K^+ Production from 8 GeV Protons using Neutrino Interactions in SciBooNE

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The SciBooNE Collaboration reports K^+ production cross section measurement using high energy daughter muon neutrino scattering data off the SciBar polystyrene (C_8H_8) target in the SciBooNE detector. The K^+ mesons are produced by 8 GeV protons striking a beryllium target in Fermilab Booster Neutrino Beam (BNB) line. Compared to Monte Carlo predictions using previous higher energy K+ production measurements, this measurement, which uses the NEUT neutrino interaction generator, is consistent with a normalization factor of 0.87±0.12. This agreement is evidence that the extrapolation of the higher energy K^+ measurements to an 8 GeV beam energy using a Feynman scaling parametrization is valid. This measurement reduces the error on the K^+ production cross section from the 40% currently used in MiniBooNE and SciBooNE to 14%, which can be applied to reduce uncertainty in the beam MC simulation for future neutrino measurements.

1 Introduction

Inclusive kaon production by low-energy protons (1 to 15 GeV) is of interest both theoretically and experimentally. In this low-energy region, kaon production is dominated by exclusive processes. Since exclusive channel threshold effects are important, theoretical models such as Feynman scaling [1] may be good in describing low-energy production cross sections. Experimentally, kaon production is also relevant for neutrino experiments since important components of the incident neutrino flux come from kaon decays, such as ν_e from K^+.

Since measurements of K^+ production does not exist at the 8 GeV incident proton energy, a Feynman scaling parametrization is used to predict the double-differential K^+ production cross-section from higher incident proton energies [2]. The Feynman scaling parametrization show that while the shape of the K^+ production cross-section as functions of momentum and angle are in good agreement for the higher incident energy K^+ production measurements, the overall production normalization is not. A conservative 40% uncertainty is applied to the K^+ production, mostly coming from the discrepancy in the production normalization from different higher energy K^+ measurements.

2 Detector Description and MC Simulation

The Fermilab BNB uses 8 GeV kinetic energy protons striking a beryllium target. Secondary mesons, including K^+ measured in this analysis, are produced and focused by a magnetic horn into a downstream beam decay pipe. The polarity of the horn can be changed on based whether a neutrino or antineutrino beam is desired. In the beam decay pipe, the secondary mesons are allow to decay into neutrinos. At the end of the beam decay pipe, a stop removes all charged particles from the beam, creating an intense neutrino beam. The SciBooNE detector

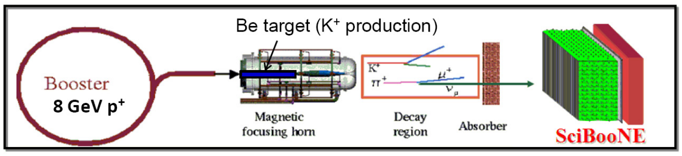

Figure 1: Schematic overview of the BNB line and location of SciBooNE.

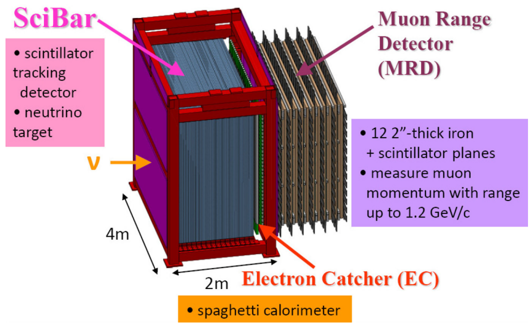

Figure 2: The different components of the SciBooNE detector.

was located 100 m downstream from the beryllium target on the axis of the beam. The BNB line with SciBooNE is shown in Fig. 1. The detector was comprised of three sub-detectors: a fully active and finely segmented scintillator tracker (SciBar), an electromagnetic calorimeter (EC), and a muon range detector (MRD) (shown in Fig. 2). Neutrino events in this analysis were required to interact in the SciBar detector.

In neutrino mode running (antineutrino mode running), defined as whether the polarity of magnetic horn is set to produce a neutrino (antineutrino) beam, the neutrino flux corresponding to 0.99×10^{20} (1.51×10^{20}) protons on target (POT) is collected and used for this analysis.

