PROCEEDINGS OF SCIENCE

Exploring the nucleon structure: Fragmentation Functions from e^+e^- annihilation experiment

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The understanding of the fundamental constituent of nucleons and the internal parton dynamics is one of main goal in modern physics. However, the description of the nucleon structure in the Quantum Chromodynamics (QCD) remains one of the most outstanding challenges in modern high energy and particle physics. Parton distribution and fragmentation functions are used to describe the distribution of partons in the nucleon and the formation of colourless hadrons starting from a coloured partonic initial state, respectively. They are non-perturbative functions which cannot be derived from first principle but for which experimental input are needed. In the last decades, a strong interest has risen about the transverse momentum dependent (TMD) functions, which can be used as a tools to investigate the 3D-structure of nucleons. In this talk we will report a review of the existing data on fragmentation function related measurements form e^+e^- annihilation experiments used for the extraction of parton distributions functions. The aim is to highlight what are the actual limit, what is needed for a better understanding of nucleon structure and the possibilities offered by nucleon-nucleon experiments.

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1. Introduction: Fragmentation Functions and Parton Distribution Functions

The nucleon structure is still a challenging problem: despite is clear that the nucleon physics is much more complex, involving quark orbital angular momenta as well as gluonic and sea quarks contributions, the nucleon spin structure remains one of the most active aspect of the Quantum Chromodynamics (QCD) researches. Many features on nucleons structure can be accessed in semi-inclusive deep inelastic scattering (SIDIS) or in proton-proton reactions. In both cases, the parton distribution functions (PDFs), which are non-perturbative functions describing the distribution of partons (quarks and gluons) in the nucleon, are not easily extractable or require additional inputs from different experiments or theoretical assumptions. In SIDIS experiment, for example, PDFs come in combination with fragmentation functions (FFs), which are non-perturbative functions needed to parametrize the formation of colourless hadrons starting from coloured partons. For a clean extraction of PDFs is still needed an independent knowledge of FFs.

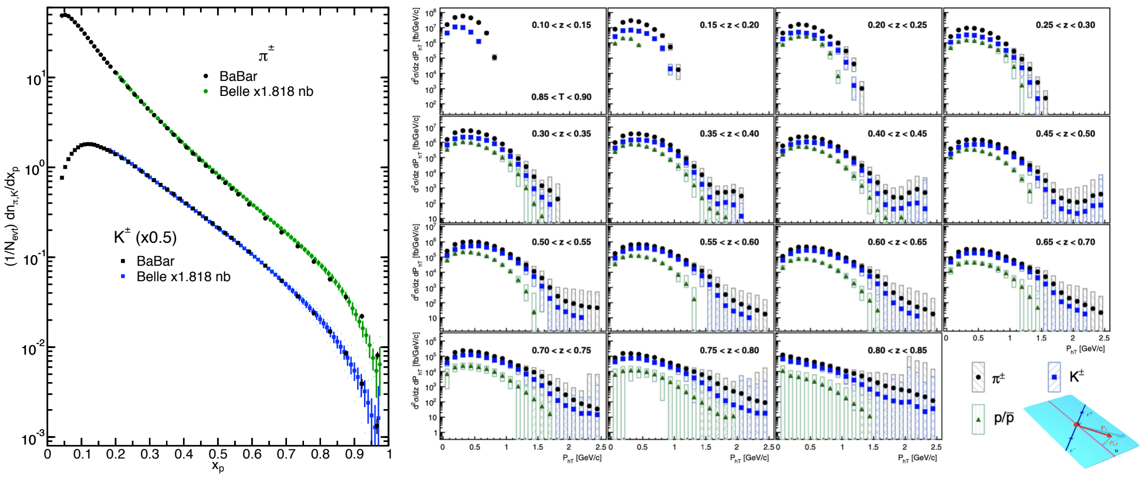
Fragmentation processes contribute to many high energy interactions with hadrons in the final state, but the golden channel is e^+e^- annihilation into hadrons, for which the fragmentations are the only non-perturbative mechanisms that contribute to the cross section, and therefore can be isolated and extracted. The differential cross section for inclusive production of a specific hadron h can be written as:

$$\frac{d\sigma}{dz}(e^+e^- \to hX) = \sum_q \sigma(e^+e^- \to q\bar{q}) \times [D_q^h(z,Q^2) + D_{\bar{q}}^h(z,Q^2)], \tag{1}$$

