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A LOI to Jefferson Lab PAC-45

# Search for a $\phi - N$ Bound State at Hall B

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**Abstract**

In light of recent experimental results of the hidden charm pentaquark candidates at LHCb, a renewed interest is invoked for other multiquark states also. We propose an experiment to search for a hidden strange pentaquark candidate, $\phi - N$ bound state from the $\phi$-meson near threshold production on a nuclear target. It has been suggested by theoretical studies that a $\phi$-meson and a nucleon may form a bound state. Such a bound state can be produced via two steps: first produce a $\phi$-meson from one nucleon, and then the $\phi$-meson interacts with another nucleon to form the bound state. Because the probability of the formation of the bound state is enhanced at a low velocity between the $\phi$-meson and the nucleon, we propose to search for this bound state through the sub- and near-threshold $\phi$-production on a nuclear target. The proposed experiments would be performed in Hall-B using a gold foil target. The scattered electron would be detected by the forward tagger, and the proton, $K^+$, and $K^-$ in the final state would be detected by the BONUS12 and the CLAS12 forward detector to reconstruct the bound state. It is a unique experiment using existing equipments to open a new direction of nuclear physics. We present our current study as a LOI to seek comments from the PAC. A full proposal is planned in the near future.

## 1 Physics Motivation

The multiquark state is one of the active frontiers since the establishment of the quark model. The recently observed hidden charm pentaquark candidates $P_c(4380)$ and $P_c(4450)$ by LHCb [1] invoked a renewed interest in this field [2]. In the quark model, ordinary mesons and baryons are described as color singlets of quark-antiquark states and three-quark states. But for exotic mesons and baryons, the minimum-quark-content is four-quark and five-quark components. QCD, as the fundamental theory of the strong interaction, does not forbid the existence of multiquark states. The study of multiquark states is an approach to understand the dynamics of the strong interaction at the hadronic scale.

The interaction between two hadrons is usually mediated by meson exchange. However, Brodsky, Schmidt, and de Téramond point out that the QCD van de Waals force, mediated by multigluon exchange, will become the dominant interaction between two hadrons when they have no common quarks [3], and they predict that such attractive force is strong enough to bind a charmonium to a nuleus. Luke, Manohar, and Savage further show that the QCD van de Waals force is enhanced at low relative velocities between the two hadrons [4]. It supports the prediction that a nuleon/nucleus-charmonium bound state can be produced near the charm production threshold.

As an extension to the strangeness, one expects the $\phi$ meson, which is almost a pure $s\bar{s}$ state, could also be bound to a nucleon/nucleus. Some chiral quark model calculation [5] and lattice QCD simulation [6] support the existence of such kind of states. It is also shown that the subthreshold quasifree $\phi$ meson production inside a nuclear medium will enhance the probability for the formation of the $\phi-N$ bound state [7]. Recently, a theoretical study predicts the existence of a $\phi - N$ bound state with the mass of 1950 MeV and the width of 4 MeV, and shows the feasibility to search for this bound state at Jefferson Lab [8].

Up to now, almost all discovered multiquark states or candidates contain at least one heavy quark. Therefore, this proposed experiment, which aims at searching for a hidden strange pentaquark state, *i.e.* the $\phi-N$ bound state, is of unique significance to understand the flavor-dependent properties of multiquark states.

The predicted $\phi - N$ bound state, which is about 7 MeV below the $N\phi$ threshold, can be produced through the quasi-real photoproduction process on a nulear target near the threshold of the $\phi$ meson production. The mechanism of the production of the $\phi-N$ bound state is illustrated in Figure 1. First a $\phi$ meson is produced from a nucleon, and then it interacts with another nucleon to form the bound state. Based on the theoretical study of the decay properties of this bound state, the decay of the bound state is dominated by the decay of bound $\phi$ meson. Thus it can be experimentally reconstructed via the $pK^+K^-$ channel.

