PROCEEDINGS OF SCIENCE

Incorporating BESIII measurements in the Updated K_S^0 Fragmentation Functions

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We revisit the extraction of parton-to-K_S^0 fragmentation functions (FF24-K_S^0) at next-to-leading-order (NLO) and next-to-next-to-leading-order (NNLO) accuracy in a QCD analysis, using single inclusive electron-positron annihilation (SIA) data. Key improvements include incorporating new BESIII data and adopting Neural Networks in the fitting process. We also discuss the impact of hadron mass corrections, particularly at small z. Our NLO and NNLO predictions show good agreement with experimental data, accounting for uncertainties via the Monte Carlo method.

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1. Introduction

Fragmentation functions (FFs) are essential for understanding parton-to-hadron transitions in QCD and have been extensively studied using data from various experiments. The K_S^0 fragmentation functions, in particular, were analyzed in previous works like SAK20 [1], based on single inclusive electron-positron annihilation (SIA) data. Recent measurements from the BESIII experiment [2], covering an energy range previously underrepresented in earlier studies, provide valuable input for updating the K_S^0 FFs. This work incorporates the BESIII data and employs machine learning techniques, specifically neural networks, to improve precision and reduce biases in the FF extraction process. The resulting updated FF sets, at both NLO and NNLO, are made publicly available in the LHAPDF format.

2. Experimental Data and Methodology of Analysis

The study utilizes experimental measurements of K_S^0 production cross-sections from SIA processes. Various collaborations, including TASSO [3, 4], HRS [5], TPC [6], MARKII [7], CELLO [8], and TOPAZ [9], provided data across different energy scales ranging from 14 GeV to 58 GeV. Datasets from ALEPH [10], DELPHI [11], and OPAL [12] at $\sqrt{s} = M_Z$ were also incorporated. Additionally, quark-tagged data for light, charm, and bottom quarks from the SLD collaboration [13] were included.

The most recent data from the BESIII collaboration [2], covering center-of-mass energies from 2.2324 GeV to 3.6710 GeV, are a significant addition. These measurements, collected at the BEPCII detector, span a wide z range of 0.2 to 0.9 and provide critical input for K_S^0 fragmentation function fits in the low-energy regime, where previous datasets were scarce.

According to BESIII paper [2], discrepancy was observed between the K_S^0 data from BESIII and theoretical predictions, especially in lower energy scales. This motivated the inclusion of BESIII data to improve fragmentation function fits at low energies. Kinematic cuts were applied to ensure the reliability of the fixed-order QCD predictions. The minimal value of z was set at $z_{\min} = 0.013$ for all datasets, with a maximum $z_{\max} = 0.9$. Some outlier points were omitted, resulting in a final dataset of 346 data points.

The analysis follows standard collinear factorization in perturbative QCD, where the total cross-section for e^+e^- annihilation into hadrons is given by:

$$\frac{1}{\sigma_{\rm tot}}\frac{d\sigma^h}{dz} = \frac{1}{\sigma_{\rm tot}} C_i(x, \alpha_s(\mu), Q^2/\mu^2) \otimes D_i^h(z/x, \mu^2), \tag{1}$$

where C_i are coefficient functions and D_i^h are the FFs. The evolution of FFs across different energy scales is governed by time-like DGLAP evolution equations:

$$\frac{\partial D_i^h(z, \mu^2)}{\partial \ln \mu^2} = P_{ji}(x, \alpha_s(\mu^2)) \otimes D_j^h(z/x, \mu^2). \tag{2}$$

Hadron mass corrections, essential at low z, are incorporated using a modified scaling variable η:

$$\eta = \frac{z}{2}\left(1 + \sqrt{1 - \frac{4m_h^2}{sz^2}}\right), \tag{3}$$

where m_h is the hadron mass. The corrected cross-section is then expressed as:

$$\frac{d\sigma}{dz} = \frac{1}{1 - \frac{m_h^2}{s\eta^2}} \sum_a \int_\eta^1 \frac{dx_a}{x_a} \frac{d\hat{\sigma}_a}{dx_a} D_a^h\left(\frac{\eta}{x_a}, \mu\right), \tag{4}$$

where $\hat{\sigma}_a$ is the differential cross-section of the hard subprocess.

