$K^+\Lambda$(1405) photoproduction at the BGO-OD experiment

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Abstract. Since the discovery of the $\Lambda(1405)$, it remains poorly described by conventional constituent quark models, and it is a candidate for having an "exotic" meson-baryon or "penta-quark" structure, similar to states recently reported in the hidden charm sector.
The $\Lambda(1405)$ can be produced in the reaction $\gamma p \rightarrow K^+\Lambda(1405)$. The pure I=0 decay mode into $\Sigma^0\pi^0$ is prohibited for the mass-overlapping $\Sigma(1385)$. Combining a large aperture forward magnetic spectrometer and a central BGO crystal calorimeter, the BGO-OD experiment is ideally suited to measure this decay with the K^+ in the forward direction. Preliminary results are presented.
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1 Introduction

For decades hadron spectroscopy has been used to investigate the strong interaction. Experiments on protons showed that baryons consist of three valance quarks and sea-quarks. While three quark models show a good agreement between calculated and measured for most of the states, the $\Lambda(1405)$ deviates from the predictions. It is lighter in mass than its non-strange counterpart, $N(1535)$, even thought it has a strange quark in its composition. Furthermore the mass distribution, also called line shape, does not follow a Breit-Wigner distribution. The initial inconsistencies elevated $\Lambda(1405)$ as an unconventional state candidate since the discovery more than 50 years ago.

Nowadays there are more theoretical models for $\Lambda(1405)$ having a molecule like structure of $N\bar{K}$. Lattice QCD calculations give more support for the molecule like structure compared to a genuine three quark state [1][2]. A study using a chiral unitarity model, where the resonance is generated dynamically from $N\bar{K}$ interactions with other channels constructed from the octets of baryons and mesons, shows that the line shape would depend on the

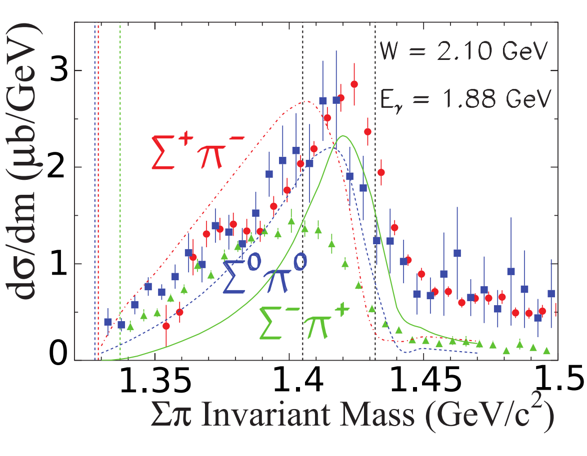

Figure 1. Line shape results from the CLAS experiment [4][5] for different decay modes. Colored lines show model predictions of Nacher et al. [3]. Figure taken from [4].

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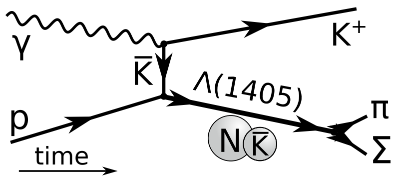

Figure 2. Possible photoproduction scheme of the $\Lambda(1405)$.

decay mode [3]. The results from the CLAS experiment are seen in figure 1 [4]. The measurements show that the line shape does differ for the decay modes. On close inspection it is visible that the measurement and predictions for the charged decays differ from the predictions and a second experiment could help to resolve this discrepancy.

$\Lambda(1405)$ can be produced via $\gamma p \rightarrow K^+\Lambda(1405)$ as seen in figure 2. With the assumption of a molecular like state, one can assume that the cross section for $\Lambda(1405)$ is increased if the transferred momentum to the baryon is low. This means that the K^+ needs to take most of the photon momentum, which corresponds to extreme forward angles in a fixed target experiment, while the $\Lambda(1405)$ decays almost at rest isotropically. The BGO-OD[1] experiment with its central calorimeter and forward spectrometer is ideally suited to measure such kinematics, which were not yet explored by other experiments for the $\Sigma^0\pi^0$ decay. In the following chapters the experimental setup and particle identification are described in more detail. The experiment is explained in section 2 and the reaction identification in section 3. Preliminary results are shown in section 4.