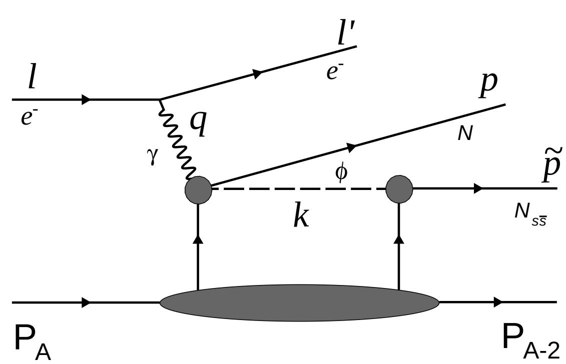



Figure 1: The mechanism of $\phi-N$ bound state ($N_{s\bar{s}}$) electroproduction on a nuclear target (from Ref. [8]).

# 2 Experiment

## 2.1 Model Study

First, we performed a study of the $\phi - N$ bound state quasi-real photoproduction on a gold target by using Monte Carlo method. This will give us some guidance about how to set up detectors

The signal channel $e\text{Au} \to e'N[p\phi]X \to e'NpK^+K^-X$ is generated according to the model calculation in Ref. [8]. Because of the detection reason, the nucleon in the bound state is restricted to the proton instead of neutron. Apart from the signal channel, some background channels with $pK^+K^-$ in the final state are also generated. They are $\phi$ meson production, $\Lambda(1520)$ production, and the direct $K^+K^-$ production. The masses of the bound state, $\phi$ meson, and $\Lambda(1520)$ are sampled according to Breit-Wigner distributions. The energy and momentum of the nucleon inside the gold nucleus is sampled according to the measurement of JLab E91-013 [9].

We only assume that the beam energy is set at 4.4 GeV and the scattered electron is restricted between 2.5 degree and 4.5 degree with the energy above 0.5 GeV, which is within the CLAS12 forward tagger detection range. The final $pK^+K^-$ are in their full phase space, not limited by any detector acceptance.

In Figure 2, we show the invariant mass spectra of $pK^+K^-$, $pK^+$, $pK^-$, and $K^+K^-$. In Figure 3, we show the momentum distributions of the proton and the kaon in the final state from each channel. One can observe that the proton and the kaons which are decay products from the bound state concentrate in the low momentum region separated from the other channels. It is clear that we need to detect $pK^+K^-$ below 500 MeV and down to 50 MeV to optimize the signal detection and we can cut away high energy particles to suppress the background.

From the model study, we conclude that combining the forward tagger, CLAS12 main detector and the BONUS12 detector for low energy particles is the best configuration for this proposed experiment.

## 2.2 Setup

### 2.2.1 Overview

We propose to search for the $\phi - N$ bound state by combining the CLAS12 forward detector, the Forward Tagger (FT), and the BONUS12 detector in Hall B at Jefferson Lab. A 4.4 GeV electron energy with 100 nA current incident on a 0.14-mm thickness gold foil target will be used for the search. We choose a large current and a thin target to minimize final particle energy loss in the target material and keep the luminosity at the CLAS12 limit of $10^{35}\, eN\,\text{cm}^{-2}\cdot\text{s}^{-1}$.

The foil target is placed at the upper end of the 40 cm long BONUS12 detector, which is the 20cm upstream of the CLAS12 center. This is to optimize the forward angle detection where most of the signal events are.

The three final state particles of the dominant $pK^+K^-$ decay channel with a suggested branching ratio of 46.5% will be detected by the CLAS12 forward detector and the BONUS12 detector. The scattered electron will be detected by the Forward Tagger to ensure that it is a quasi-real photoproduction.