In this analysis, $m_c = 1.51$ GeV and $m_b = 4.92$ GeV are used for the charm and bottom quarks, respectively, with the strong coupling constant $\alpha_s(m_Z) = 0.118$ at two-loop order. The mass corrections play a crucial role in improving the fit for low-energy data from BESIII. Particularly, corrections exceeding 50% can be observed around $z < 0.4$ at $\sqrt{s} = 2.2324$ GeV, $z < 0.3$ at $\sqrt{s} = 3.44$ GeV, $z < 0.06$ at $\sqrt{s} = 14$ GeV, $z < 0.03$ at $\sqrt{s} = 29$ GeV, and $z < 0.01$ at $\sqrt{s} = 91.2$ GeV.

The open-source frameworks MontBlanc and Ceres Solver are used for fitting, with the FFs expressed as:

$$zD_i^h(z, Q_0) = (N_i(z; \boldsymbol{\theta}) - N_i(1; \boldsymbol{\theta}))^2, \tag{5}$$

where $N_i(z; \boldsymbol{\theta})$ is the NN output. Cross-validation and Monte Carlo sampling methods are applied to ensure the robustness of the fit and account for uncertainties.

Results and Discussion

The analysis evaluates the quality of the FF24-K_S^0 fragmentation functions by comparing the experimental data with theoretical predictions. A comprehensive dataset from collaborations cover a wide range of center-of-mass energies. Kinematical cuts were applied to ensure the reliability of the data, yielding a total of 346 data points. The overall fit quality is excellent, with overall χ^2 per data point values of 0.91 at NLO and 0.87 at NNLO, indicating good agreement between the data and predictions.

To assess the impact of BESIII data on K_S^0 FFs, we compare the predictions from both SAK20 and the new FF24-K_S^0 FFs in Fig. 1. Significant differences are observed across all energies and z values. The SAK20 predictions, extracted from high-energy SIA data, show a rise in the cross sections at low z, which is not reflected in the BESIII data. This suggests that backward evolution from high to low energies is insufficient, and incorporating BESIII data improves the fit, particularly at low z.

We now compare the FF24-K_S^0 FFs at NNLO with those from SAK20 [1] and NNFF1.0 [14], as shown in Fig. 2. The central values display different behaviors across all parton species. For b^+, c^+, and s^+, FF24-K_S^0 values are smaller than those of both SAK20 and NNFF1.0. For u^+ and gluon FFs, FF24-K_S^0 exceeds SAK20 but remains lower than NNFF1.0. The uncertainty bands for FF24-K_S^0 are generally narrower than NNFF1.0, especially for $z < 0.1$, and narrower than SAK20 except for d^+ and s^+.

In summary, the FF24-K_S^0 set improves the accuracy of K_S^0 fragmentation functions, particularly at low z, thanks to the inclusion of BESIII data and the use of neural networks. This new FF set provides reliable predictions for future high-energy experiments.