[1] **B**ismuth **G**ermanum **O**xide calorimeter with a **O**pen **D**ipole magnet spectrometer

2 The BGO-OD experiment

The BGO-OD experiment is located at the ELSA[2] facility in Bonn. ELSA is an electron accelerator with a quasi continuous beam up to 3.2 GeV [6]. In figure 3 the general overview of the accelerator facility is shown. It is a three stage electron accelerator. Using a linear accelerator LINAC the electrons are accelerated to relativistic velocities before the injection into the booster synchrotron. Here the electrons are accelerated to an energy of 0.5 GeV to 1.6 GeV before they are guided to the stretcher ring. The stretcher ring needs to be filled multiple times by the synchrotron to be completely full. After this the electrons are accelerated up to 3.2 GeV. The electrons are only extracted partially to either the CBELSA/TAPS[8] or the BGO-OD experiment each revolution. This results in a quasi continuous electron beam for the duration of 5 s to 12 s until the ring is empty and the process starts anew.

In figure 4 the BGO-OD experiment is shown in more detail. The electron beam hits a radiator inside the goniometer tank, which creates a real photon beam via bremsstrahlung. The energy of the photons is determined by measurement of the bremsstrahlung electron with the Tagger detector. The photon beam interacts with the target cell inside the BGO ball, which is filled with liquid hydrogen or deuterium. The final state particles of the reaction are detected with the BGO calorimeter using bismuth germinate oxide crystals between polar angles 25° to 155°. Charged particles traveling in θ <12° are detected in the forward detector. The track trajectory before the open-dipole magnet is measured with the MOMO and SciFi2 scintillating fibre detectors, and the drift chambers measure the trajectory after the magnet. The measured track curvature is used to determine the momentum, while the ToF walls at the end of the experiment measure the veloc-

[2] The **E**lectron **S**tretcher **A**ccelerator in Bonn(Germany)

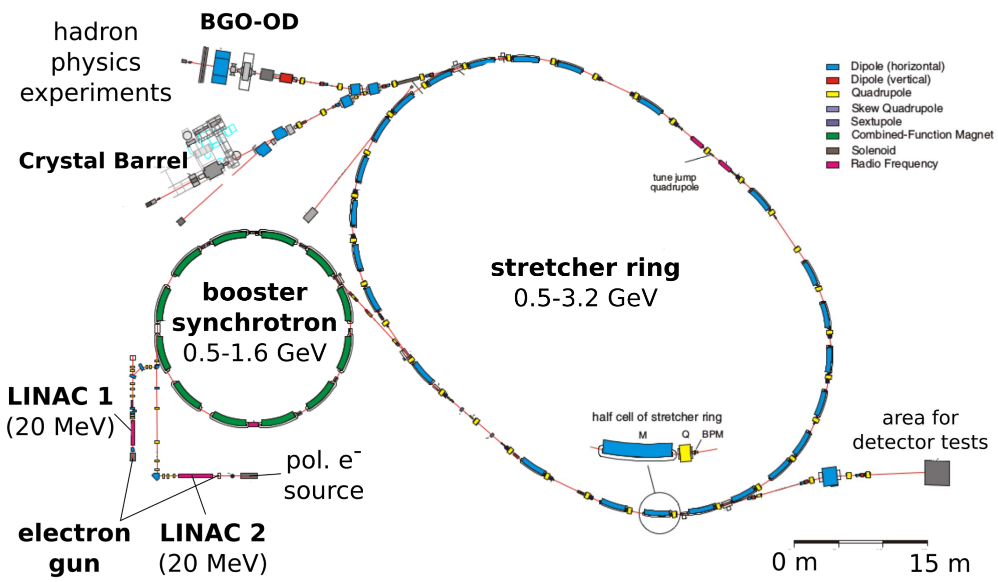

Figure 3. Overview of the Electron Stretcher Accelerator [7] in Bonn, showing the main components.

