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# Measurements of kaon and pion scattering in the WCTE facility at CERN

S. Bacca
*Johannes Gutenberg-Universität Mainz (JGU), Mainz, Germany*

M. Barbi and N. Kolev
*University of Regina, Department of Physics, Regina, Saskatchewan, Canada*

A. Bravar, S. Bordoni, and F. Sanchez
*Université de Genève, Faculté des Sciences, Département de Physique Nucléaire et Corpusculaire (DPNC), Geneva, Switzerland*

L. Berns
*Tokyo Institute of Technology, Department of Physics, Tokyo, Japan*

S. Bhadra and A. Fiorentini
*York University, Department of Physics and Astronomy, Toronto, Ontario, Canada*

A. Bubak, J. Holeczek, J. Kisiel, S. Kowalski, S. Puławski, and K. Schmidt
*University of Silesia, Institute of Physics, Katowice, Poland*

P. de Perio, M. Hartz[ab], A. Konaka[a], A. Lindner[c], and M. Pavin
*TRIUMF, Vancouver, British Columbia, Canada*

S. Fedotov, M. Khabibullin, A. Khotjantsev, Y. Kudenko, O. Mineev, and N. Yershov
*Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia*

M. Friend
*High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki, Japan*

C.S. Garde
*Vishwakarma Institute of Information Technology, Kondhwa, Pune, India*

G. Hagen
*Oak Ridge National Laboratory, Tennessee, United States*

B. Jamieson
*University of Winnipeg, Department of Physics, Winnipeg, Manitoba, Canada*

H. Kakuno
*Tokyo Metropolitan University, Department of Physics, Tokyo, Japan*

K. Kowalik
*National Centre for Nuclear Research, Warsaw, Poland*

P.F. Mendez
*University of Liverpool, Liverpool, United Kingdom*

Y. Nagai
*Eötvös Loránd University, Hungary*

M. Scott
*Imperial College London, Department of Physics, London, United Kingdom*

[a] University of Victoria
[b] Kavli IPMU, Japan
[c] University of Winnipeg

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## I. EXECUTIVE SUMMARY

This expression of interest describes a proposal to precisely measure forward hadron scattering cross-sections, namely measurement of total, coherent elastic, and quasi-elastic scatterings, on nuclear targets in the momentum range of $1 - 10$ GeV/c. The experiment fills the data gap for precision hadronic scattering data in this range and complementary to the ongoing hadron production experiments, NA61/SHINE [1] and EMPHATIC [2]. This experiment uses the proposed Water Cherenkov Test Experiment (WCTE) facility [3] by changing the configuration of the tertiary beam components into hadronic spectrometer. Additionally, the experiment uses a WCTE water Cherenkov detector to identify the scattered particles, mainly to separate pions from muons. Forward hadron scattering is currently one of the most significant systematic uncertainties in the neutrino flux prediction in long-baseline neutrino experiments, and this measurement will improve it significantly. The measurement will also improve simulations of hadronic interactions in particle detectors, which often contribute as a source of systematic uncertainties due to the lack of precise cross-section data. We propose to survey the phase space and compile data into a database in a format including covariance error matrix, which is essential for modern experimental analyses. Recently, there is excellent progress in ab-Initio calculations of scattering cross-section on nuclei in the low momentum transfer region, which is aimed at by this experiment. Comparing the results from this experiment with ab-initio effective field theory would potentially open up fruitful scientific studies and strengthen the confidence in applying ab-initio theory to neutrino scatterings.

## II. INTRODUCTION

The Standard Model provides very precise predictions of electromagnetic and weak interactions. Although strong interactions are predicted precisely at high energy by perturbative QCD, hadronic interactions from soft QCD rely on empirical models and introduce substantial systematic uncertainties in particle physics experiments. Hadron-nucleus interactions and secondary particle productions, which take place in many particle physics detectors, are in particular complex and challenging to simulate. Experiments calibrate their detectors directly with hadron beam (e.g., proto-DUNE and WCTE), use the sideband data to estimate the effect, and study hadron production using replica targets for neutrino flux predictions (e.g. NA61/SHINE). Reliable and precise data will greatly improve this situation and allow us to perform data-driven studies of systematic uncertainties.

