Studies on General Kinematic Effects of Hadrons in Electron-Positron Annihilation at High Energy

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Keywords: Hadronization model, Electron-Positron annihilation, Rapidity and transverse momentum.

Abstract. We briefly review the hadronization pictures adopted in the LUND String Fragmentation Model, Webber Cluster Fragmentation Model and Quark Combination Model respectively. Predictions of hadron multiplicity, rapidity and transverse momentum at CEPC obtained by LSFM and QCM are reported. The results are compared and discussed in detail.

Introduction

The prospect of CEPC (Circular Electron Positron Collider) was proposed by Chinese high energy physics community a few years ago. The physics at the CEPC have been studying by a great many theorists. In 2018 the CEPC Group has issued conceptual design reporter, which is an exciting development. As a future high energy and luminosity collider, the CEPC will have the electrons and positrons collisions with the center of mass energy of 250GeV and an instantaneous luminosity of $2 \times 10^{34} \text{cm}^{-2}\text{s}^{-1}$, besides giving $5 \text{ab}^{-1}$ of integrated luminosity over ten years of running with two detectors. The CEPC can also run at the $Z^0$ pole, with a preliminary target of producing $10^{10} Z$ bosons in one year of running. Lepton colliders, including the ILC, CEPC and FCC-ee, may be built and be in operation prior to the completion of the HL-LHC phase. They will provide a clean environment to study the hadronization mechanism.

The hadronization mechanism is an important but still unsolved problem up to now due to its nonperturbative nature. It is recognized that the hadronization mechanism is universal in all kinds of high energy reactions, e.g., $e^+e^-$ annihilation, hadron (nuclear) - hadron (nuclear) collisions. Among these reactions, $e^+e^-$ annihilation at high energies, especially at the CEPC in the future, is the best one for studying the hadronization mechanism, since all the final hadrons come from primary ones, all of which are hadronization results. In order to understand the hadronization phenomena, it is necessary to study the hadronization mechanism in detail in $e^+e^-$ annihilation once CEPC is available. On the other hand, the hadronization models, like LUND String Fragmentation Model (LSFM), Webber Cluster Fragmentation Model (WCFM) and Quark Combination Model (QCM), serve as bridges between the perturbative quantum chromodynamics (QCD) and experiments. So they are very important tools for studying, e.g., CEPC physics. The properties of the light hadrons have been studied in our previous works[1]. Here we focus on investigating the production of heavy hadrons (e.g., $\Lambda_c, \Lambda_b, B_s$) by LSFM and QCM.

This paper is organized as follows: In section 2, we give a brief introduction to the popular hadronization models, i.e., LSFM, WCFM and QCM. Some numerical results and discussions are given in section 3. Finally, a short summary and outlook close the study.

Hadronization Model

LUND String Fragmentation Model, first proposed by Artru and Mennesser in 1974[2], has been developed by the theory physics group of Lund University since 1978, and the corresponding Monte-Carlo programs, e.g., JETSET and PYTHIA, are written. By now PYTHIA is one of the most
widely used generators describing the high-energy collisions. The hadronization of $q\bar{q}$ color-singlet is the simplest case for String Fragmentation. Lattice QCD supports a linear confinement potential between color charges, i.e., the energy stored in the color dipole field increases linearly with the separation between them. The assumption of linear confinement is the starting point for the String Model. As the $q\bar{q}$ move away in the opposite direction, the kinetic energy of the system changes into the potential energy of the color string (or color flux tube). When the potential increases to a certain extent the string will break by the production of a new quark pair, and the production possibility is given by the quantum mechanical tunneling. When the new quark pair $q'\bar{q}'$ are excited out in vacuum, the $q\bar{q}$ color string splits into $q\bar{q}'$ and $q'\bar{q}$ two color-singlets. If the invariant mass of either of the singlet system is large enough, further break will occur. The process ends when all string pieces become exactly hadrons on their mass-shells. This picture describes meson production naturally other than the production of baryons. More complex diquark and popcorn mechanisms have to be introduced to explain the baryon production. One prominent feature of LSFM is that energy momentum and flavour are conserved at each step of the fragmentation process. In $e^+e^- \rightarrow h's$ process at high energies, multi-parton states will be produced at the end of perturbative phase, so that the multi-parton fragmentation has to be taken into account.

The Cluster Fragmentation Model has been proposed by Wolfram[3] in 1980. Webber Cluster Fragmentation Model (WCFM)[4] is the well-known example. It has three parts:

1) The formation of color-singlet cluster. Gluons split into quark pairs after parton shower: $g \rightarrow q\bar{q}$. Adjacent quark and anti-quark from different gluons combine to form a color-singlet.

2) Cluster with large invariant mass fragments into smaller ones.

3) Little cluster decays into primary hadrons. i.e., $Cluster \rightarrow hadron1 + hadron2$.

Note that only two-body decay or fragmentation is adopted in WCFM. The corresponding hadronization picture is local, universal and simple.

ShanDong Quark Combination Model (SDQCM) used by us in this work is one of Quark Combination Models. In the framework of SDQCM, Quark Production Rule (QPR), Quark Combination Rule (QCR) are adopted to describe the hadronization in a color singlet system, a simple Longitudinal Phase Space Approximation (LPSA) is used to obtain the momentum distribution for primary hadrons in its own system, and then this hadronization scheme is extended to the multi-parton states. In the framework of SDQCM, Quark Production Rule (QPR), Quark Combination Rule (QCR) are adopted to describe the hadronization in a color singlet system, and then a simple Longitudinal Phase Space Approximation (LPSA) is used to obtain the momentum distribution for primary hadrons in its own system. Finally this hadronization scheme is extended to the multi-parton states.

