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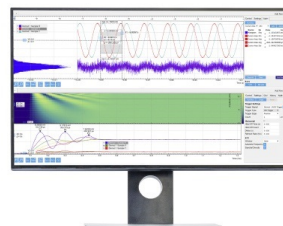
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Studies of Partonic Distributions using Kaon SIDIS

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Abstract. The E12-09007 experiment in CLAS12 of Hall B at Jefferson lab proposed to measure multiplicities and longitudinal double spin asymmetries for pions (π^+, π, π^0) and kaons (K^+, K, K^0_s) in Semi-Inclusive Deep Inelastic Scattering (SIDIS) from both hydrogen and deuterium. The data will be used to measure the x -dependence of the strange parton distribution function (PDF) and will help constrain the global fits used to obtain the fragmentation functions (FF). In addition this data will allow the extraction of the individual contributions of quarks and anti-quarks to the nucleon spin. The experiment is scheduled in two parts: the first involves unpolarized beam and targets for multiplicity and strange PDF measurements, the second uses both polarized beam and targets for the spin flavor decomposition. The measurements will cover the x -range from 0.05 to 0.7. Part of the unpolarized measurements was achieved in winter and data taking will continue at the end of this year. The polarized part of the experiment will run in a few years. The experiment requires the use of a Ring Imaging Cherenkov (RICH) detector for a successful charged kaon identification in the 3 to 8 GeV/c momentum range. One full RICH detector was recently built and is functional; a second one is under construction.

INTRODUCTION

The understanding of the spin structure of the nucleon in terms of quarks and gluons has been the goal of intense investigations during the last couple of decades. The techniques of inclusive and semi-inclusive polarized deep-inelastic scattering employed at CERN, SLAC, DESY, and Jefferson Lab have provided a wealth of information about the spin structure of the nucleon. The contributions of the u and d quarks in the valence region have now been quiet well established [1] and data from collisions of polarized protons at RHIC has done much to advance our knowledge of the limitations of the gluon spin contribution to the spin of the nucleon, although with a large uncertainty [2]. The determination of strangeness, however, is challenging as it has the same electroweak couplings as the down distribution while it is typically much smaller than it. In absence of significant experimental constraints, the lack of information on $s(x)$ and $\bar{s}(x)$ is reflected in the common practice of adopting the simplified ansatz $s = \bar{s} = r(\bar{u} + \bar{d})/2$ [3]. Accessing in more direct way the contributions of the strange quarks and antiquarks can be achieved in Semi-Inclusive Deep Inelastic Scattering (SIDIS) when hadrons are detected in the final state in addition to the scattered lepton.

The momentum distribution functions of partons (quarks, anti-quarks and gluons) inside the proton are called parton distribution functions (PDFs). They represent the probability densities to finding a parton carrying a momentum fraction x at a squared four-momentum Q^2 . The PDFs of the strange quarks in the nucleon describe important features of the structure of the quark sea [4, 5, 6, 7] and the strangeness content of the nucleon is of special interest because of its impact in calculations of short-distance processes at high energy [8], and also in view of the 2012 ATLAS results [9], which suggest that at small fractional x it could be substantially larger than previously assumed.

Results from Inclusive Deep-Inelastic Scattering (DIS) experiments, where only the scattered electron is detected, indicate that the net contribution of the quark spins to the spin of the nucleon is very small. Under the assumption of SU(3) symmetry this small contribution implies a significant negative value for the polarization of the strange quark sea in the proton. Such a value would explain the violation of the Ellis-Jaffe sum rule in inclusive DIS. However, results from HERMES for a flavor decomposition of quark helicity distributions based on SIDIS suggest that the strange sea polarization is zero or slightly positive [10, 11, 12]. This discrepancy between inclusive and semi-inclusive measurements needs to be checked by performing an independent third high precision measurement.

