Fragmentation Functions from BaBar

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Abstract: The *BABAR* experiment had been taking data for the period 1999-2008 at the PEP-II e^+e^- collider at SLAC. Data were recorded mostly at a center-of-mass (CM) energy of 10.58 GeV, corresponding to the peak of the $\Upsilon(4S)$ resonance, with about 10% of data 40 MeV below it, for an integrated luminosity of about 470 fb^{-1}. We present some of the most significant measurements of inclusive production cross sections of light and charmed hadrons, related to unpolarized fragmentation functions, as well as measurements of the spin-dependent Collins fragmentation functions.

Introduction

Although *BABAR* [1] was designed and optimized for studying time-dependent CP asymmetries in B-meson decays, the high luminosity and excellent detector performances allow also to investigate different aspects of strong interactions, in particular, measurements related to fragmentation functions (FFs) of light and heavy quarks. A FF quantifies the probability of producing a particular hadron h in a jet initiated by a given parton (quark or gluon). In e^+e^- annihilation the FFs are strictly connected to the hadron multiplicities, defined as:

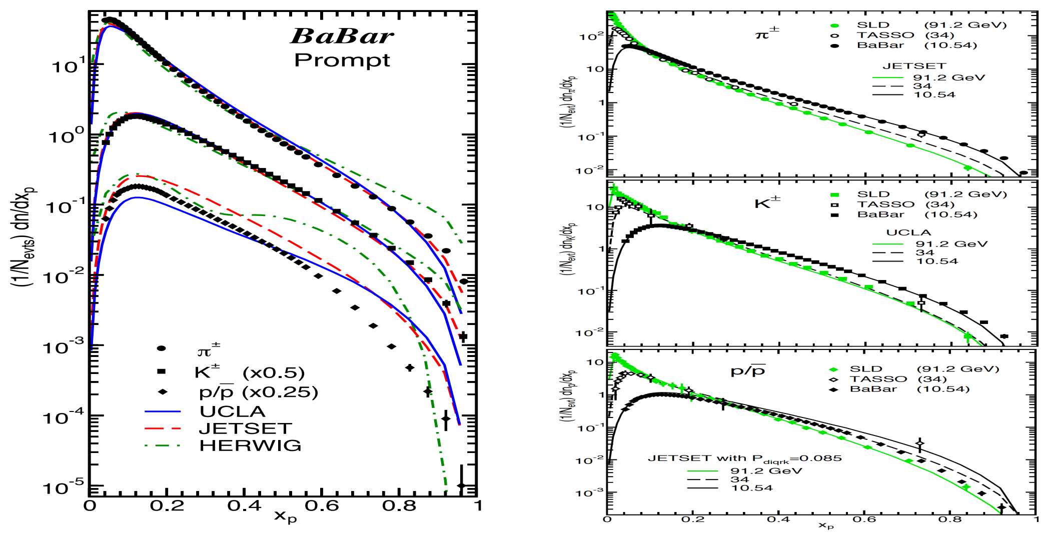
$$F^h(z, Q^2) = \frac{1}{\sigma_{tot}} \frac{d\sigma(e^+e^- \to hX)}{dz}, \tag{1}$$

where $Q^2 = s$, with $\sqrt{s}$ being the CM energy of the collision, $z \equiv 2E_h/\sqrt{s}$ is the fraction of the parton energy carried by the hadron, and σ_{tot} is the total hadronic cross section. At the CM energies of a B-factory the process is mediated by a virtual photon, $e^+e^- \to \gamma^* \to q\bar{q}$ at leading order, while at higher energies also the Z^0 exchange diagram must be taken into account, as it modifies the total cross section and the flavor composition.

So far, *BABAR* has measured hadrons multiplicities for several light hadrons, namely $\pi^\pm$, $K^\pm$, η, and protons, as well as for the charmed baryons $\Lambda_c^\pm$, Ξ_c^0, and Ω_c^0. Spin-induced correlations between particles in opposite jets, related to polarized fragmentation functions, have also been studied. A selection of these results is presented in the following sections.

Inclusive production of light charged hadrons

The *BABAR* measurements of the inclusive production cross sections of the light hadrons $\pi^\pm$, $K^\pm$, $p/\bar{p}$ are based on a data sets of 0.91 fb^{-1} [2]. In parallel, 3.6 fb^{-1} of data recorded at the $\Upsilon(4S)$ resonance are also analyzed. The latter sample provides independent, stringent systematic checks, and the combined samples provide data-driven calibrations of tracking and particle identification performances. The total systematic uncertainty on the pion cross section is at the level of few percent in the full momentum range. It is dominated at low momenta by tracking efficiencies, and at high momenta by particle identification. The uncertainties on the kaon and proton cross sections have similar patterns, but are significantly larger. The results are presented including the decay products of K_S^0 and weakly decaying strange baryons (conventional cross section), or excluding them



(a) (b)

Figure 1: (a) Comparison of the prompt $\pi^\pm$, $K^\pm$ and $p/\bar{p}$ cross sections in $e^+e^- \rightarrow q\bar{q}$ events with the predictions of the UCLA, JETSET and HERWIG models. (b) Conventional $\pi^\pm$, $K^\pm$and $p/\bar{p}$ cross sections measured at three different CM energies, compared with JETSET predictions.