where the sum is extended to all quark flavors, $D^h_{q(\bar{q})}$ represents the unpolarized fragmentation function for a quark q ($\bar{q}$) into the hadron h, X stands for additional undetected final state particles, z is the longitudinal-momentum fraction of the original quark carried by the hadron h, and $Q^2 = s$ is the squared center-of-mass energy. The $D^h_{q(\bar{q})}$ fragmentation functions are defined also "collinear" as they depend only on the longitudinal hadron momentum fraction z. The inclusion of an additional degree of freedom, the transverse momentum of the hadron with respect to the direction of the fragmenting quark, allows to shed light on the transverse dynamics of partons within the nucleons, and the related fragmentation function, named transverse-momentum-dependent (TMD) FFs, encoded all these mechanisms. One of such mechanism is the Collins effect [1], that in SIDIS can be used to access the transversity PDF h_{1T}, the latest know leading twist PDF due to its chiral-odd nature. The Collins mechanism describes how a transversely polarized (anti)quark fragments into a colorless hadron with transverse momentum $\mathbf{P}_{h\perp}$ with respect to the (anti)quark axis. The related FFs, know an Collins FFs and denoted as $H_1^{\perp,q/\bar{q}}(z,P^2_{h\perp})$ can be extracted using data from e^+e^- annihilation experiments, providing an excellent tool for nuclear structure investigation. Indeed, the chiral-odd nature of the Collins FFs make them the ideal candidate to be coupled to h_{1T}, as well as to TMD chiral-odd PDFs. The TMD functions are poorly measured due to the difficulties to reach the statistical precision on the hadrons transverse momenta determination. Direct measurements of Collins effect has been achieved by BaBar, Belle and BESIII Collaborations [2–6], but little is known about the unpolarized TMD fragmentation functions, for which only Belle data exist [7]. In the following proceeding are reported the latest experimental data on polarized and unpolarized FFs from e^+e^- experiments. The impact and the actual limit on the extraction of the nucleon structure are discussed.

2. Unpolarized Fragmentation Functions

Unpolarized FFs are related to the production rate of a particular hadron in a jet, and can be accessed by measuring the hadron production cross section. In e^+e^- annihilation experiments many precise cross section measurements are available at high $\sqrt{s}$, near the Z^0 mass [8], while the region around $\sqrt{s} \sim 10$ GeV remain poorly investigated. About 10 years ago, the BaBar and Belle Collaborations bridged this lack of information by measuring the cross sections for inclusive production of pions, kaons and protons [9, 10] with very hight precision, as shown in Fig. 1a.



(a) **(b)**

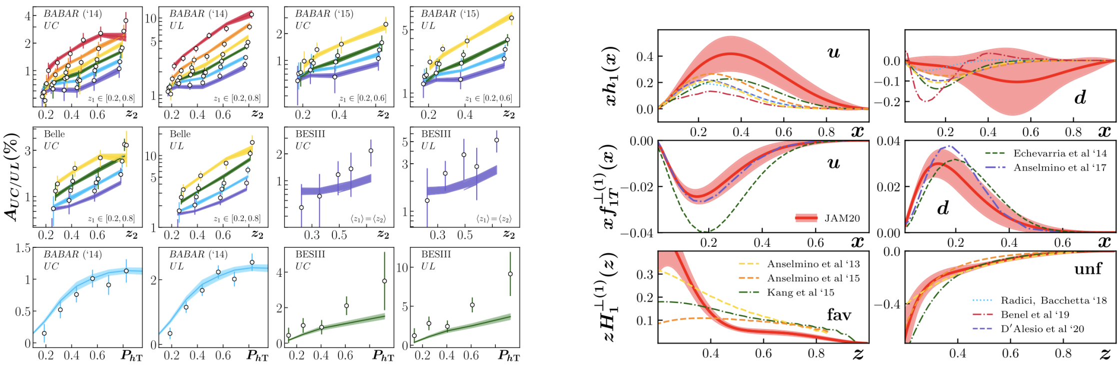
Figure 1: (a) Cross sections for $\pi^{\pm}$ and $k^{\pm}$ measured by BaBar [9] and Belle [10]. Belle data are arbitrary normalized for the comparison. (b) Differential cross sections for $\pi^{\pm}$, $K^{\pm}$, and $p(\bar{p})$ as a function of P_{hT} is bins of z and and for the thrust event-shape variable T [13] between 0.85 to 0.9.