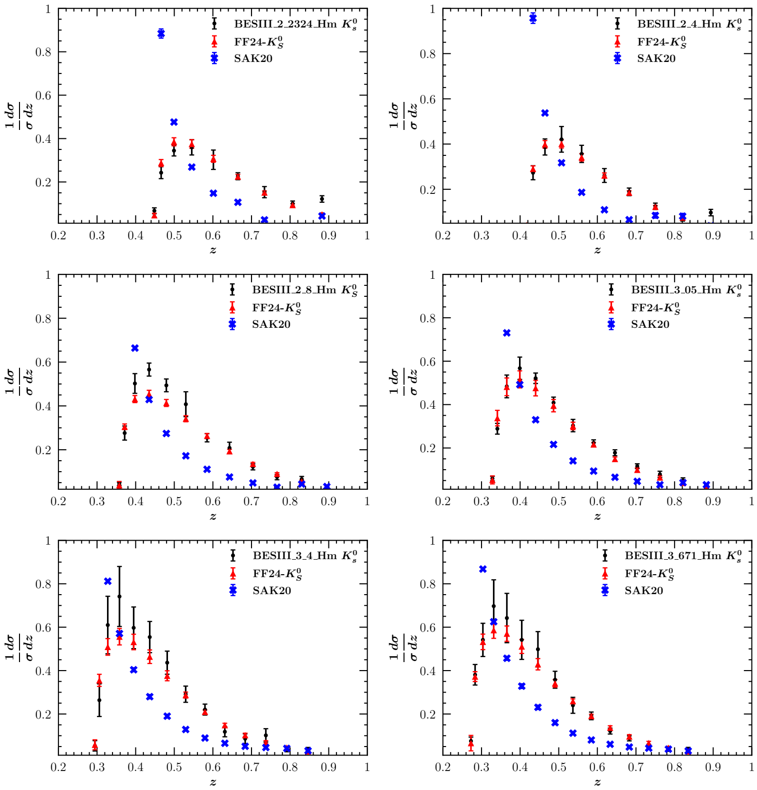

Figure 1: Comparison between the predictions for cross sections of K_S^0 production from SAK20 [1] and the present analysis at NLO accuracy and the measurements from the BESIII experiment.

Summary and Outlook

This paper presents new fragmentation functions for K_S^0, called FF24-K_S^0, derived from a QCD analysis at NNLO accuracy. The analysis incorporates recent experimental data from the BESIII collaboration, which spans collision energies below $\sqrt{s}$ = 10 GeV, addressing gaps in previous studies. The inclusion of hadron mass corrections allows for a more precise treatment of low-energy and low-z data.

Neural networks were used to parameterize the fragmentation functions, minimizing theoretical bias, while the Monte Carlo sampling method was employed to propagate uncertainties from experimental data to the fragmentation functions. The resulting fits exhibit excellent agreement with the experimental data, as demonstrated by the χ^2 values.

While the study focuses on SIA observables, the determination of gluon-to-hadron fragmentation functions remains limited and will be improved by incorporating collider data from proton collisions. The FF24-K_S^0 sets at NLO and NNLO accuracy, along with their uncertainties, are made publicly available in the LHAPDF format for future use by the scientific community [15]. For more details and discussion please see reference [16].

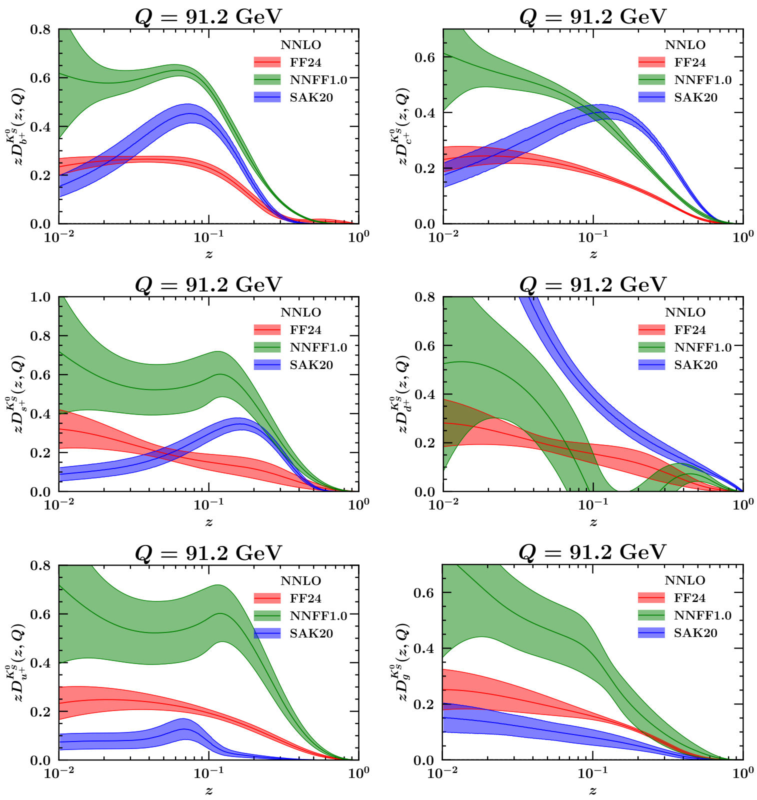

Figure 2: The `FF24-`K_S^0 at NNLO accuracy obtained for various partons at $\sqrt{s}$ = 91.2 GeV. The shaded bands represent 1σ uncertainty estimates derived from the Monte Carlo method. Results from `SAK20` [1] and `NNFF1.0` [14], along with their error bands at NNLO accuracy, are also included for comparison.

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