THE ROLE OF HADRONIZATION IN CHARM AND BEAUTY PRODUCTION

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Abstract

We discuss the relative role of fragmentation and recombination processes for heavy flavour hadron production in different kinematical regions in high energy hadron-hadron and photon-hadron collisions. We predict several qualitative features which should be observed if our picture of heavy flavour production is consistent.

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1 Introduction

The investigation of heavy flavour production in high energy hadron collisions is an important method for studying the quark-gluon structure of hadrons and the mechanism of hadroproduction at high energies.

The most popular and technically simplest approach is the so-called QCD collinear approximation, or parton model (PM). The cross sections of QCD subprocesses are calculated usually in the leading order (LO), as well as in the next to leading order (NLO) [1, 2, 3, 4, 5]. The possibility to incorporate the incident parton transverse momenta is referred to as \(k_T\)-factorization approach [6, 7, 8, 9, 10, 11], or the theory of semihard interactions [12, 13, 14, 15, 16, 17, 18]. In our previous papers [19, 20] we have presented a comparison of results obtained with the help of \(k_T\)-factorization and the parton model.

However in both approaches we calculate the cross sections, one-dimensional distributions and correlations of the produced heavy quarks, whereas experimentally we know these quantities for heavy flavour hadrons. Of course, the total production cross sections for heavy flavour quarks and hadrons are the same due to flavour conservation, however the shape of distributions and correlations can be different.

The aim of this paper is the discussion of these differences in different kinematical domains. We will give several qualitative predictions which seem to be trivial. However their experimental check is very important because their violation means that our today picture of hadronization is inconsistent. The preference of heavy flavours comes from the fact that at not asymptotically high energy only one heavy quark pair can be produced. So we have the explicit correspondence between the calculated heavy quark and experimentally measured heavy flavour hadron production.

2 Fragmentation and recombination approach for secondary production

There exist two classes of the phenomenological models for hadronization which account for two different processes: fragmentation of the produced quark into secondary hadron and recombination of the produced quark with some another quark into secondary hadron.

Experimentally we know that both these processes exist. Quark fragmentation takes place in the case of heavy flavour production in \(e^+e^-\) annihilation. On the other hand, only recombination processes of the produced heavy quark with valence quarks of incident hadrons can explain (see, for example, [21, 22, 23]) the experimental asymmetry [24, 25, 26, 27] in yields of leading (favoured) and non-leading (unfavoured) \(D\)-mesons\(^1\) which is defined as

\[
A(x) = \frac{d\sigma/dx(\text{Leading}) - d\sigma/dx(\text{Non-leading})}{d\sigma/dx(\text{Leading}) + d\sigma/dx(\text{Non-leading})}, \tag{1}
\]

\(^1\)The intrinsic charm idea [28] is slightly different.
where "leading" hadrons have the common light quark with the incident particle, and "non-leading" ones have no such quark.

The similar asymmetry was measured for charmed baryon $\Lambda_c^+$ to $\Lambda_c^-$ yields in $\pi^-n$ucleus interactions \[29\].

The total momentum distribution $D_H(p)$ of the produced heavy flavour hadron, at fixed value of transverse momenta is determined by the sum of the fragmentation and recombination processes, $D_H^F(p)$ and $D_H^R(p)$,

$$D_H(p) = D_H^F(p) + D_H^R(p).$$ (2)

The principle difference of fragmentation and recombination approaches is the difference of the ratio of the momentum of the produced heavy quark to secondary hadron. In the case of fragmentation the momentum of the hadron is smaller than the momentum of the quark, the momentum distribution of heavy flavour hadron $D_H(p)$ is

$$D_H^F(p) = \int d^3p_1 D_Q(p_1)G(p/p_1),$$ (3)

where $D_Q(p_1)$ is the momentum distribution of heavy quark and $G(p/p_1)$ the fragmentation function of the quark into registered hadron.

In the case of recombination of heavy quark $Q$ with light antiquark (or diquark) $q$ we have the opposite situation.

$$D_H^R(p) = \int d^3p_1 d^3p_2 D_Q(p_1)D_q(p_2)\delta(p-p_1-p_2),$$ (4)

and the momentum of secondary hadron is larger than the momentum of every quark.

One can see that the fragmentation contribution into some secondary hadron distribution depends only on the momentum distribution of heavy quarks, whereas the recombination distribution depends both on the momentum distributions of heavy quarks and light antiquarks (or diquark). So the relative contribution of fragmentation and recombination processes in Eq. (2) depends on the density of light antiquarks (diquarks) in the considered kinematical region.