The large number of hadron cross section measurements from different facilities allows to perform global analyses in which different data sets are simultaneously fitted and the FFs extracted. One of such global analysis [11], known as DSS, extracts next-to-leading order FFs using information from e^+e^- annihilation data, including Babar and Belle measurements, together with SIDIS and pp collision measurements.

In a more recent analysis, the unpolarized cross sections (Figure 1b) for single charged pion, kaon, and proton production as a function of fractional energy z and transverse momentum k_T were measured at Belle experiment [12]. These measurements are related to the unpolarized TMD single-hadron $D_1^h(z,k_T)$ FF, and will help to understand the intrinsic transverse-momentum dependence generated in fragmentation processes, as well as they lead the way toward high-precision measurements of TMD effects at the electron-ion collider.

3. Polarized Fragmentation Functions: the Collins effect

The Collins mechanism is associated with an asymmetry in the azimuthal distribution of hadrons generated in the fragmentation processes. The Collins function used to parametrize such process is a chiral-odd function, thus it can be accessed only when coupled to another chiral-odd function, in order to restore the chiral symmetry. The Collins effect for pions are measured by BaBar [3] and Belle [2, 14] Collaborations at $s \sim 10$ GeV^2, and by BESIII [5] at $s \sim 13$ GeV^2 by studying the process $e^+e^- \to h_1 h_2 X$, where $h_{1,2}$ identifies pions or kaons. In addition, the Collins asymmetries for $K\pi$ and KK charged hadron pairs are also been measured by BaBar in Ref. [4], while asymmetries for $\pi^\pm\eta$ and $\pi^\pm\pi^0$ by Belle [15]. The cross section for like- and unlike-sign hadron pairs are proportional to different combinations of favored and unfavored Collins functions, where favored (unfavored) refers to the fact that the fragmenting $q/\bar{q}$ is a valence (sea) $q/\bar{q}$ in the final hadron. As favored and unfavored Collins FFs are expected to differ, the Collins asymmetry can be accessed by measuring the ratio of unlike-sign and like-sign hadron pairs yields, allowing at the same time the elimination of several systematic effects, such as the detector acceptance effects. Figure 2a shows the Collins asymmetry results for pion pairs from obtained from BaBar, Belle and BESIII, and the comparisons with the expected behaviour [16], while the extraction of the Collins FFs from global fit analysis [16] for favored and unfavored processes are shown in Fig. 2b. More studies are still needed in order to extract information on the strange Collins FF [17].



(a) **(b)**

Figure 2: (a) Comparison between theory and data [16]. (b)Extraction of the first moment of the Sivers function (upper plots), transversity function (middle plots), and first momento of Collins FFs (lower plots) [16].

4. $\Lambda/\bar{\Lambda}$ hyperon fragmentation functions

In a recent Belle analysis, the transverse polarization of $\Lambda/\bar{\Lambda}$ have been used to extract for the first time the TMD fragmentation function $D_{1T}^{\perp}$ of Λ hyperons [18] in the processes $e^+e^- \to h_1 h_2 X$ and $e^+e^- \to h_1 X$, where h_1 is a spin$-1/2$ hadron, h_2 is a light unpolarized hadron produced almost back-to-back to h_1. A clear separation in flavour has been achieved, and the first moment of the polarized FFs was extracted [18]. New data with higher statistics, as well as complementary studies in other processes, will help to a deeper understanding of this TMF FF.

Regarding the Collins FF for the Λ hyperons, it also contains complementary information of the Λ fragmentation and give rise to the azimuthal asymmetries in the high energy process. No data form e^+e^- annihilation experiments are still present, but a feasible study of the unpolarized $e^+e^- \to \Lambda\bar{\Lambda}X$ and $e^+e^- \to \Lambda\pi X$ processes are performed by Authors of Ref. [19]. The Collins related asymmetry is expected to be of the order of several percent, and it increases with increasing z. This make this measurement feasible using Belle and BaBar data.

5. Conclusions

In this proceeding are discussed how from e^+e^- annihilation data can be derived important information related to the nucleon structure. Independent and essential informations on the nucleons structure can be achieved from Drell-Yan processes and polarized proton-proton (antiproton) processes. In particular, a dedicated physics program on the study of the nucleon structures is one of the key point of the Facility for Antiproton and Ion Research at GSI in Darmstadt: measurements of the proton electromagnetic form factors in the time-like region, nucleon-to-meson transition distribution amplitudes, generalised distribution amplitudes, and transverse momentum dependent parton distribution functions, will help to shed light on the hadrons 3-dimensional structure.

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