This experiment proposes to precisely measure the forward scattering cross section of hadrons, namely kaons, pions, and protons, in the momentum range of $1 - 10$ GeV/c. Understanding the forward scattering of pions and kaons with momenta $1 - 10$ GeV/c in focusing magnets and decay volume is becoming one of the leading systematic uncertainties in the neutrino flux prediction. Hadron interaction measurements are often done in two ways; one is the forward scattering measurement which covers total, elastic, and quasi-elastic cross-sections and the other is the hadron production measurement which vetos the surviving beam and measures produced particles. Forward scattering measurements also deploy transmission measurement by counting the fraction of the non-interacting particles. Depending on how the scattering angle (momentum transfer) distributions are modeled, the assignment would change among non-hadronic (Coulomb) scattering, Coulomb-nuclear interference, hadron elastic, and quasi-elastic scatterings and introduces confusion. This experiment proposes to simultaneously detect all the forward-going particles, including non-interacting particles, and provide model-independent data without relying on specific hadron-nucleus interaction models. Such measurements are possible thanks to the high data-taking rate using silicon strip detectors developed for the LHC experiments. We propose to perform this experiment in the CERN PS East hall. Since the beamline is relatively short ($\sim 50$ m) low momentum kaons and pions survive in the beamline. For example, the decay length for $1$ GeV/c pions is $56$ m and for $3$ GeV/c kaons is $23$ m. The expected flux of at T9 beamline is $10000$ $2$ GeV/c $\mathrm{K}^+$ per spill and $100000$ $1$ GeV/c $\pi^+$ per spill (Fig.1), which allows high statistics measurements for different momenta and targets in a short time period.

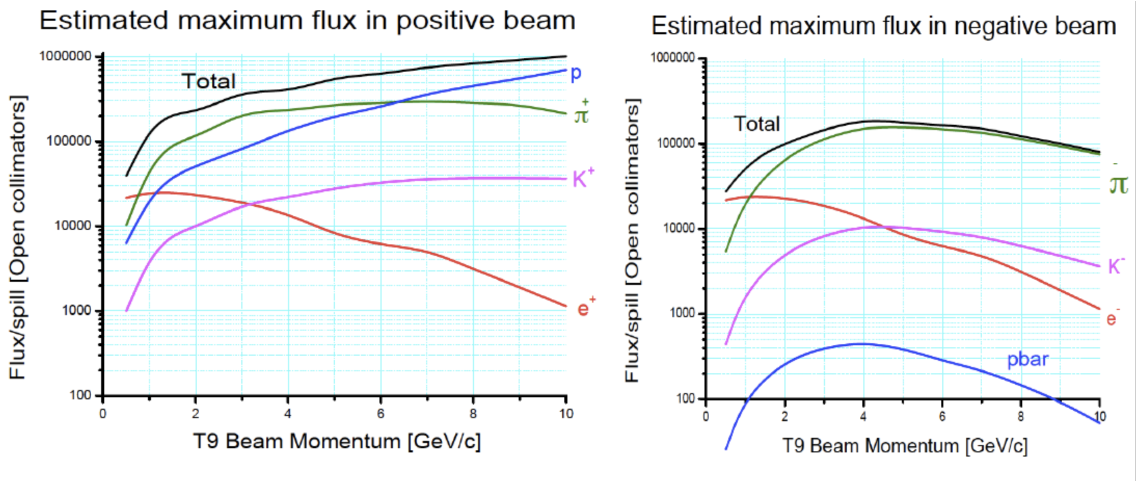


FIG. 1: Expected T9 beam flux at CERN PS.

We would like to reconfigure the tertiary beam spectrometer of the Water Cherenkov Test Experiment (WCTE) for this experiment. The spectrometer consisting of a permanent magnet and a silicon strip tracker is ideal for this forward hadron scattering measurement at a high data-taking rate. The WCTE water Cherenkov detector serves for particle identification. In particular, it provides a unique way to separate pions from muons present in the beam through hadronic interaction in the water. Typically, it is almost impossible to separate pions from muons by the beam Cherenkov counters or time-of-flight systems.

## III. PHYSICS IMPACT

Neutrino flux prediction is essential for the neutrino oscillation experiments such as T2K, NOvA, DUNE, and HyperK experiments. By taking the ratio between neutrino counting rate in the near detector and the far detector, the systematic uncertainty in the neutrino flux and cross-section cancels in principle. Since the neutrino flux shape is different between near and far detectors due to oscillations, the flux and cross-section need to be understood for the precise measurements such as the CP violation measurement. Precise neutrino flux prediction is required for the cross-section measurements in the near detector.

Neutrinos beam in accelerator-based neutrino experiments is generated by decays of pions and kaons produced by primary protons hitting the production target. Produced pions and kaons are point-to-parallel focused towards the far detector by toroidal horn magnets. Production of pions and kaons in the target is studied by injecting a proton beam onto a replica target, as demonstrated by NA61/SHINE [4]. An example of the T2K neutrino flux uncertainty calculated by using mostly NA61/SHINE replica target result is presented in Fig. 2. The neutrino flux uncertainty is reduced to $6\%$ (solid black line). In particular, the remaining systematic uncertainty comes from the hadron interactions (red line) after improving the proton beam profile measurement. These are due to the replica target data uncertainties and forward scattering of pions and kaons in the horn conductor (aluminum) or the wall of the decay volume (iron). In particular, data covering these pion and kaon interactions is sparse. Pions and kaons focused by the horn magnet have to go through the inner and downstream conductor of the horn magnet. Those pions and kaons staying inside the inner conductor will not be focused, and many of them hit the iron wall of the decay volume. Scatterings need to be in the forward direction for the pions and kaons to remain in the decay volume and contribute to the neutrino flux. Fig. 3(a) shows the pion scattering outside the target that contributes to the neutrino energy of $E_\nu = 0.1 - 0.7$ GeV. Pion scattering in the range of $1 - 10$ GeV/c and up to $500$ mrad, which is dominated by quasi-elastic scattering, is important. The higher energy neutrino flux originates from kaons and higher momentum pions. Fig. 3 also shows the