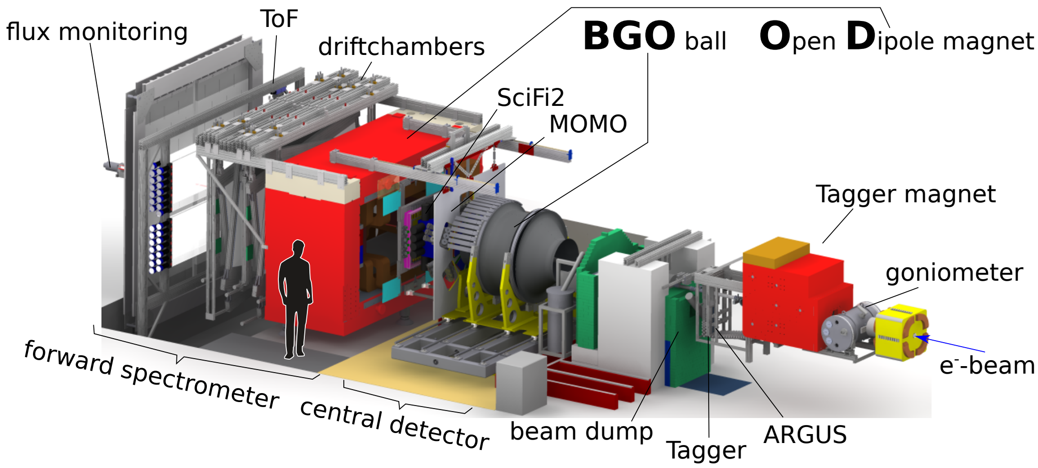

Figure 4. Overview of the BGO-OD experiment.

ity via time of flight. Both measured quantities can be used for particle identification as seen in figure 5.

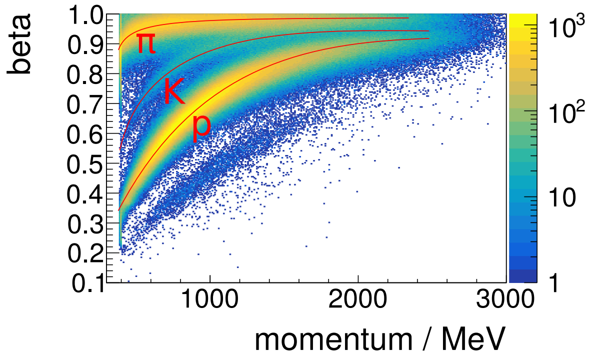

Figure 5. Particle velocity β against momentum p detected in the forward spectrometer. Due to the mass difference the charged particles π, K and p can be distinguished indicated by lines.

3 $\Lambda(1405)$ identification

$\Lambda(1405)$ was identified via the $\Sigma^0\pi^0$ decay, which is prohibited for $\Sigma(1385)$. The complete reactions is $\gamma p \to K^+\Lambda(1405) \to K^+\Sigma^0\pi^0$. The reaction can be identified by detecting K^+ and π^0, while the Σ^0 is identified via missing mass techniques. This can be achieved with the K^+ detected in the forward spectrometer and is described in section 3.1. An additional technique is used by detecting the full final state increasing the K^+ polar angle acceptance in exchange for lower statistics, which is described in section 3.2.

3.1 K^+ at extreme forward angles

The K^+ can be identified in the forward spectrometer using the measured velocity and momentum of the charged particles, as seen in figure 5. A π^0 can be identified by combining two measured photons in the central calorimeter and select events with invariant mass close to the π^0 mass. This leaves the Σ^0 particle to be identified through missing mass techniques. Figure 6 shows the missing mass to K^+ and $K^+\pi^0$ systems. The red lines indicate the possible missing hyperons in the reaction. The events with a Λ mass originate from the prominent $\Sigma(1385)^0 \to \Lambda\pi^0$ decay. While it looks like there are some events with missing Σ^0, studies showed that most of these events are combinatorial background from $\Sigma(1385)$ as seen in figure 7. First preliminary results for the differential cross section can be seen in section 4.2. Further analysis is needed to improve the signal to background ratio.

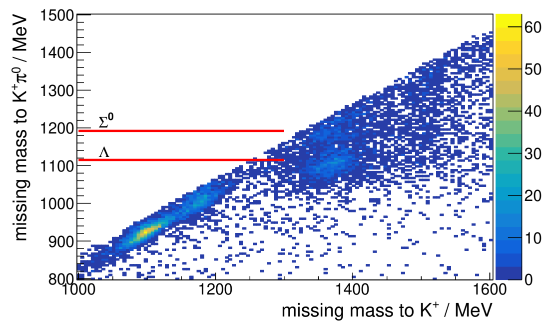

Figure 6. Missing mass to $K^+\pi^0$ against missing mass to K^+, while the K^+ was detected in the forward spectrometer.