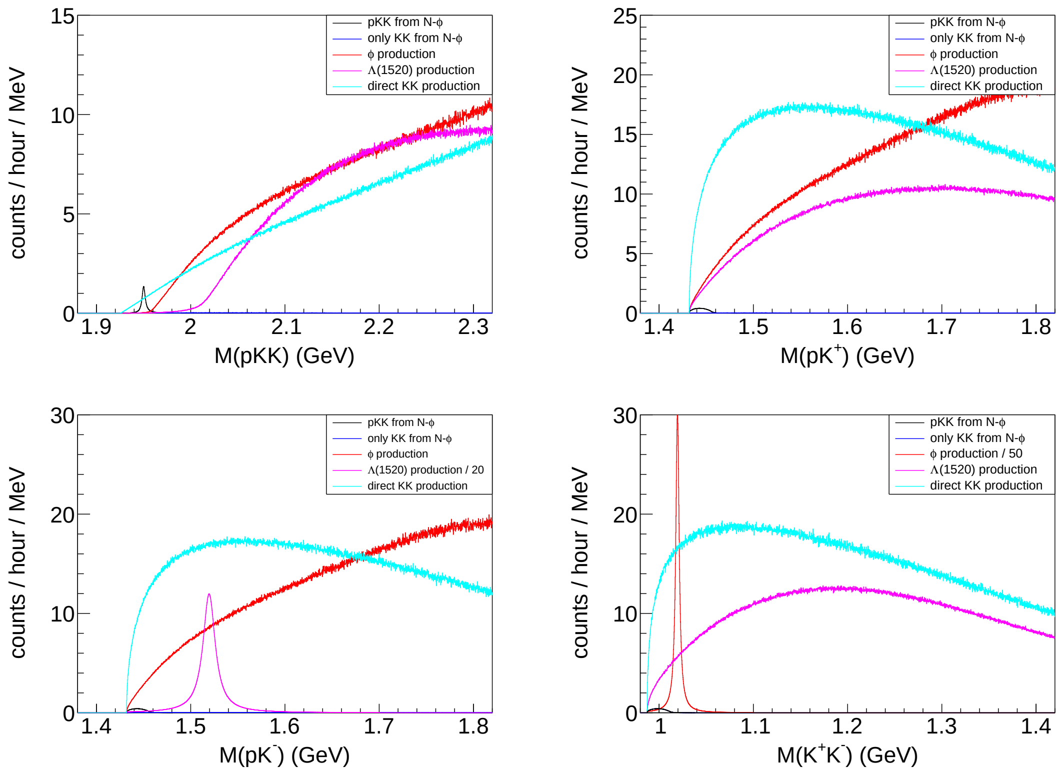



Figure 2: The invariant mass spectra of $pK^+K^-$ (upper left), $pK^+$ (upper right), $pK^-$ (lower left), and $K^+K^-$ (lower right) from different channels. The black curves show the channel with $pK^+K^-$ from the bound state decay, the blue ones show the channel with only $K^+$ and $K^-$ from the bound state decay and the other proton in the bound state production, the red ones show the channel with $\phi$ meson production, the magenta ones show the channel with $\Lambda(1520)$ production, and the light blue ones show the channel with direct $K^+K^-$ production. The $pK^-$ spectrum of $\Lambda(1520)$ production channel is scaled by a factor of $1/20$, and the $K^+K^-$ spectrum of the $\phi$ production channel is scaled by a factor of $1/50$.