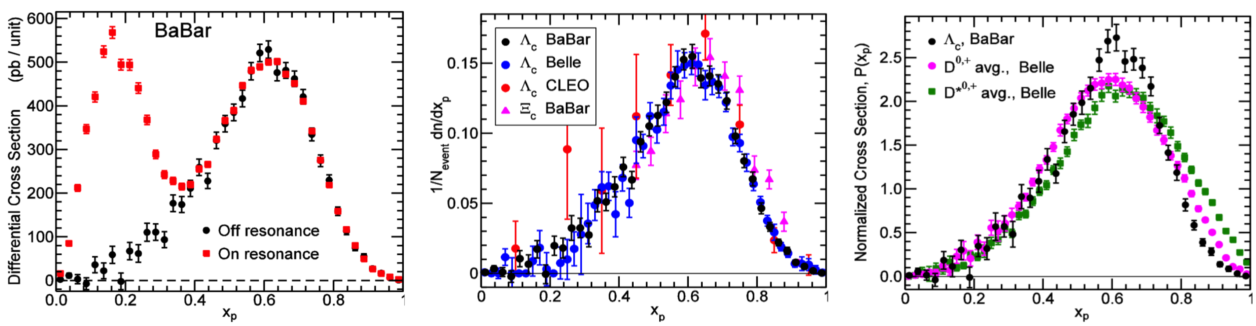
(prompt production). Figure 1a shows the differential cross sections for the prompt production of the three particles as a function of the scaled momentum $x_p = 2p^*/\sqrt{s}$ (black points), compared with the predictions of the three models JETSET, UCLA and HERWIG, which implement three different mechanisms for hadronization and for which the default parameter values have been used in the simulation. Both statistical and systematic errors are included. Note that the results are very precise and extend up to $x_p \sim 1$. All three models describe the bulk of the spectra qualitatively, but no model describes any spectrum in detail, with the largest deviations from data in the high momentum region. Large deviations are seen especially in the case of the proton cross section.

BABAR data can be used together with the very accurate measurements at the Z^0 mass to test the scaling properties of hadronization. Scaling violation effects are expected at low x_p due to the mass of hadrons, while at higher momentum a substantial scaling violation is expected because of the running of the strong coupling α_s. As an example, Fig. 1b reports the differential cross sections measured at three different energies by the *BABAR*, TASSO [3] and SLD [4] experiments, and compares them with the predictions from JETSET. Strong scaling violation is observed for the pion data, correctly reproduced by model prediction at all energies for $x_p \gtrsim 0.1$, with only a few percent difference at very high momenta with *BABAR* data. Also kaon data are consistent with JETSET predictions, which indicates that the model handles correctly the different flavor content at CM energies of 10 ad 90 GeV. On the contrary, the proton data show scaling-violation effects at large x_p smaller than model predictions (this is true also for UCLA and HERWIG, not shown here).

Inclusive production of charmed hadrons

Heavy hadrons produced in e^+e^- annihilations offer a tool for the study of heavy-quark jet fragmentation, in terms of both the relative production rates of hadrons with different quantum numbers and their associated spectra. The latter can be characterized in terms of a scaled momentum, defined in this case as $x_p = p^*/p^*_{max}$, where $p^*_{max} = \sqrt{s/4 - m^2}$ is the maximum momentum available to a particle of mass m produced via $e^+e^- \to q\overline{q}$. *BABAR* studied the production of $\Lambda_c^\pm$ [5], Ξ_c^0 [6], and Ω_c^0 [7] charmed baryons, containing zero, one and two strange valence quarks, respectively, in addition to the charm quark.

The Λ_c study uses a sample of 9.5 fb^{-1} of off-resonance data at $\sqrt{s} = 10.54$ GeV and 81 fb^{-1} at the $\Upsilon(4S)$ peak, and is based on the reconstruction of the 3-body decay mode $\Lambda_c^+ \to pK^-\pi^+$. The invariant mass resolution of the reconstructed Λ_c^+ varies from 3.75 to 5.75 MeV with increasing x_p. Track efficiencies are evaluated from data in two-dimensional (p, θ) bins, and events are weighted by the efficiency matrix. The distribution of the efficiency-corrected invariant mass is then fitted in each x_p bin to extract the signal yield.