3.2 Full topology measurement

Measuring all final state particles in the reaction:

$$\gamma p \to \Lambda(1405)K^+ \quad (1)$$
$$\to \Sigma^0\pi^0K^+ \to \Lambda\gamma\pi^0K^+ \quad (2)$$
$$\to p\pi^-\gamma\gamma\gamma K^+, \quad (3)$$

allows identification with K^+ polar angles outside the forward spectrometer acceptance. However the lack of particle identification increases the number of combinatorial background. Therefore after creating all possible combinatorics, a kinematics fit is used to improve the mass

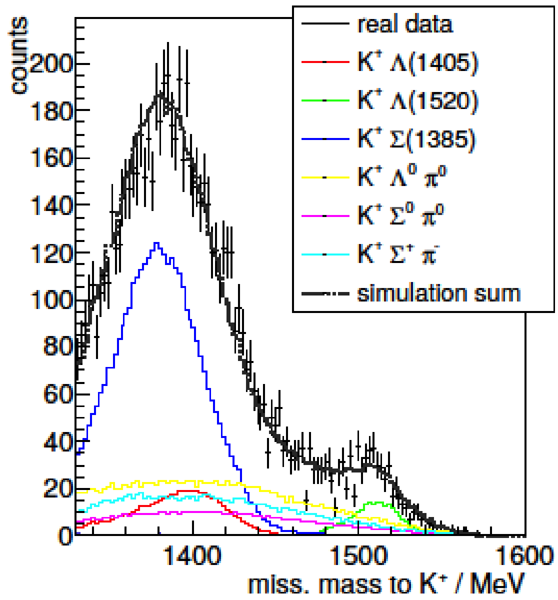

Figure 7. Missing mass to K^+. This is a projection of the two dimensional histogram in figure 6. The colored lines show the contributions of different simulated channels fitted to the data.

resolution and reduce background via confidence level selection cuts. In figure 8 the angular distribution of the photons is shown for signal and background simulation after the kinematic fit. The combinatorial background passes the selection cuts predominantly with low photon angles. Events with low photon angles are removed from the analysis to improve the signal to noise ratio at the cost of statistics. The $\gamma\Lambda$ against $\gamma\Lambda\pi^0$ invariant mass distribution is plotted in figure 9. The signal and background can be distinguished, as only the signal shows a correlation to the Σ^0 mass in the $\Lambda\gamma$ invariant mass. A peak for $\Lambda(1405)$ and $\Lambda(1520)$ is visible as both decay to $\Sigma^0\pi^0$. To subtract the background, the mass outside the signal region, marked by the red lines is used to modulate the amplitude of different simulated reactions, for example $K^+\Sigma(1385)$. In figure 10 the projection of the $\Lambda\gamma\pi^0$ mass is shown, where the signal with $\Lambda\gamma$ mass close to Σ^0 is subtracted. With this fit the background distribution is modeled and can be extrapolated to the region of the signal. In figure 11, the $\Lambda\gamma$ projection of the two dimensional fit is shown. The signal region was not included in the fit. Subtracting the fitted background distribution from the data yields the invariant mass distribution for pure $\Sigma^0\pi^0$ reactions, which is plotted in figure 12. The contribution of non $\Lambda(1405)$ events is estimated by the green line. At this point the line shape and differential cross section can be extracted by subtraction of the simulated contributions. The preliminary results are shown in section 4.

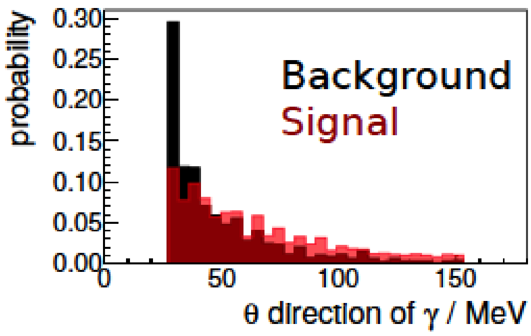

Figure 8. Angular distribution of photon compared between signal in red and background in black.