The MC simulation of the neutrino beam was modeled by the MiniBooNE collaboration using a Sanford Wang parametrization of HARP data for π^+ and π^- production and Feynman scaling for K^+ production[2]. The neutrino beam prediction is then propagated to the SciBooNE detector location where NEUT[3,4], a neutrino interaction library, models the initial neutrino interaction and subsequent nuclear modeling in SciBar. The particles that emerge from the nuclei are then propagated through GEANT4 and SciBooNE reconstruction algorithms to obtain hit and track based information.

3 Event Selection

While the neutrino flux at SciBooNE is predominantly due to π^+ decay in neutrino mode running and π^- decay in antineutrino mode running, K^+ decay is the dominant source of neutrinos above neutrino energy of 2 GeV for both running modes. The aim is to search for events where the high energy ν_μ from K^+ interacts within the volume of the SciBar detector through a charged current interaction, producing a high energy muon that penetrates though the SciBar, EC, and MRD detectors. Backgrounds include high energy ν_μ from π^+ and high energy $\bar{\nu}_\mu$ from π^-, which also produce a muon track that is indistinguishable from our signal. Fig. 3 shows a typical K^+ candidate event in the selected events. Tab. 1 shows the selected events in data and MC for neutrino and antineutrino mode. Separate samples are extracted for neutrino mode running and antineutrino mode due to different backgrounds. The selected events are further separated into three sub-samples based on the number of reconstructed SciBar tracks in each event: 1, 2, or 3-Track. The 1-Track sample has the largest statistics but contains mostly background events

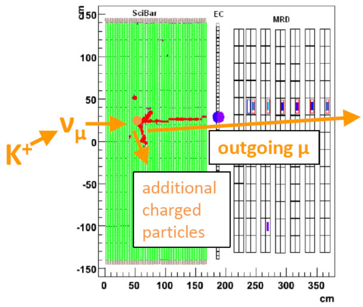

Figure 3: Event display of a K^+ candidate event.

Table 1: Number of selected events for data and MC in neutrino and antineutrino mode. The rightmost column shows the predicted contribution from K^+.

	Data	MC	K^+
Neutrino Mode	3,090	3,527	1398
Antineutrino Mode	1,699	1,604	285

(π^+ and π^-). The 2-Track sample contains a split between K^+ and background. The 3-Track sample contains mostly K^+ but has the smallest statistics.

The high energy muons penetrate through the entire SciBooNE detector so the reconstruction of the total muon energy, and thus the neutrino energy, cannot be done. The reconstructed muon angle relative to beam axis will be used as the primary kinematic variable for the analysis. Neutrinos produced from K^+ decay have a higher energy on average than neutrinos from π^+ and π^- decay. Therefore, the angular distribution of the resulting muon from the neutrino interaction of a neutrino from K^+ will be more forward peaked than those from neutrinos from π^+ and π^- and can help separate the signal from background.

4 Covariance Fit

The muon angle distributions are fitted to isolate the neutrinos from K^+ decay and determine the K^+ production normalization relative to the Feynman scaling predicted K^+ production currently implemented the beam MC. The following χ^2 function is minimized:

$$\chi^2 = \chi^2_\nu + \chi^2_{\bar{\nu}} = \sum_{i,j}^{N}(N_i^{obs} - N_i^{pred})(V^\nu_{stat} + V^\nu_{sys})^{-1}_{ij}(N_j^{obs} - N_j^{pred}) + \\ \sum_{p,q}^{M}(M_p^{obs} - M_p^{pred})(V^{\bar{\nu}}_{stat} + V^{\bar{\nu}}_{sys})^{-1}_{pq}(M_q^{obs} - M_q^{pred}). \quad (1)$$

The χ^2 function in Eq. 1 contains two terms: the former χ^2_ν term is associated with events for neutrino mode running and the latter $\chi^2_{\bar{\nu}}$ term is associated with events for antineutrino mode running. $N^{obs}_{i(j)}$ and $N^{pred}_{i(j)}$ are the numbers of observed and predicted events in the $i(j)$-th angle bin for the neutrino mode analysis. $M^{obs}_{p(q)}$ and $M^{pred}_{p(q)}$ are the same quantities in the $p(q)$-th angle bin for the antineutrino mode analysis. The functions that describe the number of predicted events $N^{pred}_{i(j)}$ and $M^{pred}_{p(q)}$ are functions of the K^+ production normalization.