(a) (b) (c)

Figure 2: (a) Differential cross sections for $\Lambda_c^+ + \Lambda_c^-$ production in the off-(circles) and on-resonance (squares) data as functions of x_p. The errors are statistical only. (b) Differential Λ_c production rate compared with previous measurements. The Ξ_c^0 rate is normalized to match the peak Λ_c rate. (c) Comparison of Λ_c data with charmed mesons rates from Belle [8].

The measured cross sections in the off- and on-resonance data sets are reported in Fig. 2a. There are two broad peaks in the on-resonance cross section, corresponding to the contributions from $\Upsilon(4S)$ decays at low x_p and from $e^+e^- \to c\overline{c}$ events at high x_p. For $x_p > 0.47$, the kinematic limit for a B-meson decay including a Λ_c^+ and an antiproton, the two cross sections are consistent, indicating no visible contribution from $\Upsilon(4S)$ events. The cross section is obtained assuming a branching fraction $\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+) = 5.0 \pm 1.3\%$.

The shape of the differential production rate is quite hard, as expected, peaking near $x_p = 0.6$; it is consistent with previous results and is measured more precisely, as shown in Fig. 2b, where the *BABAR* Λ_c off-resonance data are compared with CLEO and Belle data, and with the analogous *BABAR* measurement of Ξ_c^0 inclusive production [6]. The peak of the Ξ_c^0 distribution, scaled to to the peak height of the Λ_c distribution, is slightly shifted to an higher value of x_p.

Figure 2c compares the Λ_c production rates normalized to unity area measured by *BABAR* with those obtained by Belle for the inclusive production of charmed D and D^* mesons [8]. Although qualitatively similar, the $D^{(*)}$ meson distributions show broader peaks than the Λ_c distribution and differ greatly in the way they drop to zero at high x_p.

The measured $\Lambda_c^{\pm}$ differential cross section can be used to test several models of heavy-quark fragmentation, none of which, however, provides a complete description of the data (see [5] for details).

Polarized fragmentation functions and Collins asymmetries

Transverse spin effects in fragmentation processes were first discussed by Collins, who introduced the chiral-odd polarized fragmentation function $H_{1,q}^{\perp h}(z, P_{h\perp})$ [9]. The probability that a transversely polarized quark ($q^{\uparrow}$), with momentum direction $\hat{\mathbf{k}}$ and spin $\mathbf{S}_q$, fragments into a spinless hadron h with momentum $\mathbf{P}_h$ is defined in terms of the unpolarized $D_{1,q}^{h}$ and the Collins fragmentation functions:

$$D_{q^{\uparrow}}^{h}(z, P_{h\perp}^2) = D_{1,q}^{h}(z, P_{h\perp}^2) + H_{1,q}^{\perp h}(z, P_{h\perp}^2)\frac{(\hat{\mathbf{k}} \times \mathbf{P}_{h\perp}) \cdot \mathbf{S}_q}{zM_h}, \tag{2}$$

where M_h, $\mathbf{P}_{h\perp}$, and z are the hadron mass, momentum transverse to $\hat{\mathbf{k}}$, and fractional energy, respectively, in the e^+e^- CM energy. The term including $H_1^{\perp}$ introduces a modulation of the azimuthal angle distribution of the final-state hadrons around the direction of the fragmenting quark, called Collins asymmetry.

In $e^+e^- \to q\overline{q}$ events, the quantities $\hat{\mathbf{k}}$ and $\mathbf{S}_q$ of the two quarks are not experimentally accessible. However, the quarks must be produced back-to-back, with their spins aligned to each other and polarized along the e^+ or e^- direction. This results in an azimuthal correlation between pairs of spinless hadrons h_1 and h_2 in the opposite jets originated by the $q - \overline{q}$ pair, reflecting the product of two Collins functions. The Collins asymmetries can be therefore studied through the process $e^+e^- \to q\overline{q} \to h_1h_2X$, where X represents the remainder of the particles produced in the event.