The E12-09-007 experiment [15] proposed to further elucidate the flavor contributions to the nucleon spin through “The study of parton distribution functions using semi-inclusive production of Kaons”. This A[−] rated experiment is granted 110 full running days using CLAS12 spectrometer in Hall B of Jefferson Lab. The goal of the experiment is to perform high precision multiplicity and asymmetry measurements and reduce the systematics related to our knowledge of quark helicity distributions and fragmentation functions. These fragmentation functions describe the

phenomenon of hadronization, i.e., how quarks or gluons transform into hadrons before even being detected as free particles, they are essential manifestations of Quantum Chromo-Dynamics (QCD) and confinement. The ensuing dramatic improvement in the knowledge of fragmentation functions will be an important ingredient in the global analysis of the nucleon structure from SIDIS and proton-proton collision data, therefore contributing in a unique way to the challenge of understanding how partons build up all intrinsic properties of the nucleon, in particular how they share the nucleon's spin. This is one of the main goals of the upgraded 12 GeV CEBAF at JLab and the future Electron Ion Collider (EIC). The experiment will in addition test whether or not the light sea is symmetrically polarized and improve the next to leading order (NLO) global analysis of the Helicity Parton densities and their uncertainties. The full program of the experiment is summarized in Fig. 1.

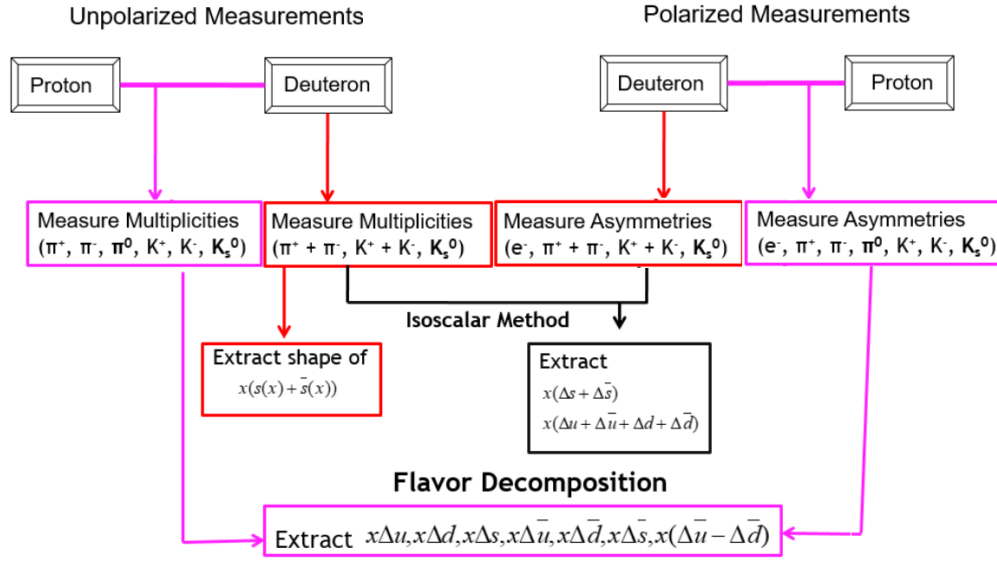


FIGURE 1. Program proposed by the E12-09-007 Experiment in CLAS12 at Jefferson Lab.

FORMALISMS

Hadron production in DIS is described by the absorption of a virtual photon by a quark followed by the fragmentation of this quark into hadronic final states as shown in Fig. 2. The first process is characterized by the quark distribution functions and the second by the fragmentation functions.

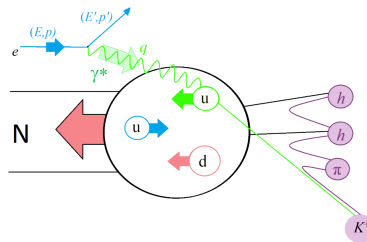


FIGURE 2. Hadron creation in SIDIS reactions.

The proposed measurements are two-fold. **First**, the multiplicities for several hadron species ($\pi^+, \pi^-, \pi^0, K^+, K^-, K_s^0$) using both hydrogen and deuterium targets will be measured. The goal of these measurements is the control of the fragmentation functions used in the extraction of the individual quark and anti-quark contributions

to the nucleon spin. In addition to the measurement of the shape (x dependence) of the strange parton distribution function for several z and Q^2 bins with three independent measurements ($\pi^+ + \pi^-$, π^0 , $K^+ + K^-$ and K^s). All these measurements are scheduled to take place for 56 days in the periods: January to March then November to December 2019.