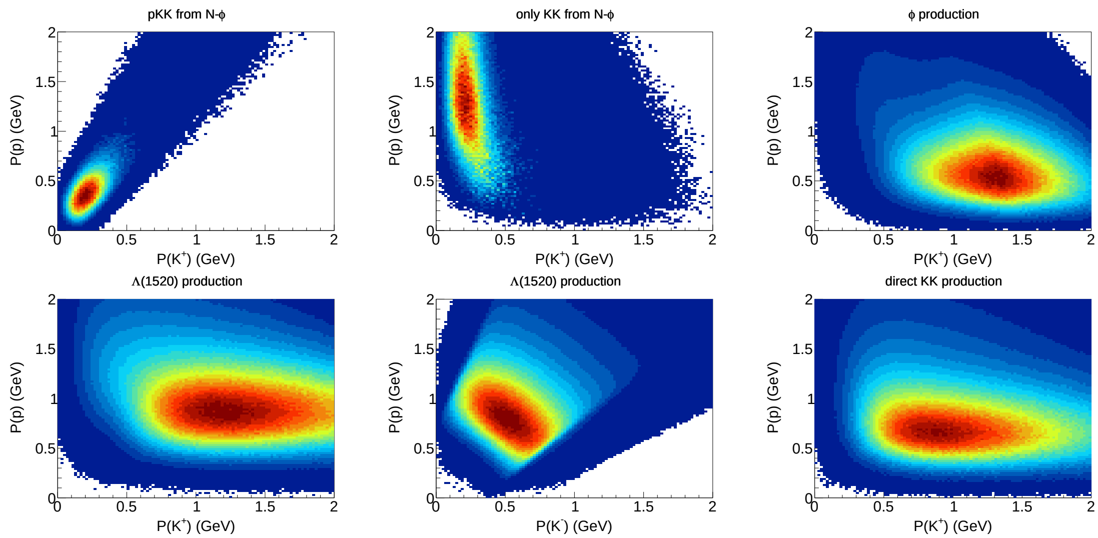



Figure 3: The proton-kaon momenta distributions from different channels. The upper left panel shows the momenta distribution of the proton and kaon decayed from the bound state. The upper middle panel shows the momenta distribution of the proton associated with the bound state production and the kaon decayed from the bound state. The upper right panel shows the distribution of the proton associated with the $\phi$ production and the kaon decayed from the $\phi$. The lower left panel shows the distribution of the proton decayed from $\Lambda(1520)$ and the $K^+$ associated with the $\Lambda(1520)$ production. The lower middle panel shows the distribution of the proton and $K^-$ decayed from the $\Lambda(1520)$. The lower right channel shows the distribution of the proton and kaon from direct two kaons productions.

### 2.2.2 CLAS12 and Forward Tagger

Table 1: CLAS12 design characteristics.

| Parameters | Forward Detector | Central Detector |
|---|---|---|
| Charged tracks: | | |
| polar angular range ($\theta$) | 5° to 35° | 35° to 125° |
| resolution: | | |
| polar angle ($\delta\theta$) | < 1 mr | < 10 mr to 20 mr |
| azimuthal angle ($\delta\phi$) | < 4 mr | < 5 mr |
| momentum ($\delta$p/p) | < 1% at 5 GeV/c | < 5% at 1.5 GeV/c |
| Neutral particles: | | |
| angular range ($\theta$) | 5° to 40° | 40° to 125° (neutrons) |
| angular resolution ($\delta\theta$) | < 4 mr | < 10 mr |
| Energy resolution | $< 0.1/\sqrt(E)$ | < 5% |
| PID: | | |
| e/$\pi$ | full momentum range | N/A |
| $\pi$/p | full momentum range | < 1.25 GeV/c |
| K/$\pi$ | < 3 GeV/c | < 0.65 GeV/c |
| K/p | < 4 GeV/c | < 1 GeV/c |

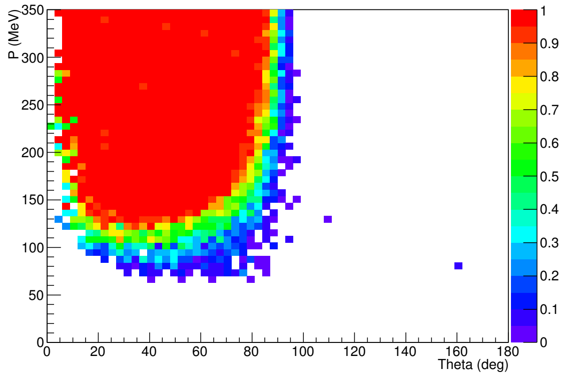
The CLAS12 detector in Hall B is designed to carry out experiments using high energy electron beams incident on polarized and unpolarized targets at luminosities up to $L = 10^{35}$ $\text{cm}^{-2}$ $\text{sec}^{-1}$. CLAS12 consists of two parts, the forward detector (FD) and the central detector (CD). The design characteristics of CLAS12 are presented in Table 1.