**Results and Discussion**

In this paper, we study the hadronization process at CEPC by LSFM and SDQCM. We focus on investigating the properties of the heavy hadrons. For LSFM, we use the default parameter values in PYTHIA, while for SDQCM, we adopt the parameters used in Ref. [5,6] which fit data quite well.

The final hadron multiplicity at high energy $e^+e^-$ reactions is always an important topic. We list the predictions of final hadron multiplicities at CEPC ($\sqrt{S} = 250 GeV$) by LSFM and SDQCM in Table 1. The results of LSFM are obtained by running PYTHIA6.4 with the default parameters. It is found that the predictions of LSFM and those of SDQCM are consistent with most of the experimental data. However, the multiplicity of the heavy baryons, e.g., $\Xi_b, \Sigma_b, \Omega_b$ are still not measured, and the corresponding theoretical predictions obtained by LSFM and SDQCM are quite different. Therefore it is important to measure their production rates at CEPC in order to discriminate different hadronization mechanisms.
Table 1. Results for average hadron multiplicities at CEPC.

| Particle | $\pi^+$ | $\pi^0$ | $K^+$ | $K^0$ | $\eta$ | $D^+$ | $D^0$ | $B^+$ | $B^0$ |
|----------|---------|---------|-------|-------|-------|-------|-------|-------|-------|
| LSFM     | 24.817  | 14.008  | 3.190 | 2.876 | 1.479 | 0.186 | 0.561 | 0.126 | 0.126 |
| SDQCM    | 26.650  | 14.348  | 3.026 | 2.485 | 1.165 | 0.252 | 0.548 | 0.133 | 0.134 |

| Particle | $B_s^0$ | $\omega$ | $\rho^0$ | $K^{*+}$ | $K^{*0}$ | $D^{*+}$ | $D^{*0}$ | $p$ | $\Lambda$ |
|----------|---------|----------|----------|----------|----------|----------|----------|-----|---------|
| LSFM     | 0.032   | 2.059    | 2.264    | 1.592    | 1.561    | 0.2738   | 0.2570   | 1.9203 | 0.5904 |
| SDQCM    | 0.040   | 2.813    | 2.828    | 1.522    | 1.458    | 0.2953   | 0.3003   | 1.4516 | 0.6585 |

| Particle | $\Sigma^0$ | $\Sigma^-$ | $\Sigma^+$ | $\Lambda^+_c$ | $\Lambda^0_b$ | $\Sigma^0_c$ | $\Sigma^0_b$ | $\Xi^0_b$ | $\Omega^+_b$ |
|----------|------------|------------|------------|---------------|---------------|-------------|-------------|----------|------------|
| LSFM     | 0.1159     | 0.1074     | 0.1149     | 0.0027        | 0.0254        | 0.0026      | 0.0014      | 0.0002   | 0.00004   |
| SDQCM    | 0.2026     | 0.1754     | 0.1890     | 0.0141        | 0.0353        | 0.0127      | 0.0074      | 0.0005   | 0.00066   |

We also show the results for the momentum, rapidity and transverse momentum distributions of the hadrons like $\pi^\pm$, $K^\pm$, $p\bar{p}$, $D^\pm$, …… in Fig. 1-3 respectively. The momenta spectrum and transverse momentum spectrum are shown in Fig.1 and Fig.2. The rapidity spectrum can be seen in Fig.3, which is based on LSFM.

![Figure 1](image1.png)

Figure 1. The momenta spectrum of (a) $\pi^\pm$, (b) $K^\pm$, (c) $p\bar{p}$, (d) $D^\pm$, (e) $\Lambda^0$ and (f) $\Sigma^0$ at CEPC.
Figure 2. The transverse momenta spectrum of (a) $\pi^\pm$, (b) $K^\pm$, (c) $p\bar{p}$, (d) $D^\pm$, (e) $\Lambda^0$ and (f) $\Sigma^0$ at CEPC.
Figure 3. The rapidity spectrum of (a) $\pi^\pm$, (b) $K^\pm$, (c) $p\bar{p}$, (d) $D^\pm$, (e) $\Lambda^0$ and (f) $\Sigma^0$ at CEPC.

We also compared the momentum distributions of LSFM with SDQCM in Fig. 4. It is obvious that the curves of LSFM are smoother than the SDQCM ones. This is easy to understand, since SDQCM does not include any complicated inputs for the hadron momentum distributions, which can be improved in the future.

All of the results above indicate that it will be a good test for the two hadronization models to compare the predictions under the two models with the data which will come from the CEPC, especially for D mesons.
Summary and Outlook

The initial particles of $e^+e^-$ annihilation reactions (i.e. positive and negative electrons) are all leptons without internal structure, and the corresponding background is relatively clean. In present, China is actively pre-researching and preparing the CEPC. Its first stage is to achieve the circular electron-positron colliding, and the collision energy is 250GeV. For this stage, we give the theoretical predictions on the general and important physical quantities of the momentum, transverse momenta and rapidity distributions of the hadrons in this work. It will provide a valuable reference and useful information for the measurements of common hadrons, even exotic hadrons in the CEPC energy zone, as well as indispensable scale information in the future testing process of CEPC.

Acknowledgement

This work is supported by the following funds: the National Natural Science Foundation of China (11605075), Natural Science Foundation of Shandong Province (ZR201709180126, ZR2018JL006).

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