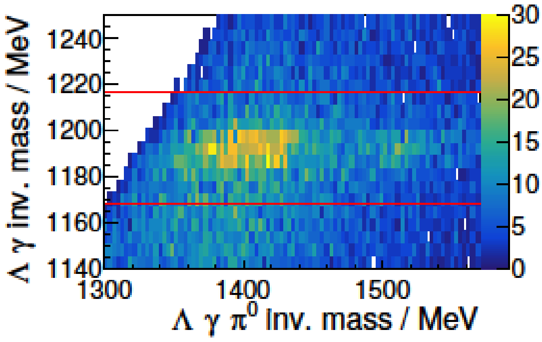

Figure 9. Invariant mass of $\gamma\Lambda$ against $\gamma\Lambda\pi^0$ in the reaction $\gamma p \to \Sigma^0\pi^0 K^+$.

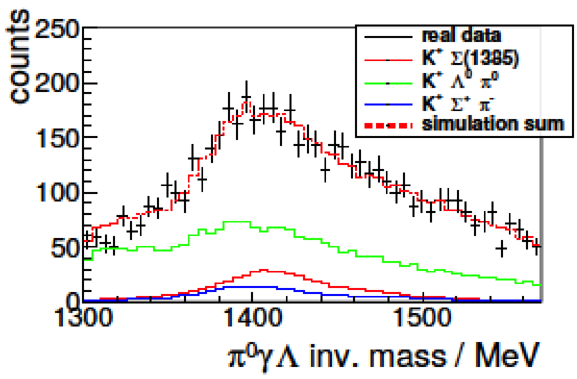

Figure 10. $\Lambda\gamma\pi^0$ mass projection of figure 9, without events where $\Lambda\gamma$ mass is close to Σ^0 mass. The colored lines show example reactions contributing to the background shape, while the red dotted line shows the total fit including also reactions not shown in figure.

4 Preliminary results for $\Lambda(1405) \to \Sigma^0\pi^0$ line shape and differential cross section

Using the analysis steps from the previous section the line shape and differential cross section was determined. For now only the $\Sigma^0\pi^0$ decay was analyzed, as the BGO-OD setup is well suited to measure the decay particles. In sec-

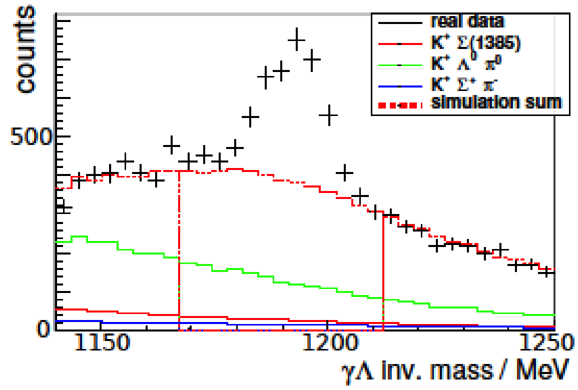

Figure 11. $\Lambda\gamma$ mass projection of figure 9. The colored lines show example reactions contributing to the background shape, while the red dotted line shows the total fit including also reactions not shown in figure.

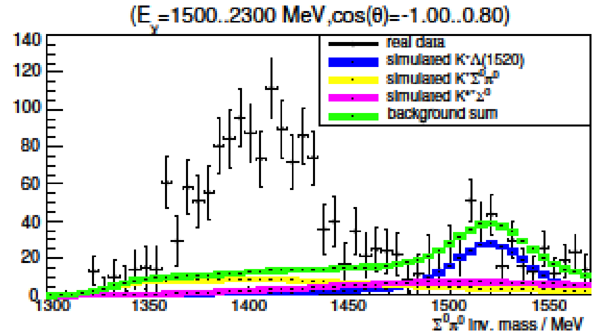

Figure 12. Invariant mass of $\Sigma^0\pi^0$ after all analysis steps. The colored lines show the estimation for not $\Lambda(1405)$ reactions.

tion 4.1 the line shape results are shown, while section 4.2 shows the differential cross section.

4.1 Line shape

The preliminary results on the line shape are compared to other experimental results in figure 13. The $\Lambda(1520)$ signal was not subtracted for consistency checks. The results are statistically comparable to the CLAS experiment, which derives from the better acceptance for this decay mode compared to the CLAS setup. Comparing the ANKE and BGO-OD results indicates a double peak structure in the line shape, which agree to the two pole structure of $\Lambda(1405)$[10]. This seems not to be present in the CLAS data and the statistical error is too big to make a definite statement. All experimental results agree statistically to the predicted line shape in the figure. As mentioned in the introduction the deviations to the predictions show up in the charged decay modes, which will be analyzed in the future.