The forward detector will be able to detect and identify charged and neutral particles scattered between 5° and 35° over the full momentum range. Particles will be detected in six identical magnetic spectrometers based on a six-coil, superconducting toroidal magnet. Each spectrometer (sector of the forward detector) will be equipped with a forward vertex tracker (FVT) and a set of drift chambers (FDC) for tracking, a high-threshold Cherenkov counter (HTCC) for electron identification, a low-threshold Cherenkov counter (LTCC) for pion identification, scintillation counters (FTOF) for time of flight, and electromagnetic calorimeters (FEC). Particles in the CLAS12 forward detector will be detected and identified by measuring their momenta, time-of-flights, number of photons produced in threshold Cherenkov counters, and energy losses in the calorimeters and scintillator counters. Because the momentum of particles $pK^+K^-$ relevant for this experiment are all below 3 GeV, time of flight is sufficient to detect them. We don't plan to use the CLAS12 central detector, but the 5T superconducting solenoid magnet will be used for the BONUS12 detector.

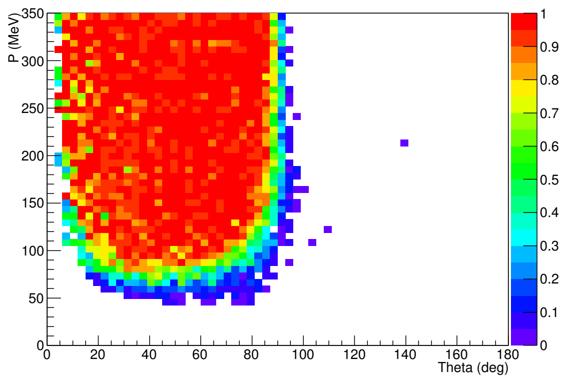
The CLAS12 forward tagger consists of a hodoscope, a tracker and a EM calorimeter and covers from 2.5 to 4.5 degree in polar angle. The scattered electron above 0.5 GeV will be detected to ensure that the reaction is quasi-real photoproduction.

### 2.2.3 BONUS12

We plan to use BONUS12 detector to detect low energy kaons and protons. The BONUS12 cylindrical radial time projection chamber (RTPC) is being developed for experiment E12-06-113 [10], which is based on the successful cylindrical RTPC built for experiment E03-012 [11]. The sensitive drift region of the RTPC is a 40 cm long annulus with the inner




(a) $p$




(b) $K^+$

Figure 4: The momentum and angle acceptance of the BONUS12 detector for $p$ and $K^+$.

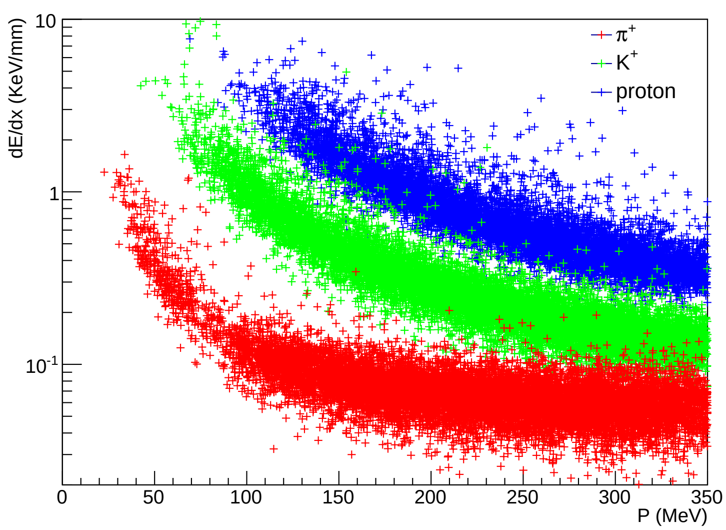



Figure 5: $dE/dx$ for $p$, $K^+$ and $\pi^+$ with momentum $p = 0 - 350$ MeV/c detected in the drift region of the RTPC.

radius of 30 mm and outer radius of 70 mm, filled with a mixture of 82% He gas and 18% dimethyl ether gas. The amplification of the drifting electrons is achieved by three layers of cylindrical Gas Electron Multiplier (GEM, see [12]) foils at radii of 70 , 73 and 76 mm. The foils are surrounded by a cylindrical readout surface featuring rectangular pads at a radius of 78 mm. The GEMs are 50 $\mu$m thick polyamide foils coated on both sides with a 5 $\mu$m copper layer and punctured with 70 $\mu$m holes. By applying a voltage in the range of 200 V to 300 V across the two copper layers a very high electric yield is formed inside the holes. Ionized electrons drifting towards the GEM foil will produce an avalanche of secondary electrons when captured and accelerated through the holes. The maximum drifting time in the RTPC is $\sim$7 $\mu$s. After passing three GEM foils, the resulting electron pulse will be detected on the readout plane. Materials between the target and the sensitive detector volume are minimized to prevent energy loss of the recoiled particles and to minimize the interaction of background particles.