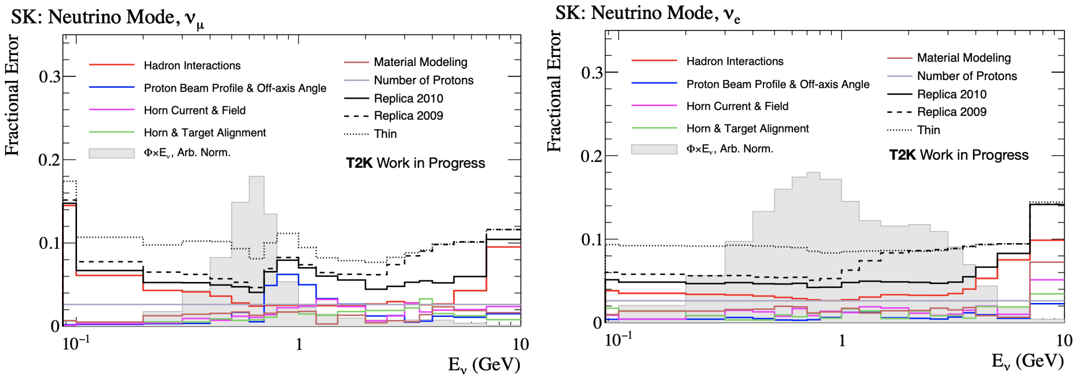
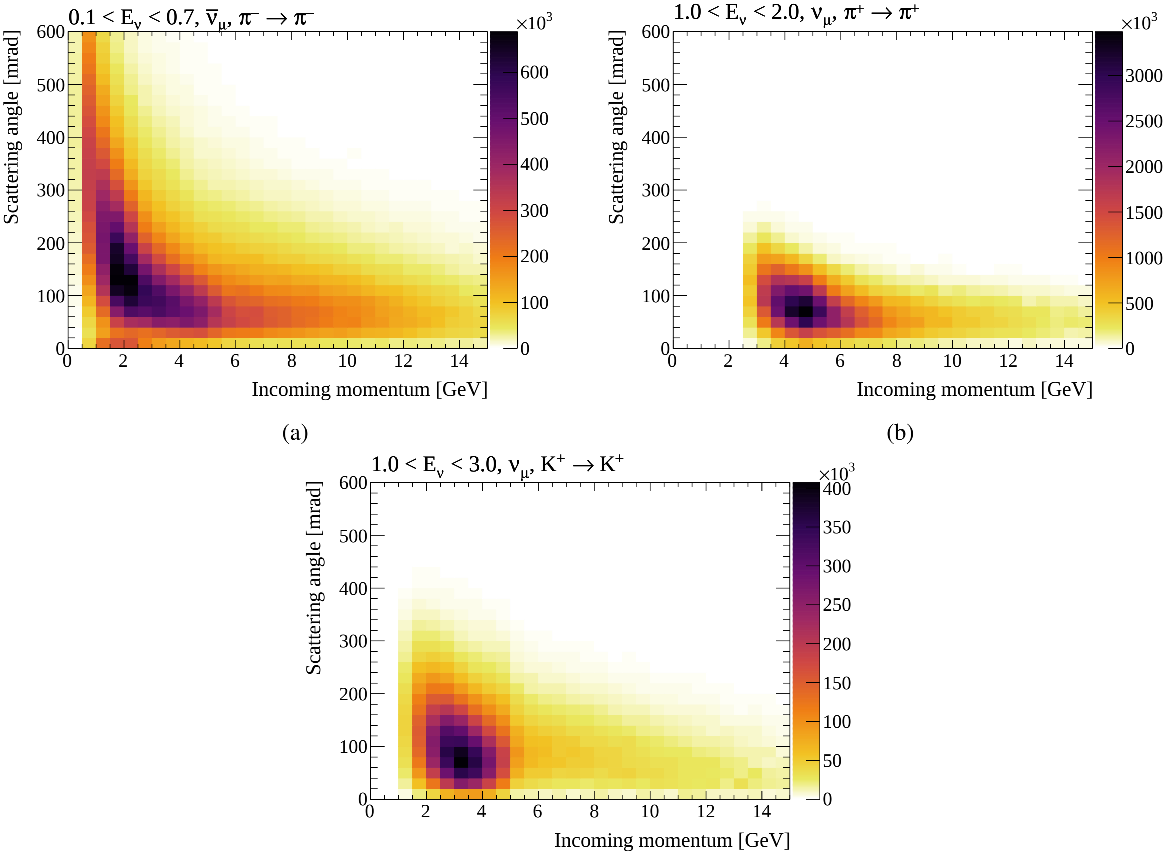


FIG. 2: Preliminary study of the T2K systematic uncertainty on (a)[Left] $\nu_\mu$ flux and (b)[Right] $\nu_e$ flux. The flux error is 6% thanks to the NA61 replica target measurement [4] (black solid line). The main remaining systematic uncertainty comes from the uncertainty in the hadron interaction (red).