Sometimes it was sayd that heavy flavour hadron can not be produced via recombi-
nation of a heavy quark with light antiquark/diquark because of significant difference in their average transverse momenta. However the average transverse momenta of secondaries (mesons) produced centrally at high energy are of the order of their masses, $\langle p_T \rangle \sim m_H$. On the other hand in a fast heavy flavour meson most probably both, heavy and light quarks have almost equal velocities\[3\]. Taking into account that the constituent mass of heavy quark is parametrically larger than the constituent mass of light quark, $m_Q \gg m_q$, we will find in heavy flavour meson $H$ with standard transverse momentum $p_T \sim m_H$ a heavy quark which carries $p_T \sim m_Q$, and a light quark which carries its usual transverse momentum $p_T \sim m_q$.

\[2\]This configuration gives the main contribution, say, in nonrelativistic quark model.
As both fragmentation and recombination processes exist, the question is – which process is the most important for the heavy flavour hadron production in the high energy hadron collisions, and how this can depends on the kinematical region. The experimental fact [24, 30] is that the calculated Feynman-\(x\) distribution of produced heavy quarks in \(\pi p\) collisions at fixed target energies are in good agreement with the experimental distributions of produced \(D\)-mesons, see Fig. 5 in [31]. So we can say that in the averaged events with charm production the fragmentation and recombination processes in charm quark hadronization balanced each other.

However, this balance should be violated if we will consider Feynman-\(x\) distribution of heavy flavoured mesons with some restriction in their transverse momenta. For example, in events with heavy quark pair production at comparatively small \(p_T \sim m_Q\) the multiplicity of light quarks is several times (in dependence on the initial energy) larger than the multiplicity of heavy quarks. So here we have many objects (antiquarks or diquarks) which can recombine with heavy quark. However, in the region of \(p_T \gg m_Q\) the \(p_T\)-distributions of light and heavy quarks should be practically the same, because both are determined by the same QCD diagrams with scale, equal to large \(p_T\) value. In this kinematical region the probability of recombination should decrease (see examples in [32]), due to decrease of the relative density of light antiquarks/diquarks with the needed comparatively large transverse momentum, \(D_q(p)\) in Eq. (4), whereas the probability of fragmentation should be the same as at small \(p_T\). So we can expect that the balance between recombination and fragmentation will be changed and the spectra of secondary heavy flavour hadrons should be more soft than the spectra of produced heavy quarks. The experimental check of this behaviour seems to be very interesting. By the way, possibly the dependence of the difference in \(x_F\)-distribution of heavy quarks and hadrons on the \(p_T\) values can explain why \(p_T\) distributions of heavy quarks are changed after \(k_T\) kick and fragmentation (where \(p_T\) values are comparatively large), whereas \(x_F\)-distributions (which are controlled by low \(p_T\) values) becomes practically the same as before fragmentation [33].

At the same time, if the contribution of recombination for heavy flavour hadrons with large \(p_T\) decrease, we predict the decrease of the asymmetry Eq. (1) in the production of leading to non-leading secondaries. Besides this, the measurement of the dependence of asymmetry on the transverse momenta of secondaries gives information about wave function of heavy flavour hadrons.

Very interesting behaviour is expected for the energy behaviour of the asymmetry (1) in \(ep\) collisions. As is well-known, at not very high initial energy the direct \(\gamma p\) interactions dominate, when the incident photon goes into \(Q\bar{Q}\) pair with production another secondaries via soft parton shower. So the heavy quark pair and the proton remnant are in different hemispheres, and the difference of their rapidities increase with initial energy fast enough. In this configuration the probability of heavy quark recombination with proton remnant is small and the asymmetry should decrease with the energy. However, with the growth of energy the resolved process starts to contribute more and more. Here heavy quark pair is produced in parton-parton collision via the hadron component of a photon. The cross sections of the last processes are determined by both parton structure functions of proton and photon. The photon structure functions are known not good
enough, so the ratio of resolved to direct contributions can be changed several times, by using different sets of parton distributions in the photon, one can see several numerical examples in [34].

In the resolved photon process heavy quarks are produced in the central region, similarly to the \( pp \) case, so the asymmetry should be practically the same. The direct interactions should give only small correction. So the measurement of the ratio of heavy flavour hadron asymmetry in \( \gamma p \) (in the proton fragmentation hemisphere) and in \( pp \) collisions at the same energy can estimate the ratio of resolved to direct processes. It seems to be also interesting to consider these ratios in different \( p_T \) regions.

3 Conclusion

We have discussed the qualitative features of heavy quark hadronization. It seems that in very general approach the hadronization mechanism should depend on the transverse momentum of heavy quark/hadron. This results in some qualitative predictions for the data. Probably the most important feature should be the decrease of the asymmetry, Eq. (1) with the transverse momenta of heavy flavour hadrons.

The comparison of heavy flavour hadron asymmetries in \( \gamma p \) and \( pp \) collisions at similar energies allows one to estimate the part of interactions with resolved photon.

Of course, all quantitative estimations here are model dependent [21, 32, 33, 36].

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