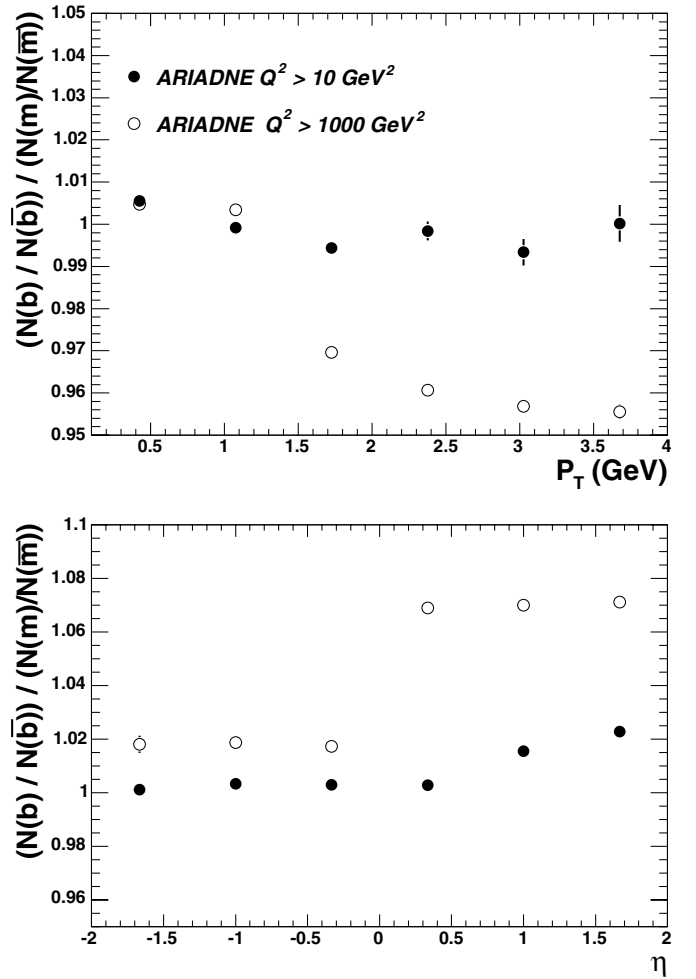


Fig. 2. The double ratio (see the text) as functions of p_T and η for ARIADNE. The ratios are shown for two regions in Q^2

resolved and direct contributions were included in the simulation. The events were generated by requiring the minimum transverse momenta $E_T^{\text{min}} = 8 \text{ GeV}$ for the hard subprocess. The asymmetry shown in Fig. 3 is significantly smaller than for DIS. For the double ratio, the effect is below 0.5% for $-2 < \eta < 2$.

Thus, the MC simulations indicate that, for DIS events, a contribution from fragmentation of the diquark is present even in the central fragmentation region, $|\eta| < 1.5$, i.e. where the $\Theta^+(1530)$ state was observed by ZEUS. This observation has a potential to explain the presence of the $\Theta^+(1530)$ state as well as other possible exotic baryonic states in ZEUS DIS data [9,22]. At the same time, this mechanism leads to a reduction of the $\Theta^+(1530)$ production rate at low Q^2 and photoproduction, which is consistent with the ZEUS studies of $\Theta^+(1530)$ peak². Since there is no strong evidence for antipentaquarks, the proposed explanation is not in contradiction with the ZEUS data.

² Another possible explanation of the reduction of $\Theta^+(1530)$ signal at low Q^2 was discussed in [9].