(a)

(b)

(c)

FIG. 3: Scattering angles and momenta of (a) pions contributing to neutrino energy of $0.1 < E\nu < 0.7GeV$, (b) pions contributing to $1 < E\nu < 2GeV$, and (c) kaons contributing to $1 < E\nu < 3GeV$.

momentum and scattering angle of pions (b) and kaons (c) that scatter outside the target and produce neutrinos in the energy range of $1 < E\nu < 2GeV$ for pions and $1 < E\nu < 3GeV$ for kaons. Scattering of pions and kaons in the momentum of $2 - 8$ GeV/c and scattering angle of up to $200$ mrad are important in the higher momentum region.

Atmospheric neutrino oscillations covers wide range of baseline length (up to 10,000km) and neutrino energy. The long travel in the earth causes significant matter effect, which can for example resolve the neutrino mass ordering. Current atmospheric neutrino measurement is limited by the systematic uncertainties of the atmospheric neutrino flux. The atmospheric neutrinos are produced by the primary cosmic rays (protons, helium) hitting the upper earth atmosphere and producing pions and kaons. Those pions and kaons decay to produce neutrinos. The primary cosmic ray hadron flux is very well measured for example by the ALPHA Magnetic Spectrometer (AMS), and the earth magnetic field is also mapped reasonably well. The main systematic uncertainty in predicting the atmospheric neutrino comes from the hadron production and the following hadron scattering in the atmosphere. The on-going hadron production experiments, NA61/SHINE and EMPHATIC, are ideal for the hadron production measurement and scattering of high momentum mesons. This experiment can cover forward meson scatterings in the range of 1-10GeV/c that are harder to study at these on-going hadron production experiments due to longer secondary beamlines.

Hadron interaction is a major source of the particle physics experiments. Hadrons interacts strongly in the detector which creates systematic uncertainties. Production of hadrons also involves significant uncertainties. It is important to systematically compile the hadron interaction data and understand it. Currently, the main approach for such effort is to model the data into simulation code, such as GEANT and FLUKA. The models are not perfect and often creates unwanted bias and more importantly systematic uncertainties that are difficult to characterize. The community is moving towards recording model independent data with well characterized errors including the covariance matrix. Data is then used as control samples to evaluate systematic uncertainties. We would like to take such data systematically covering the phase space.

Recently, prediction of neutrino, electron and hadron scattering at low momentum transfer region is becoming possible using ab-initio effective field theory. The calculation works for hadron scattering in the elastic and quasi-elastic scatterings that are measured by this experiment. Forward scattering is modelled by Coulomb-nuclear interference, elastic and quasi-elastic scatterings, but such modelling introduce confusion in the measurements, and ab-initio calculation has a potential to overcome it. Forward hadron scattering data taken from this experiment can be used to test ab-initio theory and expend our understanding of soft QCD phenomenon. This will also strengthen the ab-initio theory applied to quasi-elastic scattering of neutrinos.

## IV. EXPERIMENTAL SETUP

Fig.4 shows the setup of the experiment. It is located in the T9 experimental area of the CERN East Hall. The main spectrometer consists of a permanent magnet (Fig.6 (a)) and silicon strip tracker (Fig.6 (b)), which will be moved from the WCTE tertiary beamline to the secondary beam side. Target located upstream of the spectrometer will be about $5\%$ interaction length. Data collected with graphite, aluminum, and iron targets will be used to improve neutrino flux prediction. Materials used in neutrino detectors, such as water, plastic scintillator, and calcium (as a replacement for argon), will be used to understand neutrino detectors' responses better. For the atmospheric neutrinos, data collected with boron, boron oxide ($B_2O_3$), and boron nitride (BN) would be used to extract cross-sections on oxygen and nitrogen. Particle identification detectors will be placed upstream from the target. A threshold gas Cherenkov counter ($n=1.0001$) will identify electrons, and another gas Cherenkov counter ($n=1.001$) will serve pion-kaon separation at $4 - 10$ GeV/c. The pion-kaon separation at $1 - 6$ GeV/c and kaon-proton separation at $2 - 10$ GeV/c will be done by an Aerogel Ring Imaging Cherenkov detector (ARICH) constructed for the phase-1 of the EMPHATIC experiment. The pion-kaon separation at $0 - 1$ GeV/c and proton-kaon separation at $0 - 3$ GeV/c will be covered by the time of flight scintillation counter. These beam particle identification detectors are common in the WCTE facility. The resistive plate chambers (RPCs) and water Cherenkov detector will be placed downstream from the spectrometer. The WCTE water Cherenkov detector serves for the particle identification of scattered particles, particularly identifying pions from muons in the beam that the other particle identification detectors can not separate.