The **second** goal is the polarized measurements. The aim is to use two different methods to access the quark polarization. The first is the so-called isoscalar method where only polarized deuterium is used to extract the non strange and strange polarized parton distribution functions. The second method is a full flavor decomposition method using the information on both hydrogen and deuterium targets to extract individual contributions of the quarks to the nucleon spin. Both polarized and unpolarized measurements will cover the x range from $0.05 < x < 0.7$.

Finally, a very important piece of these measurements is the extraction of $\Delta\bar{u} - \Delta\bar{d}$: Measuring the spin asymmetry for K^- jet off a hydrogen target is of a special interest since it is particularly sensitive to $\Delta\bar{u} - \Delta\bar{d}$ which provides an excellent test for theoretical models describing the unpolarized densities $\bar{u} - \bar{d}$. Two of such models are the Chiral Quark Soliton Model (χ QCM) [17], which is based on an effective theory in which baryons appear as soliton solutions of the Chiral Lagrangian. The second one is a meson cloud model [18] that describes the nucleon as a bare nucleon surrounded by a cloud of virtual mesons. Fig. 6 right shows the existing data on $\bar{u} - \bar{d}$ measured at HERMES. While the data tend to prefer flavor symmetry, no decisive conclusion can be made due to the lack of statistical precision. The blue points in the figure are the projected high statistics data one can achieve with CLAS12.

The polarized measurements are planned to run after the polarized deuteron and hydrogen targets are installed in Hall B in 2021.

Formalism for unpolarized deuteron target: Multiplicities and Strange PDFs

Polarized and unpolarized deuteron and proton data are necessary for the full flavor decomposition. Same technique as for the isoscalar method will be applied, but with the use of the purities that will be obtained from unpolarized PDFs and fragmentation functions from the first part of the experiment. One can constrain the fragmentation functions using pion and kaon multiplicities in the same kinematical range from unpolarized data. The system in equation 12 can be solved by a χ^2 minimization accounting for the correlations between the various asymmetries.

$$\vec{\mathcal{A}}(x, Q^2) = \mathcal{P}(x, Q^2) \cdot \vec{\mathcal{Q}}(x, Q^2) \quad (1)$$

At the leading order of QCD and for unpolarized SIDIS, the cross section for hadron production at a given x , Q^2 and z , normalized to the corresponding inclusive cross section takes the factorized form

$$\frac{d\sigma^h(x, Q^2, z)/dx dQ^2 dz}{d\sigma^{DIS}(x, Q^2)/dx dQ^2} = \frac{dN^h(x, Q^2, z)}{dN^{DIS}(x, Q^2)} = \frac{\sum_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}{\sum_q e_q^2 q(x, Q^2)} \quad (2)$$

where q is the parton distribution function for a quark of flavor q , e_q its charge. D_q^h is the fragmentation function, a measure of the probability that a quark of flavor q fragments into a hadron of type h . At our kinematics, only light quarks and anti-quarks flavors, $q = (u, \bar{u}, d, \bar{d}, s, \bar{s})$, are considered. z is the fraction of the photon energy carried by a hadron h . For deuterium; an isoscalar target, the fragmentation functions become isospin independent. By assuming isospin symmetry, the strange PDF to be same for both nucleons and charge conjugation invariance in the fragmentation functions, the multiplicity for a final product (H) simplifies to:

$$\frac{dN^H(x, Q^2)}{dN^{DIS}(x, Q^2)} = \frac{Q(x, Q^2) \int D_{NS}^H(z, Q^2) dz + S(x, Q^2) \int D_S^H(z, Q^2) dz}{5Q(x, Q^2) + 2S(x, Q^2)} \quad (3)$$

where $H = K^+ + K^-$, $\pi^+ + \pi^-$ or K_s^0 . The sum of non strange and strange parton distribution functions are $Q = u + \bar{u} + d + \bar{d}$ and $S = s + \bar{s}$, respectively. Furthermore, $D_{NS}^H = 4D_u^H + D_d^H$ and $D_S^H = 2D_s^H$ are the non strange and strange

fragmentation functions, respectively. The term $2S(x, Q^2)$ is at the most 1% ($0.05 \leq x \leq 0.075$) of the $5Q(x, Q^2)$ term, therefore one can safely drop it off. We then realize that once we are in the region where the sum of the strange parton distribution functions $S(x)$ vanishes, the multiplicity becomes independent of x

$$\frac{dN^H(x, Q^2)}{dN^{DIS}(x, Q^2)} = \frac{\int D_{NS}^H(z, Q^2) dz}{5} \quad (4)$$