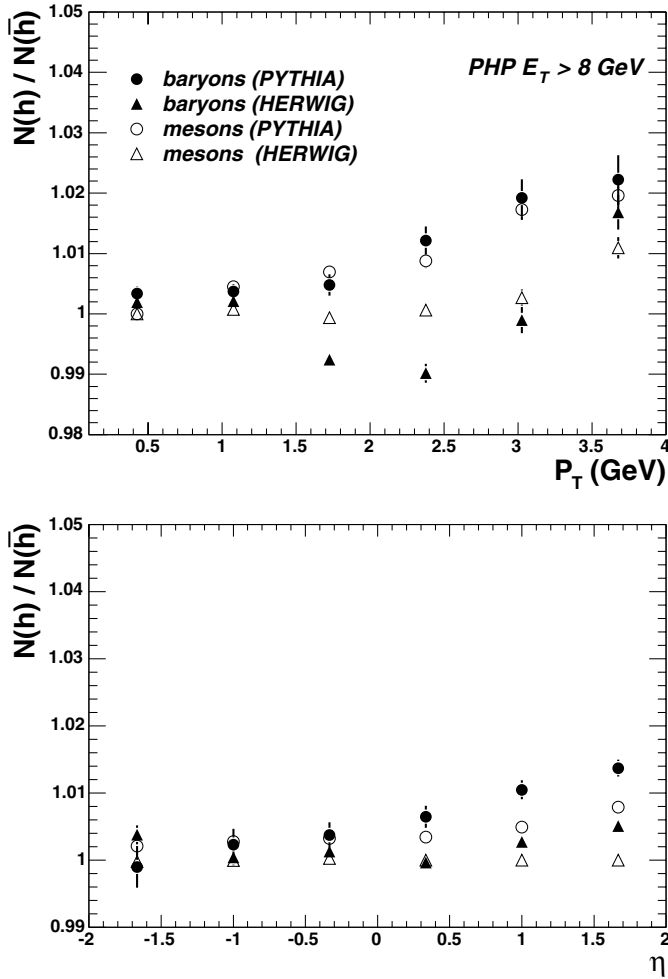


Fig. 3. The ratio of the total number of final-state hadrons to antihadrons as functions of p_T and η . The photoproduction events were generated with PYTHIA 6.2 and HERWIG 6.5 using the minimum transverse momentum for the hard scale $E_T^{min} = 8$ GeV. The ratios are shown for mesons and baryons separately

The baryon-antibaryon asymmetry can also be studied by reconstructing $\Lambda/\bar{\Lambda}$, p/\bar{p} etc. ratios. For the $\Lambda/\bar{\Lambda}$ ratio [22], there is indeed a large asymmetry, but it is difficult to decouple it if from secondary-scattering interactions. Recent study of Ξ baryons [22] shows that the current statistical precision of HERA-I data is not yet sufficient to establish the $\Xi/\bar{\Xi}$ asymmetry at the 1–2% level. One should again note that the baryon-antibaryon ratio measured in the central pseudorapidity region cannot give ultimate proof of the enhanced baryon production due to fragmentation of the proton remnant, because a similar asymmetry should also be expected for all hadrons (including mesons) due to leading hadrons in the current jet. As was discussed before, the double ratio is more appropriate tool to observe the discussed effect, since the contribution from leading hadrons in the current jet is removed.

In summary, if the pentaquark production is related to the proton-remnant (diquark) fragmentation, then pen-