We consider two spectrometer configurations, small and large solid angles (Fig.5). The small solid angle setup has direction measurement of scattered particles both upstream and downstream of the magnet. This provides precise scattering angle and momentum measurements for measurements with higher momentum particles (above 2 GeV/c) with a solid angle of $150$ mrad and an integrated bending power of $0.2$ Tm. In the large-angle setup, the target is moved to the upstream end of the magnet, and a larger aperture magnet (10 cm in diameter) is used. The particle momentum in the second configuration is measured by reconstructing particle direction downstream from the magnet and comparing it with the hit position in the tracking plane just after the target. Although the momentum resolution is compromised,

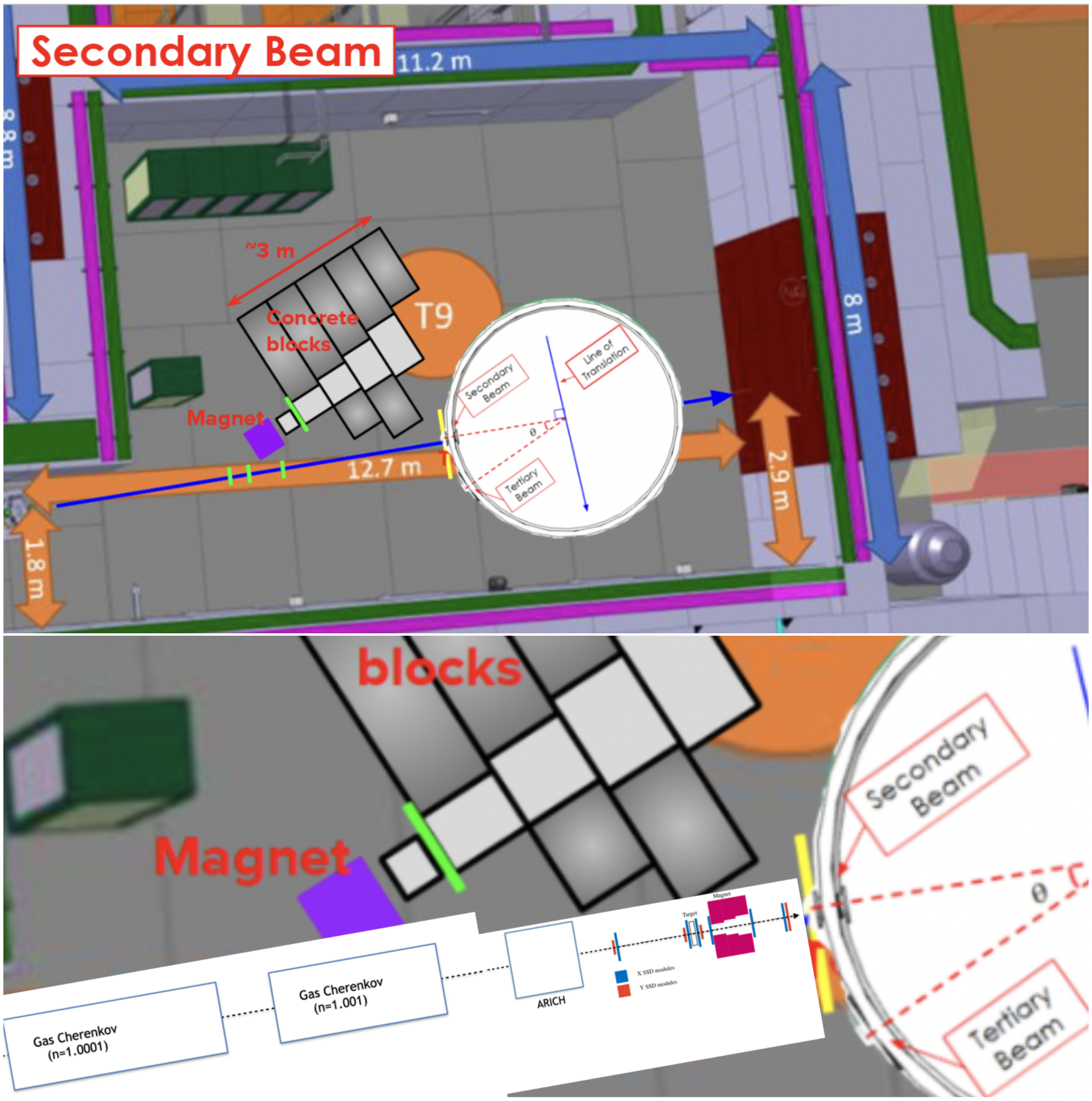
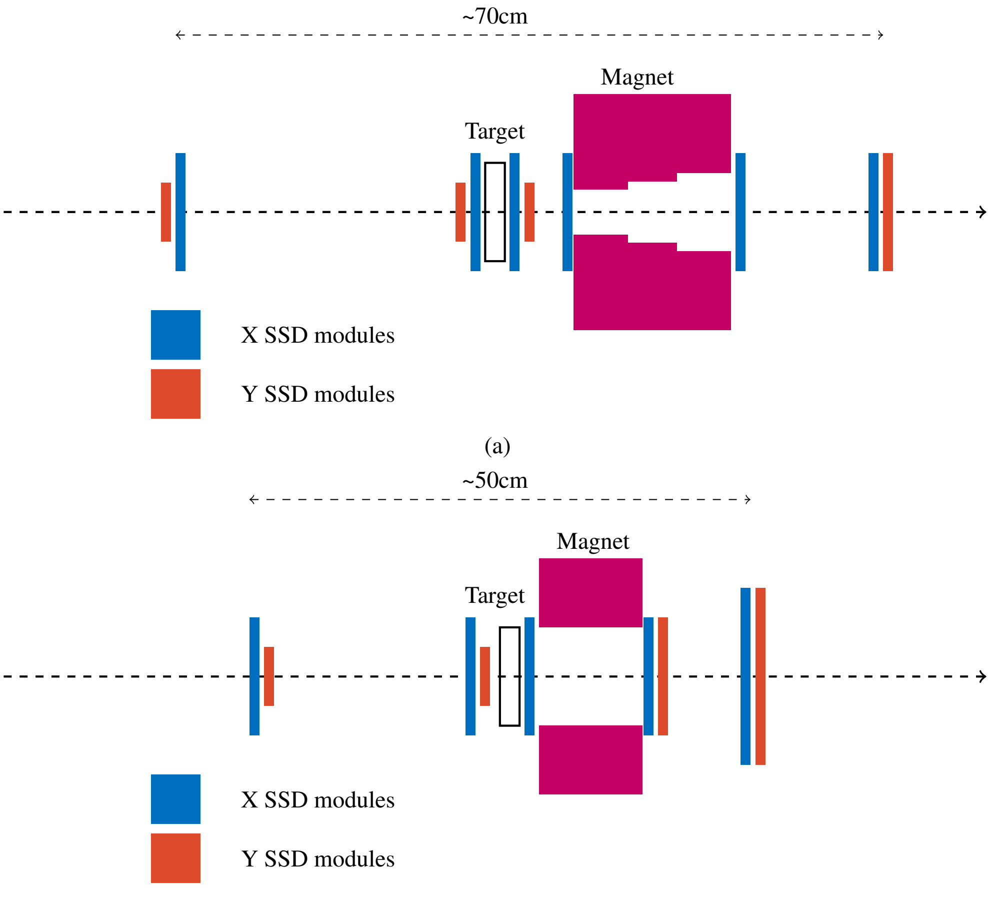