Once in that region, one can extract for each z bin, the Q^2 dependence of the NS fragmentation function from the measured multiplicities. By taking the non strange PDFs from most up to date parameterizations available at the time of the data analysis and plugging them back to the multiplicity equation, one can extract the x dependence of strange contribution $S(x, Q^2) \int D_S^H(z, Q^2) dz$ for specific (z, Q^2) bins. This method is very reliable in getting the shape of the sum of the strange PDFs. However its absolute value $S(x, Q^2)$ relies on the quality of the used parameterization for the fragmentation functions.

Formalism of the Isoscalar method

Following the parton model, at leading order (LO), the semi-inclusive double-spin asymmetry for charged-kaon production can be written in terms of quark helicity distributions $\Delta q(x, Q^2)$ and kaon fragmentation functions $D_q^K(z, Q^2)$. Applied to a deuteron target, assuming isospin symmetry and charge conjugation invariance and by integrating over $z = E_h/v$, this asymmetry can be reduced to:

$$A_{1,d}^K(x) = \frac{\Delta Q(x) \int \mathcal{D}_Q^K(z) dz + \Delta S(x) \int \mathcal{D}_S^K(z) dz}{Q(x) \int \mathcal{D}_Q^K(z) dz + S(x) \int \mathcal{D}_S^K(z) dz} \quad (5)$$

where $Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$, $S(x) = s(x) + \bar{s}(x)$, $\int \mathcal{D}_Q^K(z) dz = 4 \int D_u^K(z) dz + \int D_d^K(z) dz$ and $\int \mathcal{D}_S^K(z) dz = 2 \int D_s^K(z) dz$. The Q^2 dependence is omitted for simplicity. The corresponding inclusive double spin asymmetry is given by:

$$A_{1,d}(x) = \frac{5\Delta Q(x) + 2\Delta S(x)}{Q(x) + S(x)} \quad (6)$$

The non-strange $\Delta Q(x)$ and the strange $\Delta S(x)$ helicity distributions are obtained by combining Eqs. (5) and (6) in a matrix form:

$$\begin{pmatrix} A_{1,d}(x) \\ A_{1,d}^K(x) \end{pmatrix} = \begin{pmatrix} P_Q(x) & P_S(x) \\ P_Q^K(x) & P_S^K(x) \end{pmatrix} \begin{pmatrix} \Delta Q(x)/Q(x) \\ \Delta S(x)/S(x) \end{pmatrix} \quad (7)$$

$$\text{where} \quad P_Q(x) = \frac{5Q(x)}{5Q(x) + 2S(x)}, \quad P_Q^K(x) = \frac{Q(x) \int \mathcal{D}_Q^K(z) dz}{Q(x) \int \mathcal{D}_Q^K(z) dz + S(x) \int \mathcal{D}_S^K(z) dz}, \quad (8)$$

$$\text{and} \quad P_S(x) = \frac{2S(x)}{5Q(x) + 2S(x)}, \quad P_S^K(x) = \frac{S(x) \int \mathcal{D}_S^K(z) dz}{Q(x) \int \mathcal{D}_Q^K(z) dz + S(x) \int \mathcal{D}_S^K(z) dz}. \quad (9)$$

In order to get the non-strange and the strange helicity distributions, we need to determine $Q(x)$, $S(x)$, $\int \mathcal{D}_Q^K(z) dz$ and $\int \mathcal{D}_S^K(z) dz$. $Q(x)$ will be taken from the most up to date CTEQ parametrization at the time of the analysis and $\int \mathcal{D}_S^K(z) dz$ is taken from the analysis of the fragmentation functions. $S(x)$ and $\int \mathcal{D}_Q^K(z) dz$ are to be extracted from the charged-kaon multiplicities which, for a deuteron target and at LO, are expressed by:

$$\frac{d^2 N^K(x)/dx dQ^2}{d^2 N^{DIS}(x)/dx dQ^2} = \frac{Q(x) \int \mathcal{D}_Q^K(z) dz + S(x) \int \mathcal{D}_S^K(z) dz}{5Q(x) + 2S(x)}. \quad (10)$$

