$K^+\Lambda$ photoproduction at forward angles and low momentum transfer

S. Alef, P. Bauer, D. Bayadilov, R. Beck, A. Bella, J. Bieling, A. Braghieri, P.L. Cole, D. Elsner, R. Di Salvo, A. Fantini, O. Freyermuth, F. Frommberger, F. Ghio, S. Goertz, A. Gridnev, D. Hammann, J. Hamnappel, T.C. Jude, K. Kohl, N. Koslenko, A. Lapik, P. Levi Sandri, V. Lisin, G. Mandaglio, F. Messi, R. Messi, D. Moricciani, V. Nedorezov, V.A. Nikonov, D. Novinskiy, P. Pedroni, A. Polonskiy, B.E. Reitz, M. Romanuk, A.V. Sarantsev, G. Scheluchin, H. Schmieden, A. Stugelev, V. Sumachev, V. Tarakanov, and T. Zimmermann

1 Rheinische Friedrich-Wilhelms-Universität Bonn, Physikalisches Institut, Nüfallee 12, 53115 Bonn, Germany
2 Rheinische Friedrich-Wilhelms-Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik, Nüfallee 14-16, 53115 Bonn, Germany
3 Petersburg Nuclear Physics Institute, Gatchina, Leningrad District, 188300, Russia
4 INFN sezione di Pavia, Via Agostino Bassi, 6 - 27100 Pavia, Italy
5 Lamar University, Department of Physics, Beaumont, Texas, 77710, USA
6 INFN Roma “Tor Vergata”, Via della Ricerca Scientifica 1, 00133, Rome, Italy
7 Università di Roma “Tor Vergata”, Dipartimento di Fisica, Via della Ricerca Scientifica 1, 00133, Rome, Italy
8 INFN sezione di Roma La Sapienza, P.le Aldo Moro 2, 00185, Rome, Italy
9 Istituto Superiore di Sanità, Viale Regina Elena 299, 00161, Rome, Italy
10 Russian Academy of Sciences for Nuclear Research, Prospekt 60-letiya Oktyabrya 7a, 117312, Moscow, Russia
11 INFN - Laboratori Nazionali di Frascati, Via E. Fermi 54, 00044, Frascati, Italy
12 INFN sezione di Catania, 95129, Catania, Italy
13 Università degli Studi di Messina, Dipartimento MIFT, Via F. S. D’Alcontres 31, 98166, Messina, Italy
14 Institute for Nuclear Research of NASU, 03028, Kyiv, Ukraine

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Abstract. $\gamma p \to K^+\Lambda$ differential cross sections and recoil polarisation data from threshold for extremely forward angles are presented. The measurements were performed at the BGOOD experiment at ELSA, utilising the high angular and momentum resolution forward spectrometer for charged particle identification. The data discriminates between confictions in the world data set and describe the cross section as minimum momentum transfer to the recoiling hyperon is approached.

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1 Introduction

Associated strangeness ($K\Lambda$) photoproduction is a crucial area of study to elucidate the nucleon excitation spectrum and the relevant degrees of freedom. There remain many resonances predicted by constituent quark models (CQMs) [12,13], lattice QCD calculations [5], harmonic oscillator and hypercentral CQMs [6,7] and Dyson-Schwinger equations of QCD [8] that have not been observed experimentally. A main motivation of the study of $K\Lambda$ photoproduction channels over the last 15 years has been to search for these “missing resonances which may only couple weakly to $K\Lambda$ final states [9,10]. The ensuring wealth of high statistics data from the Crystal Ball @ MAMI [11,12,13,14,15,16,17], SAPHIR [18], LEPS [19,20] and GRAAL [21] collaborations have rendered the $K\Lambda$ channels the closest to a “complete measurement, where a judiciously selected set of polarisation observables permit a complete description of the photoproduction mechanism [22]. This is partly due to the weak, self analysing decay of the $\Lambda$ enabling easier access to the recoiling baryon (single and double) polarisation observables. Despite this data and support from partial wave analyses (PWA) with dynamical coupled-channel frame works [23,24,25], isobar models [26,27,28,29,30,31,32,33], and models incorporating Regge trajectories [34,35,36], a mutually consistent description between theory and data of $K\Lambda$ photoproduction channels has not been realised.

The $K^+\Lambda$ threshold is in the third resonance region, where an abundance of $s$-channel resonances up to high
spin states, $u$-channel hyperon resonances and $t$-channel $K$, $K^*$ and $K_1$ exchanges contribute. The isospin singlet $\Lambda$, however, acts as a filter to remove intermediate $\Delta^*$ states which are present in $K\Sigma$ channels, enabling a “cleaner” study of $t$-channel processes. At forward angles, where the cosine of the centre of mass $K^+$ polar angle, $\cos \theta^K_{CM}$, exceeds 0.9, there is a paucity of data to constrain the reaction mechanism, and the existing cross section data of SAPHIR \[18\] and CLAS \[12,13,16\] have pronounced inconsistencies.\[1\] This has led to a poor understanding of the dynamics of the Born terms and $t$-channel $K^+$ and $K^*$ exchanges which dominate at forward angles.\[37\] PWA solutions have also included different $s$-channel resonance contributions, depending if the fits used the SAPHIR or CLAS data sets (see for example ref. \[38\]). Data with high $\cos \theta^K_{CM}$ resolution at forward (and backward) angles is also sensitive to high-spin intermediate states, where the corresponding Legendre polynomials change quickly with respect to $\cos \theta^K_{CM}$. States with spin 5/2 and 7/2 have been incorporated in previous PWA and isobar model solutions (see for example refs. \[23,24\] \[39,40,41,42,43,44\]).