FIG. 4: Top figure shows the secondary beam configuration of the WCTE experiment, and the bottom figure shows the modified hadron scattering setup. It consists of a pair of Cherenkov counters (n=1.0001, 1.001), aerogel Ring Imaging Cherenkov (ARICH) and the spectrometer, followed by WCTE TOF wall and water Cherenkov detector.

the spectrometer covers up to 430 mrad. The large angular acceptance is necessary for lower momentum particles ( 1 GeV/c) whose quasi-elastic scattering angle extends to 400 mrad.



(a)

(b)

FIG. 5: Schematic overview of the proposed experimental setup with the EMPHATIC phase-1 magnet (a) and with the WCTE magnet.

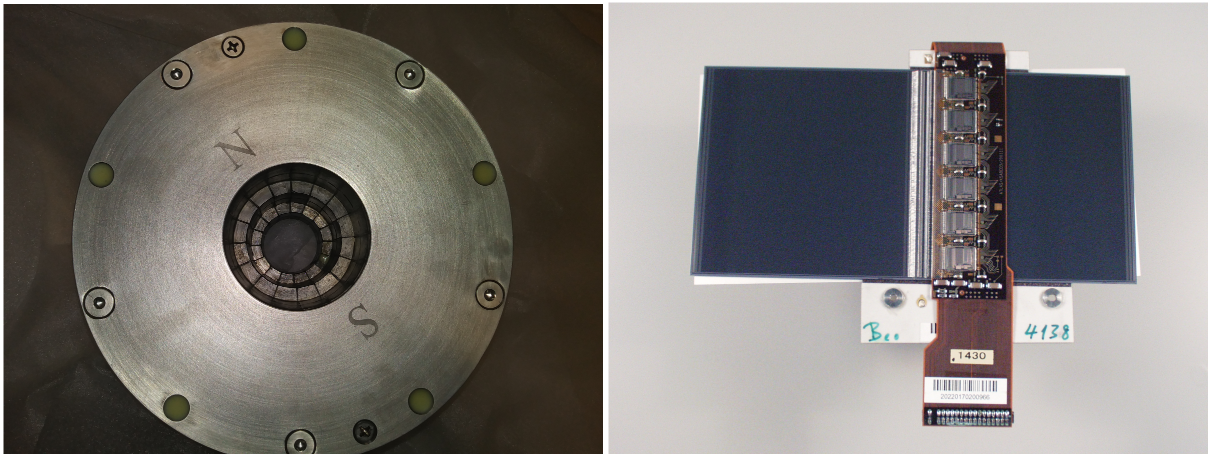
## V. EXPECTED MEASUREMENTS

The simple experimental setup presented in Sec. IV allows reconstruction of the incoming beam track and the scattered track downstream from the target. By comparing directions of two tracks we are able to measure the scattering angle. The momentum transfer of the (quasi-)elastically scattered particle is low compared to the incoming momentum. Assuming incoming beam particles are pions with momenta above 1 GeV/c and kaons with momenta above 2 GeV/c, the four-momentum transfer is proportional to the square of the scattered angle $\theta$ if the angle is small:

$$t \approx -p_{beam}^2 \theta^2, \tag{1}$$

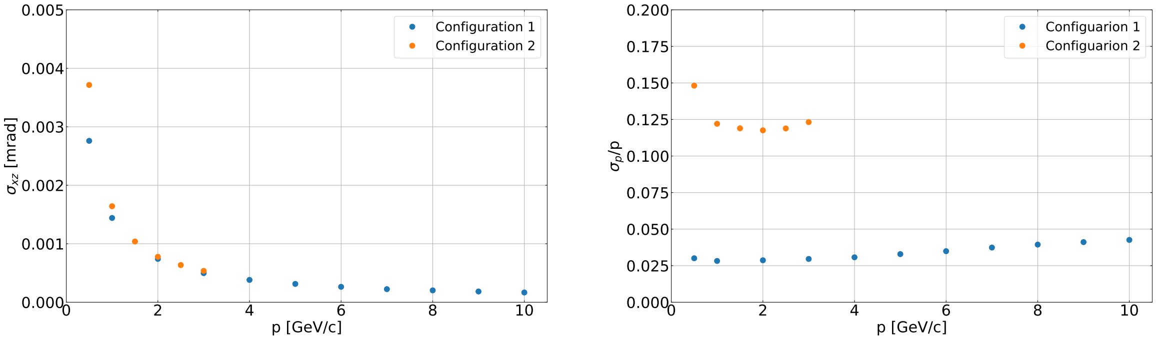
Therefore, the most important characteristics of the experimental setup for measuring (quasi-)elastic hadron-nucleus scattering is the effective angular resolution. The effective angular resolution for two configurations presented in Fig. 5 depends on the spatial resolution of the individual silicon strip modules, separation between modules and the material budget. We have estimated the angular resolution by simulating the setup and reconstructing beam and scattered tracks with an algorithm based on Kalman filter and analytical method for the extrapolation in the magnetic field [5]. Results are presented in Fig. 7.

Measurements of (quasi-)elastic interaction relies on identifying events with a single charged track in a final state and momentum comparable to the momentum of the incoming beam track. The measured differential cross-section is defined as:



(a) (b)

FIG. 6: The EMPHATIC phase-1 Halbach array magnet (a), and ATLAS SCT barrel module (b).



(a) (b)

FIG. 7: The angular resolution in x-z plane for both experimental setups (a) and the momentum resolution (b). The configuration 1 includes the smaller acceptance EMPHATIC magnet, while configuration 2 includes the WCTE magnet.

$$\left(\frac{d\sigma}{dt}\right)_i = \frac{1}{N_B}\frac{1}{nd}\frac{N_i}{\Delta t_i}, \tag{2}$$

where $N_B$ is the number of beam particles hitting the target, $nd$ is a product of the target number density and thickness, $N_i$ is the measured number of scattered tracks in the four-momentum transfer bin $i$, and $\Delta t_i$ is the width of the four-momentum transfer bin $i$. However, it is not possible to separate elastic, quasi-elastic and non-interacting events without very precise momentum measurements and $4\pi$ detector coverage. This is illustrated in Fig. 8.

The main background in proposed measurements comes from production events. Production events include interactions which produce at least one new hadron if not counting nucleus fragments ($\alpha$, p, n, ...). Some of production events cannot be differentiated from (quasi-)elastic events due to detector acceptance and inability to detect neutral particles. Typically, such events will have a single forward charged track that has momentum much lower compared to the beam track. Therefore, an analysis cut on measured momentum removes majority of background events:

$$|p_b - p| < 3\sigma_p + m_\pi, \tag{3}$$

where $p_b$ is the beam momentum, $p$ is the measured momentum, $\sigma_p$ is the momentum resolution and $m_\pi$ is the pion mass. The effect of the momentum cut is presented in Fig. 9. According to Geant4 simulation, the background can is comparable to the signal in quasi-elastic region. However, after the event selection, the background rate drops to $1\%$ level compared to the signal.