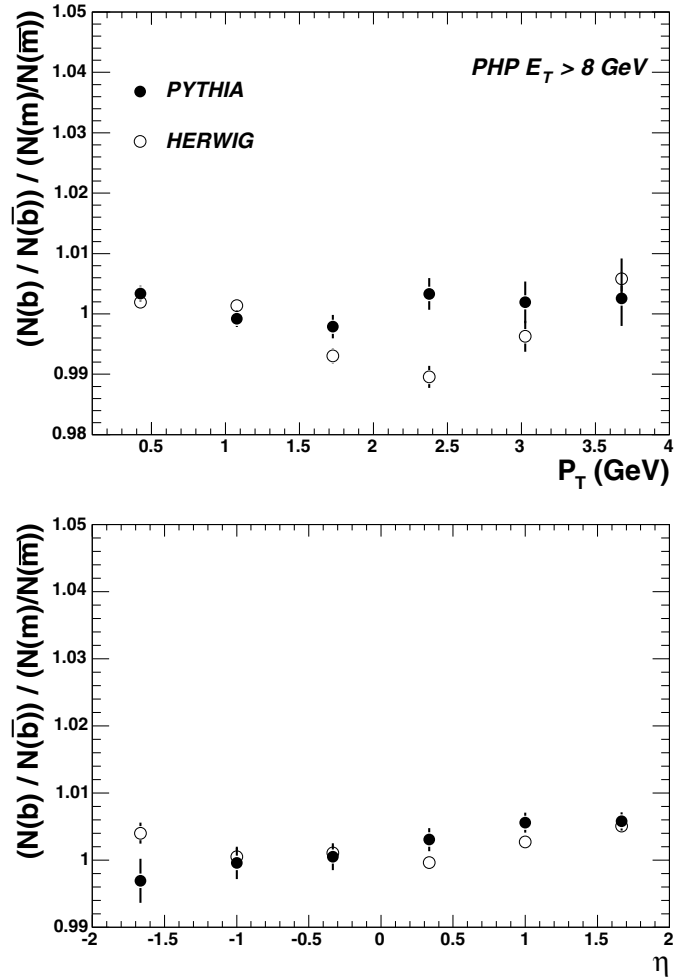


Fig. 4. The double ratio (see the text) as functions of p_T and η for photoproduction using the minimum transverse momentum for the hard scale $E_T^{min} = 8$ GeV. Monte Carlo studies were performed using PYTHIA 6.2 and HERWIG 6.5

taquarks should be best seen at low p_T in the laboratory frame, and for positive values of η . The production of antipentaquarks should be suppressed relative to pentaquarks. In addition, high- Q^2 region is more favourable, as the incoming proton receives a stronger kick from the virtual photon; in the LUND fragmentation picture, a colour string stretched between the diquark and the struck quark has a higher chance for dragging the diquark system to low values of pseudorapidity than for low Q^2 events. To verify this mechanism, high statistics data from HERA-II are necessary in order to perform more differential studies of the $\Theta^+(1530)$ signal.

3 Experimental reconstruction

It is noteworthy that, from the experimental point of view, the decay channel $\Theta^+(1530) \rightarrow K_S^0 p$ is not simple since the dE/dx method is often used to identify the protons, while K_S^0 are reconstructed using the secondary-vertex al-

gorithms. In this approach, the identification of protons is only possible at low-momenta ($p < 1.5 \text{ GeV}$ in ZEUS case). However, in this case, the phase space available for $\Theta^+(1530)$ decay is dramatically reduced as the decay kinematics requires that the momenta of the proton candidates should be typically higher than the momenta of K_S^0 [39]. Note, in colliding experiments, a significant fraction of K_S^0 mesons have momenta above $p \simeq 1.5 \text{ GeV}$, which is the ZEUS cut used for the proton identification.

The HERA data [8,9] indicates that the $K_S^0 p$ invariant-mass spectrum has non-negligible contributions from not well established PDG Σ states. Such baryons are not implemented in MC simulations, therefore, the MC predictions (scaled to the luminosity of the data) are significantly below the data for the $K_S^0 p$ spectrum. Such sensitivity to the Σ states may also be used by current and future experiments to test the sensitivity to $\Theta^+(1530)$.

The resolution for the $K_S^0 p$ invariant mass is another central problem for pentaquark searches as the width of the $\Theta^+(1530)$ baryon is predicted to be narrow. ZEUS is among the experiments which have excellent resolution for this study, $\simeq 2.5 \text{ MeV}$ [9] (using the PDG mass for K_S^0 to improve the resolution for the $K_S^0 p$ mass distribution). Keeping in mind the difficult background near the 1480 MeV mass region due to the PDG $\Sigma(1480)$ bump, a structure near the 1520 MeV region will be difficult to observe if the resolution would be 3 – 4 times larger.

As was discussed before, if the contribution of the proton remnant to the central fragmentation region is expected at high Q^2 , then one may expect that the pentaquark production is also enhanced at high Q^2 . However, from the experimental point of view, pentaquark studies at very high Q^2 could be affected by high combinatorial background. This will be discussed in more details below.