The BONUS12 detector will be located inside the CLAS12 5T superconducting solenoid magnet. The track of the particle is fitted by a pattern-recognition algorithm from the hits reconstructed with the position and the drifting time recorded in the readout system. The momentum and the charge of the particle can be calculated from the curvature and polar angle of the track and the magnetic field. In combination with the measured momentum, energy deposit of the particle ($dE/dx$) derived from the signal pulse heights can be used to provide particle identification.

A Geant4 simulation package of the BONUS12 detector was set up to determine the kinematic coverage and the particle identification. In the simulation, the gold foil target is located at the upstream edge of the detector to maximize the forward angle acceptance. Particles have been produced at angle $\theta = 0 \sim 100$ ° with momentum $p = 0 \sim 350$ MeV/c. Figure 4 shows the momentum and angle acceptance for $p$ and $K^+$. The step-by-step information along the particle tracks produced by the simulation have also been analyzed to determine the $dE/dx$ in the detector for $p$, $K^+$ and $\pi^+$. Figure 5 displays the $dE/dx$ for each particle in our simulated momentum range. We expect kaons and protons can be identified below 250 MeV and pions can be suppressed with at least a factor of 10. Further study is needed to verify its performance.

### 2.3 Event Distribution

Combining the generated signal events with the detector acceptance and resolution, the distributions of the detected proton and kaons from the bound state are shown in Figure 6. A major portion of signal events are detected by the BONUS12 detector, while the CLAS12 forward detector loses many kaons due to their decay before they reach the FTOF detector more than 6 m away.

The background events are studied as the same way like the signal events. The momentum distributions of the detected proton and kaons from each channel are shown in Figure 7. And the invariant mass spectra of the detected $pK^+K^-$ from each channel is shown in Figure 8. The background channels are small comparing to the signal channel. We can choose to further reduce it by removing high momentum particles.

## 3 Projected Results

To obtain our final result of reconstructed $\phi - N$ bound state with least $pK^+K^-$ background from other channels, we apply the cuts: $M(pK^{\pm}) < 1.48\,\mathrm{GeV}$, $M(K^+K^-) <$

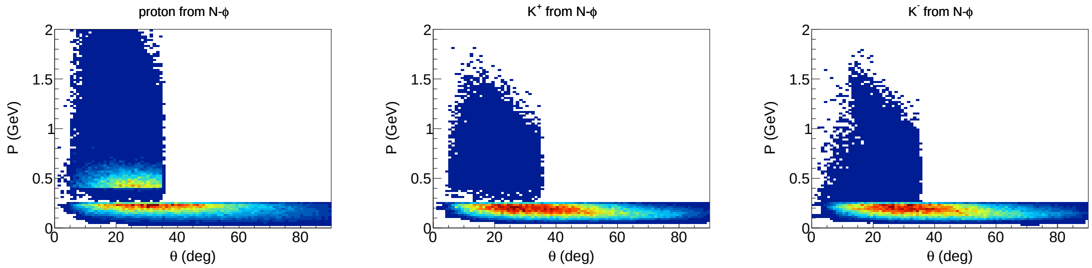



Figure 6: The momentum-polar angle distributions of the detected proton and kaons from the bound state. The left panel is the distribution of the detected proton, the middle panel is the distribution of the detected $K^+$, and the right panel is the distribution of the detected $K^-$.