By neglecting the term $2S(x)$ compared to $5Q(x)$ we get

$$S(x) \int \mathcal{D}_S^K(z) dz = Q(x) \left[5 \frac{d^2 N^K(x)}{d^2 N^{DIS}(x)} - \int \mathcal{D}_Q^K(z) dz \right]. \quad (11)$$

Finally, the strange parton distribution $xS(x)$ can be extracted from dividing $S(x) \int \mathcal{D}_S^K(z) dz$ by the value of $\int \mathcal{D}_S^K(z) dz$ at a certain Q^2 .

Formalism of the Full Flavor Decomposition

Polarized and unpolarized deuteron and proton data are necessary for the full flavor decomposition. Same technique as in sec. will be applied, but with the use of the purities that will be obtained from unpolarized PDFs and fragmentation functions from the first part of the experiment. One can constrain the fragmentation functions using pion and kaon multiplicities in the same kinematical range from unpolarized data. The system in equation 12 can be solved by a χ^2 minimization accounting for the correlations between the various asymmetries.

$$\vec{\mathcal{A}}(x, Q^2) = \mathcal{P}(x, Q^2) \cdot \vec{\mathcal{Q}}(x, Q^2) \quad (12)$$

THE E12-09-007 EXPERIMENTAL SETUP

CEBAF accelerator at Jefferson Lab (Jlab) was upgraded to provide highly polarized electron beams at a maximum energy of 11 GeV and a luminosity up to $10^{35} \text{cm}^{-2} \text{s}^{-1}$ for Hall B, providing a world-leading facility for the study of electron-nucleon/nucleus scattering with a wide angular coverage. CLAS12, in Hall B, is a magnetic spectrometer which consists of two parts, a forward detector (FD) and a central detector (CD). The FD is built around a superconducting torus magnet. The toroidal field is produced by six coils that naturally divide the spectrometer in six independent sectors. The CLAS12 baseline equipment comprises a time-of-flight system (TOF), able to efficiently identify hadrons up to a momentum of about 3 GeV/c, and two Cherenkov gas detectors of high (HTCC) and low (LTCC) threshold. This system is able to reach the needed pion rejection power up to the upper limit of hadron momenta (around 8 GeV/c) but is not able to distinguish kaons from pions above 3 GeV/c with the accuracy needed to perform SIDIS experiments. To improve the particle identification of CLAS12 two sectors of the LTTC will be replaced by two sectors of a RICH detector. One sector of the RICH was built and installed in January 2018 as shown in Fig. 3. A second sector is under construction and will be installed opposite to the first one.

A Ring-Imaging Cherenkov (RICH) detector is a device that allows the identification of electrically charged subatomic particle types through the detection of the Cherenkov radiation emitted (as photons) when a fast particle crosses a radiator with a velocity β larger than the velocity of the light in that medium. The light is emitted in a cone with opening angle θ_C given by $\cos(\theta_C) = 1/\beta n(\lambda)$, where $n(\lambda)$ is the refractive index of the radiator which depends on the photon wavelength (λ). The particle identification is achieved by measuring the Cherenkov angle.

Particles of different masses but same momentum can be distinguished by the distinct contours of their emitted photons. Photons emitted by heavier particles (like Kaons) fall into smaller radius circle than the ones emitted by a lighter particles (like pions).

A hybrid design is adopted for CLAS12 RICH, incorporating: aerogel radiators, spherical mirror and planar mirrors, and Multi-Anode PMTs (MA-PMTs) for the photons detections. Figure 4 represents a photograph (left) and detector response (right) of the RICH MAPMT array during beam operation. One event with the ring of Cherenkov photons is shown in the right plot and the radius of the ring corresponds to a pion.