4.2 Differential cross section

The results on the cross section are plotted in figure 14. In general the cross section agrees to the CLAS

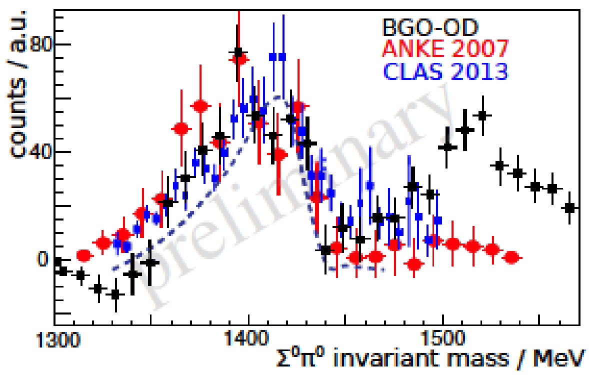

Figure 13. Preliminary line shape of $\Lambda(1405)$ for E_γ = 1500 to 2300 MeV compared to the CLAS experiments in blue[5] and ANKE in red[9]. The dashed blue line marks the predictions by J.C.Nacher[3]. The BGO-OD and ANKE results are in yield with no normalization. To compare the line shape, the results of the experiments were scaled such that the maximum values agree.

results. The forward spectrometer analysis extends the CLAS results to extreme forward angles, which correlates to minimum transfer momentum. While the results agree for higher energies, it suggest the photon energy bin E_γ = 1550..1750 MeV shows a more flat distribution compared to the CLAS results. The charged decay modes results of CLAS also show this behavior compared to the their measured neutral decay mode. Further investigation is needed to clarify this.

5 Summary and Outlook

The BGO-OD experiment is ideally suited to investigate the formation of unconventional states. Since more than 50 years $\Lambda(1405)$ is a potential candidate for such a state. Models describe $\Lambda(1405)$ as a $N\bar{K}$ molecule-like structure, which is formed below the free $N\bar{K}$ production threshold. This is also used as an explanation of the sudden cut-off in the invariant mass distribution (line shape) above 1426 MeV as this marks the free production threshold. Thus the line shape is of great interest for the study of $\Lambda(1405)$. Preliminary results for the decay mode $\Lambda(1405) \rightarrow \Sigma^0\pi^0$ line shape and differential cross section agree within statistics to the CLAS experiment, while the differential cross section could be extended to extreme forward angles thanks to the forwards spectrometer of the BGO-OD experiment. The charged decay modes of $\Lambda(1405)$ will be investigated in the future.

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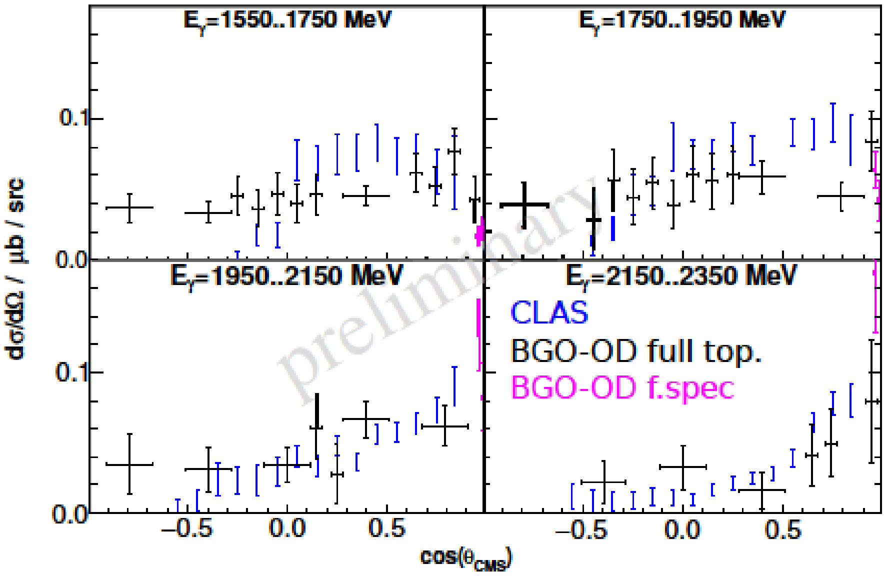

Figure 14. Preliminary differential cross section against angle compared to the CLAS experiment[5] in blue. The black points mark the full topology reconstruction while magenta shows the K^+ in the forward spectrometer analysis.

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