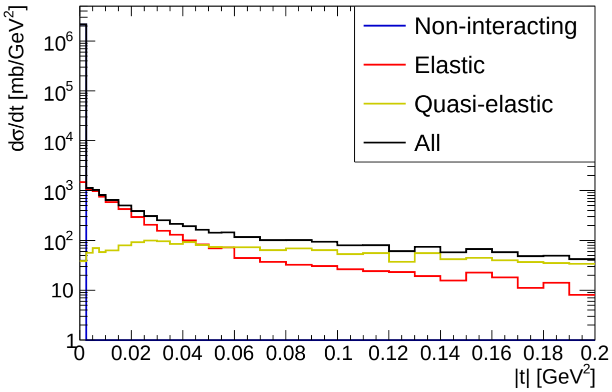
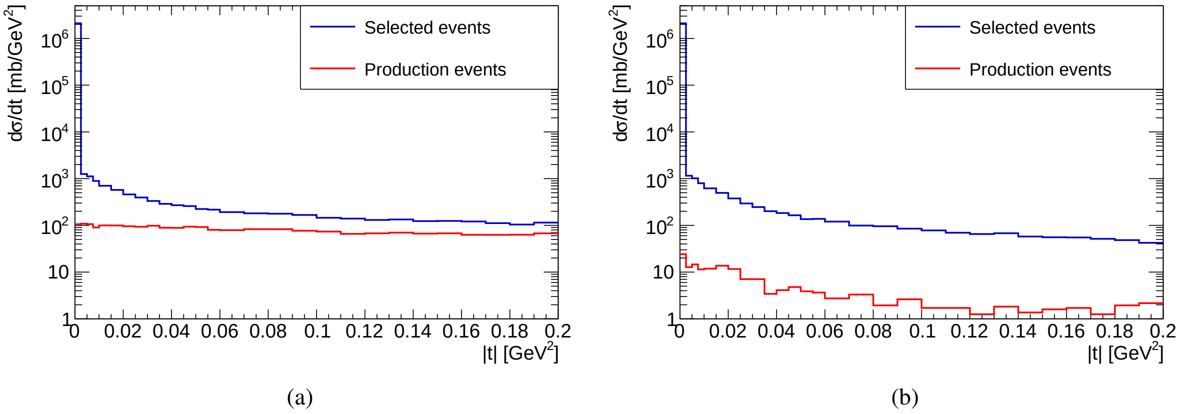


FIG. 8: The true differential cross-section extracted from Geant4.10.05 FTFP_BERT physics list for K$^+$-carbon interactions at 6 GeV/c. The elastic, quasi-elastic and non-interacting component are overlaid on top.



(a)

(b)

FIG. 9: The reconstructed differential cross-section for K$^+$-carbon interactions at 6 GeV/c and hadron production background before (a) and after momentum cut of the scattered particles.

We have shown a potential clean measurement of forward kaon scattering on carbon as an example. Forward scattering provides total, elastic and quasi-elastic cross sections, the basic hadron cross sections. In addition, momentum and direction of other forward going particles, which can contribute to the neutrino flux. The expected systematic uncertainty is small thanks to almost 100% detection efficiency by fully covering the forward angle and the separation of particle production events by outgoing particle momentum. By taking a few million events at each momentum setting, which would take less than 2 hours, more than hundred thousand scattering events can be measured for the 5% interaction length targets. We plan to use carbon, aluminium, and iron targets, which are relevant for the accelerator neutrino flux predictions, scintillator, water (ice) and calcium (in replacement of Ar) for neutrino detector responses, and boron, boron nitrate, and boron oxide for the atmospheric neutrino flux predictions. Additional nuclear target, such as copper and lead would be considered for other particle detectors and test of the ab-initio model.

## VI. SUMMARY

This Expression of Interest describes a new hadron interaction measurement at the CERN PS T9 test beam using the WCTE facility by reconfiguring the tertiary beam equipments. The goal is to perform high statistics precision measurement of forward kaon and pion scatterings on various nuclear targets for the momentum range of 1-10GeV/c, where precision data are needed and in particular very little data available for kaons. This measurement is important for the neutrino flux predictions of neutrino oscillation experiments, and more broadly serves the particle physics community by providing basic cross section data,. We would like to perform this experiment before the long shut down. The collaboration is being formed and we plan to submit a proposal for the following SPSC.

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[5] S. Gorbunov and I. Kisel, “Analytic formula for track extrapolation in non-homogeneous magnetic field,” *Nucl. Instrum. Meth.*, vol. A559, pp. 148–152, 2006.