3.1 Combinatorial background and experimental sensitivity

At high energies, the combinatorial background for the invariant-mass reconstruction scales approximately as $\langle n \rangle^2$, where n is the number of produced tracks. Going to a high energy (\sqrt{s} , jet E_T , Q^2 , W , etc.) available for hadroproduction, combinatorics for fully-inclusive events is rising due to a large production rate of non-heavy flavour hadrons produced by quark fragmentation and resonance decays. For HERA, an increase in the track multiplicity and combinatorial background is expected for high- E_T photoproduction events, or for very high Q^2 events in DIS. This should mask the peaks from hadrons which may carry the quantum numbers of colliding beams, or states which can only be produced after the fragmentation of partons created by hard subprocesses.

The most relevant example illustrating this point is heavy-flavour mesons or baryons. The production of such states by pure fragmentation is significantly suppressed, but they can be produced in the hard BGF subprocess $\gamma^* g \rightarrow c\bar{c}$ at the fragmentation stage. Thus, for high-energy processes (or for high- E_T jets), there is a stronger combinatorial background than at low energy, since a sig-

nificant fraction of strange kaons and baryons produced by hadronisation and resonance decays can contribute to the relevant invariant-masses distributions.

This point has been checked by using the same MC samples as those shown in Figs. 1–4. First, the decay channel $D^0 \rightarrow K^- \pi^+$ was reconstructed by combining the momenta of two final-state charged particles. It was found that, for the ARIADNE event sample generated at $Q^2 > 10 \text{ GeV}^2$, the ratio of the signal events over the background was about 2.3, while for the photoproduction sample of PYTHIA with $E_T^{min} = 8 \text{ GeV}$, this ratio was 1.5. Such difference is mainly related to a high particle multiplicity in photoproduction data than in DIS. In contrast, when $\phi(1020)$ mesons decaying to $K^+ K^-$ are reconstructed, the signal-over-background ratios were 1.3 and 1.2 for DIS and photoproduction, respectively. Thus, the signal-over-background ratio for the states which can be produced by pure fragmentation (like ϕ -mesons) is about the same for DIS and photoproduction, while it is significantly different for hadrons which have a production mechanism driven by the hard subprocess or by other mechanisms unrelated to pure fragmentation and resonance decays.

In this respect, the statement [26] that experiments with superior statistics for known hadrons (such as $\Lambda(1520)$) have better chances to find $\Theta^+(1530)$ is not fully correct for high-energy experiments. The production mechanism of such states is soft fragmentation, thus the signal-over-background ratio does not change significantly as a function of the energy available for the hadronic final state. In contrast, the production mechanism of the $\Theta^+(1530)$ state is unlikely related to pure fragmentation mechanism, thus the combinatorial background for the $\Theta^+(1530)$ reconstruction is expected to increase with energy. Therefore, high statistics for reconstructed non-heavy flavour mesons and baryons can only indicate the quality of particle identification. This is an important issue, but not the most important compared to possibly exotic production mechanism of the $\Theta^+(1530)$ state, and the experimental difficulties related to the increase of combinatorial background with energy.

Note that for the $\Lambda(1520)$ baryons, which have a similar decay mode $K^- p$ as the $\Theta^+(1530)$ state, in some cases it is also difficult to say about the experimental sensitivity to the $\Theta^+(1530)$, even if one assumes the same production mechanism as for the pentaquark state. Indeed, the ZEUS preliminary results [23,24] showing the $\Lambda(1520)$ signal at $Q^2 > 20 \text{ GeV}^2$ does not look impressive compared to the corresponding peak from BaBar [16]. This is due to the fact that the reconstruction of $\Lambda(1520)$ at ZEUS was done in a significantly smaller allowed phase space than that for the $\Theta^+(1530)$, since K^\pm mesons were reconstructed by using the dE/dx , i.e. only K^\pm mesons with relatively low momenta, $p < 0.8 \text{ GeV}$, were used. In contrast, the K_S^0 sample used for the $\Theta^+(1530)$ searches did not have such limitation, since no the dE/dx requirement was used (there is only 20% of K_S^0 in the range $p < 0.8 \text{ GeV}$). The protons used for the $\Lambda(1520)$ reconstruction were also selected by using a significantly stronger dE/dx cut.