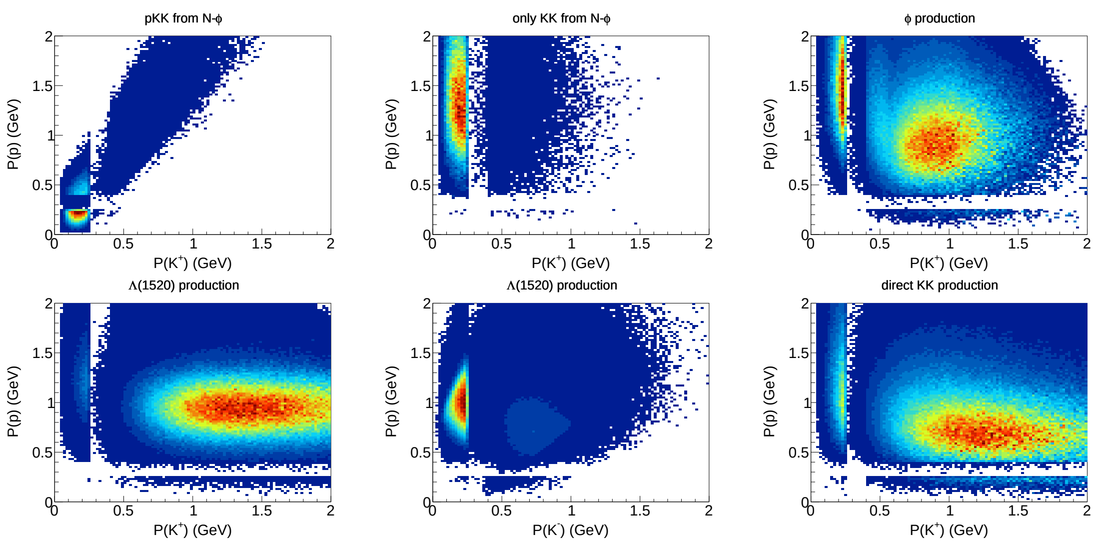



Figure 7: The momenta distributions of detected protons and kaons from different channels, which are described in the caption of Figure 3.

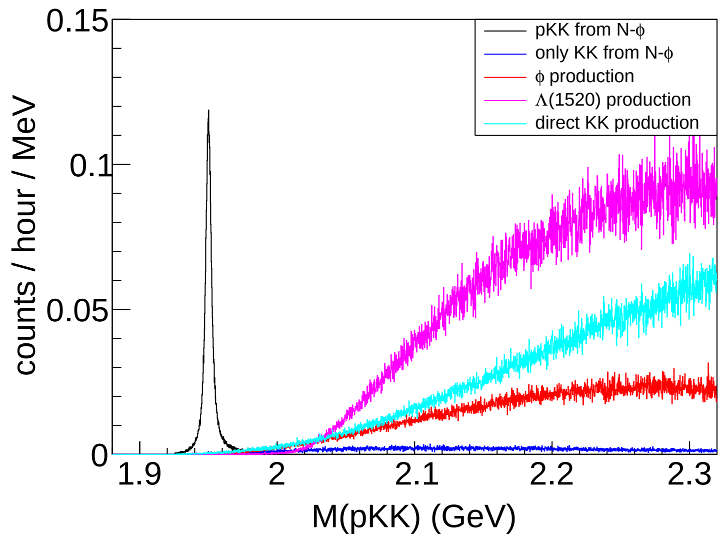



Figure 8: The invariant mass of detected $pK^+K^-$ from different channels, which are described in the caption of Figure 2.

1.04 GeV, $P(p) < 0.8$ GeV, and $P(K^{\pm}) < 0.5$ GeV. The invariant mass spectra after these cuts are shown in Figure 9.

Apart from the $pK^+K^-$ channels, we also simulate the $p\pi^+\pi^-$ channel to account for the background due to $\pi/K$ misidentifications, because the cross sections for pion productions is much larger than those of kaon productions. We assume that 10% pions are misidentified as kaons. The comparison between the signal channel and this background is shown in Figure 10.

Within the region 1935 MeV $< M(pK^+K^-) <$ 1965 MeV, the signal rate is 0.75/h, and the misidentified two-pions background rate is 3.13/h. If assuming 200 hours beam time, we expect to have 150 signal events, and 626 background events. So the excess, 150, is about $5\sigma$ ($\sigma \approx \sqrt{150 + 626} = 28$). We think total 25 days beam time, including 20 day for production and 5 days for calibration, would be good for searching this bound state.