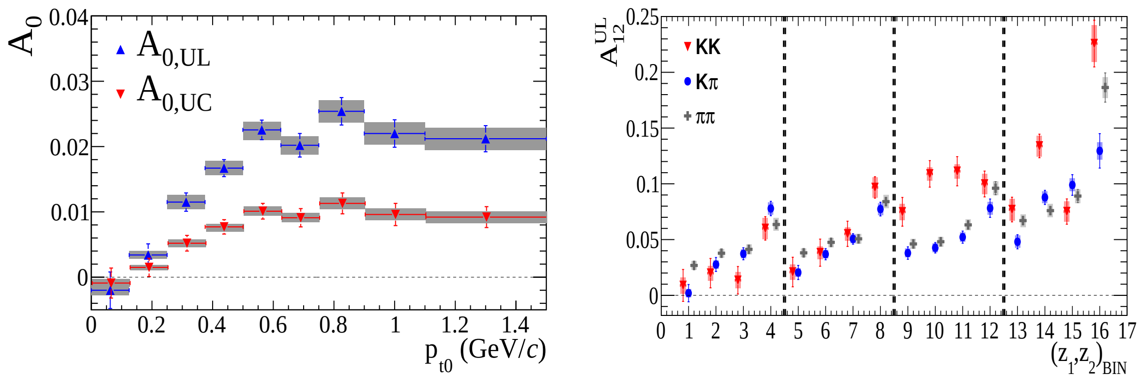
Following the prescription given in Ref. [10], two different reference frames are used: RF12, where the azimutahl angles ϕ_1 and ϕ_2 of the two hadrons are defined with respect to a plane spanned by the thrust axis and the e^+e^- axis, and RF0, where the the azimuthal angle ϕ_0 of one hadron with respect to the plane made by the e^+e^- axis and the momentum of the other hadron is defined.

The first measurements of the Collins effect in e^+e^- annihilation experiments were performed by the Belle Collaboration [11], which studied the dependence of the asymmetry as a function of the pion fractional energies z_1 and z_2.

BABAR published two analyses on Collins asymmetries: the first one [12] reports the Collins asymmetries for charged pion pairs as a function of fractional energies and transverse momenta of the pions, while in the second analysis [13] a simultaneous extraction of the asymmetries as a function of z_1 and z_2 for $\pi\pi$, $K\pi$ and KK pairs is performed.

The azimuthal distributions are strongly distorted by detector acceptances and possibly gluon radiation, which can hide the true asymmetry. To get rid of these effects which are independent of the hadrons electric charge, the selected candidate pairs are subdivided in two samples, formed by pairs of unlike-charge (U) and like-charge (L) pions, and the ratio of the two corresponding normalized yield is built. These so-called double ratios can be fitted with a function

$$F_i^{UL} = B_i^{UL} + A_i^{UL} \cos\phi_i, \tag{3}$$



(a) (b)

Figure 3: (a) Collins asymmetries for pions as a function of p_{t0} in RF0. Statistic and systematic uncertainties are represented by the bars and the bands around the point, respectively. (b) Asymmetries in RF12 for KK, $K\pi$, and $\pi\pi$ pairs in 16 (z_1, z_2) bins: in each interval between the dashed lines, z_1 varies in the following ranges: $[0.15, 0.2]$, $[0.2, 0.3]$, $[0.3, 0.5]$, and $[0.5, 0.9]$, while within each interval the points correspond to the analogous four bins in z_2.

where $\phi_i \equiv \phi_{12} = \phi_1 + \phi_2$ or $\phi_i \equiv 2\phi_0$ for RF12 and RF0, respectively. The fitted asymmetries A_i are proportional to a particular combination of favored and disfavored Collins and unpolarized fragmentation functions. The A_i need to be corrected by several experimental effects, such as resolution, particle misidentification, and background contamination (in particular by light mesons produced from weak decays in $e^+e^- \to c\bar{c}$ events). The results reported in Ref. [12] obtained for the asymmetries in the two-dimensional (z_1, z_2) bins are generally consistent with those from Belle in the common explored range. The asymmetries are of the order of several percent, and clearly rise with increasing fractional energies. *BABAR* provided the only measurements of the asymmetries as a function of the pions transverse momenta, which can be used to study the Q^2 evolution of the Collins function. As an example, Fig. 3a shows the asymmetries A_0^{UL} and A_0^{UC} (where UC stands for the ratio of unlike-charge over all charged pion pairs) as a function of $p_{t,0}$.

A slightly different event and track selection and a coarser binning is used for the second analysis, in which the asymmetries for $\pi\pi$, $K\pi$ and KK pairs have been measured simultaneously [13]. The asymmetries measured as function of the fractional energies in RF12 for the U/L sample are shown in Fig. 3b. These results provide the first information ever obtained in e^+e^- annihilation on the kaon Collins function, which is sensitive to the strange quark.

The results by *BABAR* and Belle have been used in combination with data from Semi-Inclusive Deep-Inelastic Scattering experiments to extract simultaneously the Collins FFs and the *transversity* distribution function (see for example the recent works by Anselmino *et al.* [14]).

With the much larger data sets expected at Belle II, it will be possible to improve these studies by measuring the asymmetries in multi-dimensional bins of fractional energies, transverse momenta and polar angles, to access the fully differential cross sections.

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