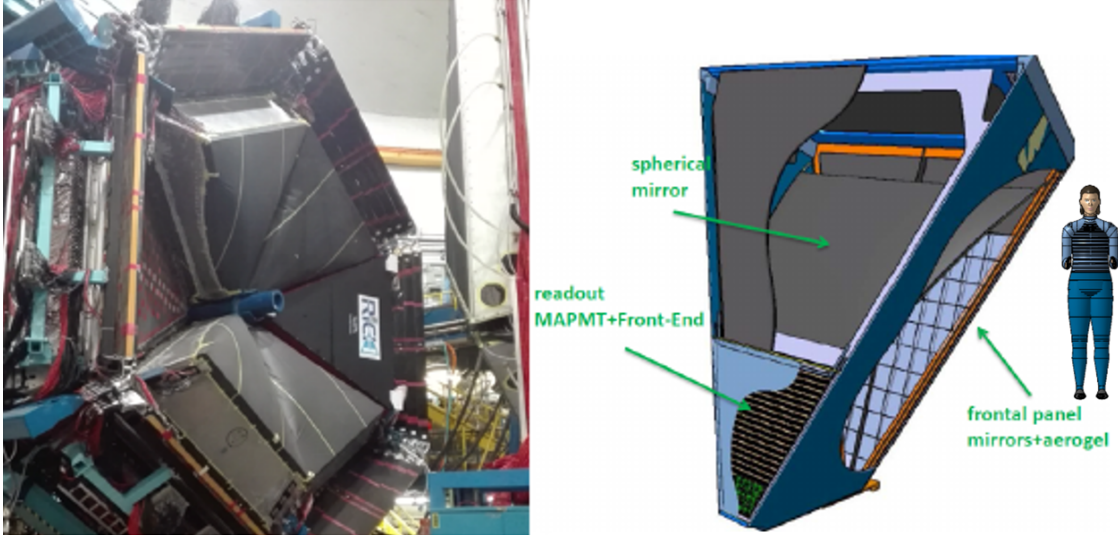


FIGURE 3. Left: RICH installed in CLAS12. Right: RICH components.

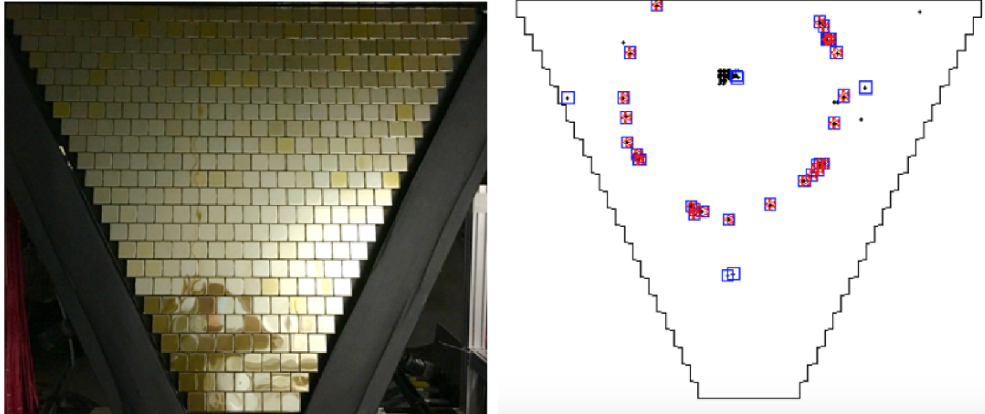


FIGURE 4. Photograph (left) and detector response (right) of the RICH MAPMT array during beam operation. Right: One event with the ring of Cherenkov photons. The radius of the Cherenkov ring corresponds to a pion.

EXPECTED PRECISIONS

A large amount of measurements, as can be seen from the program chart in Fig. 1, will be done during the E12-09-007 experiment and only some of the predicted results are presented here: Kaon multiplicities are presented in Fig. 5 left. The strange distribution $xS(x)$ is presented at the right of this figure and the predictions are compared to HERMES results at $Q^2 = 2.5 \text{ GeV}^2$. The dashed curve gives $xS(x)$ from CTEQ6L, and the dot-dashed curve is the sum of light antiquarks from CTEQ6L. The dotted curve is from CTEQ6.5S-0, a PDF reference set [13]. The broad band is the zone of allowed values predicted by the neural network (NNPDF2.3) reference set [14]. The band at the bottom represents the propagated experimental systematic uncertainties. Predictions of the planned E12-09-007 measurements are the blue points.