## 4 Discussions

Together with the hidden charm pentaquark candidates discovered by LHCb, the investigations of this hidden strange pentaquark candidate may unravel the flavor dependent properties and the structures of multiquark states. So while the rewards are rich, we also realize that the experiment is challenging in a number of aspects. In particular, using BONUS12 detector to do kaon PID is new. We will work closely with its design and hardware groups to study this. It could include fine tuning the design and planing some tests during the experiment E12-06-113. More detailed background studies will be conducted also with the valuable input from the upcoming CLAS12 and forward tagger data taking.

We plan to submit a full proposal to the PAC in the near future.

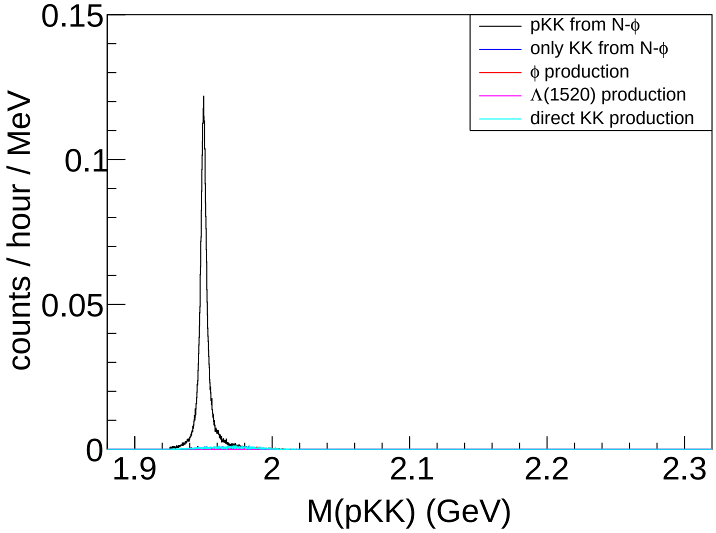



Figure 9: The invariant mass of the detected $pK^+K^-$ after a set of cuts: $M(pK^\pm) < 1.48\,\mathrm{GeV}$, $M(K^+K^-) < 1.04\,\mathrm{GeV}$, $P(p) < 0.8\,\mathrm{GeV}$, and $P(K^\pm) < 0.5\,\mathrm{GeV}$.

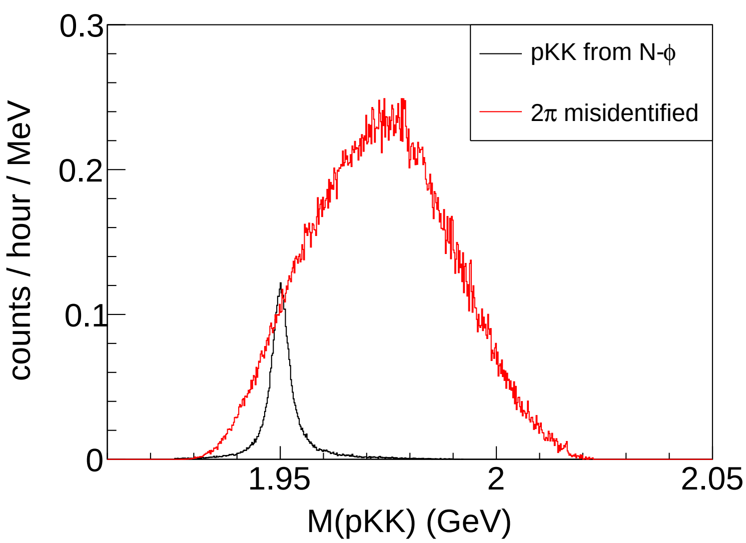



Figure 10: The comparison between the invariant mass distribution of the $pK^+K^-$ from the bound state (black) and the one of the $p\pi^+\pi^-$ production with the pions misidentified to kaons (red).

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