It seems that the best known state which can be used to check the experimental sensitivity to $\Theta^+(1530)$, and to compare it with other experiments, is Λ_c (using the $K_S^0 p$ decay channel). For ep collisions, the Λ_c baryons are produced through the BGF mechanism, $\gamma^* g \rightarrow c\bar{c}$. Thus the cross section for Λ_c is decreasing with increase of Bjorken x and Q^2 . Unfortunately, if the $\Theta^+(1530)$ production mechanism proposed in Sect. 2 is correct, the yield of Λ_c baryons decreases for the kinematic regions where the $\Theta^+(1530)$ cross section is expected to be high.

3.2 Particle misidentification

Particle misidentifications in hadron spectroscopy can roughly be divided into the following categories: 1) misinterpretation of a peak which may correspond to a known state when a different mass assumption for the decay products is used, and 2) misreconstruction of a state after using the same tracks twice (track splitting). We will not discuss here the first problem as this is always a first check to be made to exclude possible reflections (which usually never produce a very sharp peak consistent with the detector resolution).

Here we will concentrate on the second problem. It was already pointed out by several authors [40] (see other details in [26]) that, for example, using ghost tracks associated to Λ -baryon decays can lead to peaks at 1540 MeV.

Generally, the experiments which have reported the $\Theta^+(1530)$ state are well aware of the danger related to the ghost tracks. The issue is probably more important for high-energy experiments with large combinatorial background under the observed peak as it is impossible to scan each event by eye in order to verify which track belongs to which decaying state.

Note that all experiments which observe the $K_S^0 p$ peak claim the reconstructed $\Theta^+(1530)$ masses somewhere between 1520 and 1530 MeV, so the spurious peak shown in [26] is by 20 – 10 MeV shifted from the observed peak. At ZEUS, everything was done to avoid such double counting by removing Λ hyperons from the consideration and by reducing the background under the K_S^0 peak as much as possible. The contribution from the Λ decays was further reduced using the tracks fitted to the primary vertex for the proton candidates.

Finally, ZEUS observes the $\Theta^+(1530)$ peak only for a specific type of events, mainly for DIS. It is hard to imagine why the spurious peak appears in DIS only, but not for high- E_T photoproduction events which have a high average track multiplicity and a larger production rate of Λ baryons compared to DIS.

The last observation is probably a good hint for future pentaquark searches: if a signal disappears for certain class of events (where it can potentially disappear due to some physical reasons, and assuming that such class of events was not preselected using track-related quantities), this would likely mean that the observed peak is not due to track-related misreconstructions.

3.3 Conclusions

The HERA collider is unique and plays a significant role in pentaquark searches. This uniqueness is in a possible access to the net baryon number from the colliding proton beam, even when the most central fragmentation region is used for the baryon reconstruction. This conclusion is mainly relevant for DIS, while the effect is significantly smaller for gluon-driven photoproduction. If the assumptions made in this paper are correct, the pentaquark signal should be best seen in the forward region of pseudorapidity, at low p_T and at medium or high Q^2 regions. The signal from antipentaquarks should be suppressed compared to pentaquarks.

Another feature of ep collisions at HERA is relatively low energy for the hadronic final state compared to the Tevatron experiments. This has a clear advantage as it leads to a low combinatorial background for the $K_S^0 p$ mass reconstruction. Furthermore, according to several predictions [41,42], the $\Theta^+(1530)$ production cross section can be suppressed at high energies.

For the nearest future, HERA could be the only high-energy colliding experiment which is well suited for the exotic baryon searches, since the pentaquark production in e^+e^- annihilation is expected to be suppressed compared to the experiments with baryons in the colliding beams. Therefore, the future Linear Collider is likely to be not well suited for such searches. From the other hand, the hadronic final state in pp collisions at LHC is expected to be too complicated, and a significant effort should be made to deal with the combinatorial background for the $K_S^0 p$ invariant mass.

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