$(V^\nu_{sys})_{ij}$ and $(V^{\bar{\nu}}_{sys})_{pq}$ are the elements of the covariance matrix for systematic uncertainties in neutrino and antineutrino mode running, respectively. The systematic uncertainties consid-

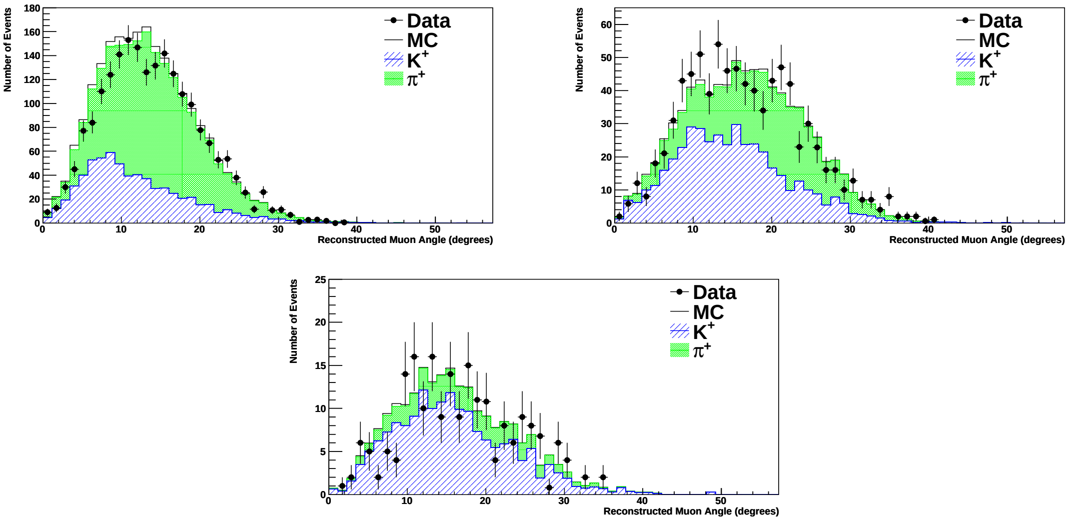

Figure 4: The reconstructed muon angle relative to beam axis for the SciBar 1-Track (upper left), 2-Track (upper right), and 3-Track (lower center) samples in neutrino mode running after the application of the K^+ production normalization of 0.87.

ered fall into three broad categories: the neutrino flux production uncertainties (initial meson production at target, magnetic horn current,etc.), neutrino cross-section and nuclear modeling uncertainties, and detector uncertainties (uncertainties associated with the instrumentation of the various detector components). V^{ν}_{stat} ($V^{\bar{\nu}}_{stat}$) represents the statistical error in neutrino mode running (antineutrino mode running).

After the χ^2 minimization, a K^+ production normalization of 0.87±0.12 is obtained. The reconstructed muon angle for the SciBar 1,2,3-Track samples in neutrino mode after the application of the K^+ production normalization are shown in Fig. 4. To ensure that the lack of the exact neutrino cross-section knowledge does not influence the final K^+ production result, this analysis was also performed using NUANCE [5], an alternate neutrino interaction library to NEUT. The result from NUANCE is in good agreement with the result stated here.

5 Conclusion

The K^+ production normalization relative to beam MC is obtained by fitting the muon angle relative to beam axis for a K^+ rich sample obtained by selecting ν_μ induced high energy muons that penetrate the entire SciBooNE detector. The K^+ production normalization of 0.87±0.12 shows that Feynman scaling is valid down to the 8 GeV incident proton energy. The measurement reduces the uncertainty on the K^+ production cross section from 40% (currently used in MiniBooNE and SciBooNE) to 14%, since most of the uncertainty is concentrated in the overall normalization. The measurement will also reduce uncertainty in neutrino backgrounds from K^+, which is essential for future precision neutrino measurements.

References

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