In Fig. 6, left, the predictions of $x\Delta(S)$ from the isoscalar measurements are compared to *GRSV* [19] and *DSSV* [20] parameterizations along with the previously cited HERMES data in red and COMPASS measurements in gray. The right plot presents the statistical projections of $\Delta\bar{u} - \Delta\bar{d}$ compared to HERMES results.

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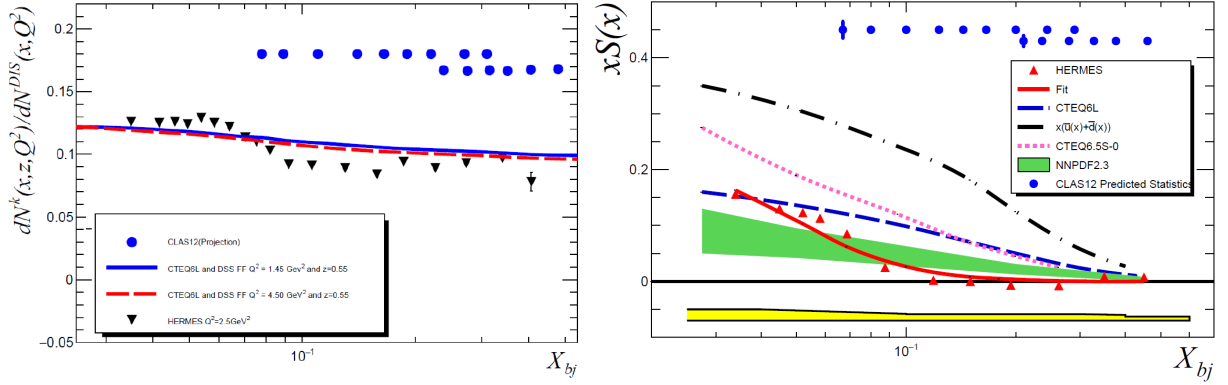


FIGURE 5. Left: Predictions of the kaon multiplicities for E12-09-007 (blue points) along with results from HERMES (black triangles). Right: Strange-parton distribution predictions (blue points) $xS(x)$. Both are compared to HERMES results.

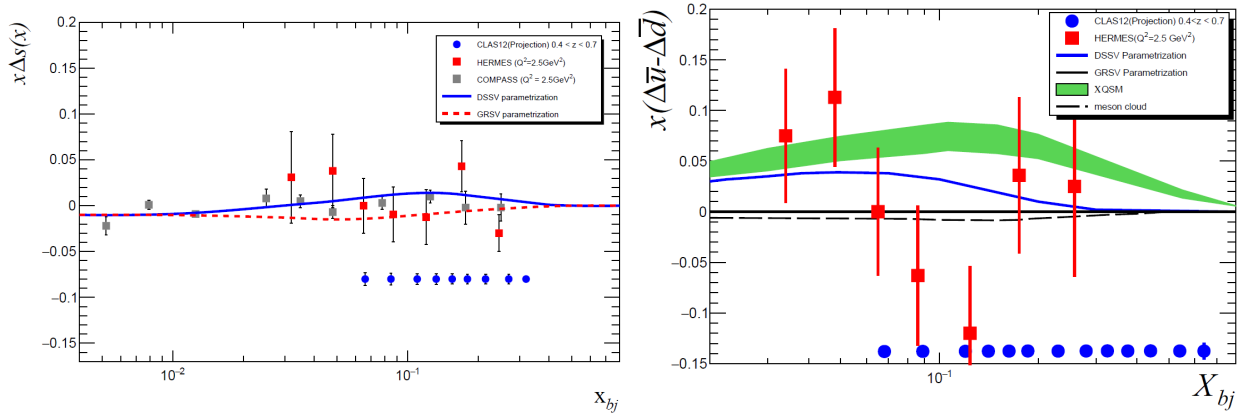


FIGURE 6. Left: predictions of $x\Delta S$ (blue points) compared to HERMES (red squares) and COMPASS (gray squares) results. Right: Statistical projections for $x(\Delta\bar{u} - \Delta\bar{d})$ (blue points) compared to HERMES results (red squares).

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