Forward angle kinematics also enables access to a regime where the momentum transfer to the recoiling hyperon is minimised. This is a vital input for the description of hypernuclei electroproduction at low $Q^2$.\[39,40,11,12,43,44\] Studying the $Y-N$ interaction is crucial for an SU(3)$_{flavour}$ description of baryon interactions and provides important astrophysical constraints, for example upon the equation of state for neutron stars (see ref. \[45\] and references therein).

The BGOOD experiment \[16\] (shown in fig. 1) at the ELSA facility \[47,48\] in Bonn, Germany, is ideally suited for $\gamma p \rightarrow K^+ A$ measurements at forward angles. BGOOD is composed of two distinct parts: a forward magnetic spectrometer, ideal for the detection of forward going $K^+$, and a central calorimeter, suited for the identification of hyperons at low momentum, decaying almost isotropically. The presented data resolve discrepancies in existing data sets for $\cos \theta^K_{CM}$. A measurement at minimum momentum transfer is approached can be determined in 0.02 $\cos \theta^K_{CM}$ intervals.

This paper is organised as follows: sect. 2 describes the BGOOD experiment and the running conditions during the data taking. Section 3 explains the identification of the reaction channel and corresponding systematic errors. Differential cross sections and recoil polarisation measurements are presented and discussed in sect. 4. Concluding remarks are made in sect. 5.

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1 The LEPS collaboration data \[19,20\] starts at a photon beam energy of 1.5 GeV and is generally in agreement with CLAS data.
particles from the reaction vertex in the target. Downstream from these is the Open Dipole Magnet, operating at an integrated field strength of 0.7 Tm and covering polar angles 1° to 12° or 8° in the horizontal or vertical planes respectively. Particle trajectories downstream from the Open Dipole Magnet are determined using eight double layered drift chambers, and particle momentum is subsequently determined by the deflection of the trajectory in the magnetic field. Three time of flight (ToF) walls at the end of the spectrometer measure particle $\beta$.

The region between the BGO Rugby Ball and the Forward Spectrometer is covered by the SciRi detector, which is a ring of plastic scintillators for charged particle detection.

3 Event selection

$^+K$ were identified in the Forward Spectrometer from spatial coincidences between MOMO, SciFi, the Drift Chambers and the ToF walls. The momentum calculation used a three dimensional magnetic field description, including fringe fields extending beyond the magnet yoke, and particle energy loss from the target, air and detector materials. The particle trajectory was stepped through in discrete, dynamically determined intervals, and a minimisation method was used to determine the optimum trajectory and momentum, given the hit positions in the detectors. A momentum resolution of approximately 5% of the measured momentum was achieved.

Particle $\beta$ was determined by time measurements in the ToF walls, accounting for the trajectory length and particle energy loss. Contrary to the default track finding routine described in ref. [46], a cluster in MOMO was not required to form a forward track due to an efficiency of only 80%. If no MOMO cluster was identified, it was sufficient to use only a SciFi cluster and the target centre as a space point. The increase in background and reduction in spatial resolution were proved to be negligible.

The mass of forward particles was calculated from momentum and $\beta$: $m = p/(\gamma \beta)$. Figure 3 shows two examples of the reconstructed $K^+$ mass for different momentum intervals, with good agreement between real and simulated events. The low energy shoulder in the real data spectrum is from misidentified $\pi^+$ from other hadronic reactions, and positrons from pair production in the beam.

Candidate events were selected over $\pm 2\sigma$ of the reconstructed $K^+$ mass. This was a function of $K^+$ momentum, varying from $\pm 47$ MeV/c and $\pm 106$ MeV/c at 450 MeV/c and 1000 MeV/c respectively.

Due to the relatively small cross section compared to non-strange channels, identification of the decay $\Lambda \rightarrow \pi^0 n$ was required to enhance the signal relative to background. $\pi^0$ were identified in the BGO Rugby Ball via the two photon decay, where the measured invariant mass was required to be $\pm 30$ MeV/c$^2$ from the accepted $\pi^0$ mass, corresponding to $\pm 2\sigma$. Figure 3 shows the missing mass from the $K^+\pi^0$ system corresponding to the neutron mass for the $K^+\Lambda$ channel, plotted against the missing mass from the forward $K^+$. Events were selected above the red line.

![Fig. 2. Mass reconstruction for $K^+$ candidates in the forward spectrometer for real and simulated data (red and blue lines respectively).](image)

Events were rejected if a charged particle was identified in either the BGO Rugby Ball (via coincidence with the plastic scintillating barrel) or the intermediate SciRi detector. The total energy deposition in the BGO Rugby Ball was also required to be lower than 250 MeV. The simulated data shown in fig. 2 demonstrates this removes approximately half of the most significant background from falsely identified $\pi^+$ from $\Delta^0\pi^+$ events.

Figure 5 shows the $K^+$ missing mass for different photon beam intervals. The distribution of the $\pi^+$ and $e^+$ background was described by an equivalent analysis of negatively charged particles, where $\pi^-$ and $e^-$ have similar kinematics. To extract the $K^+\Lambda$ yield, a combined fit of this background and simulated $K^+\Lambda$ and $K^+\Sigma^0$ was used.

3.1 Detection efficiency calculations

The detection efficiency was determined using a Geant4 [49] simulation of the experimental setup. This included all spatial, energy and time resolutions, efficiencies for all detectors in the forward spectrometer (described in ref. [46]) and the modelling of the hardware triggers described below.

Three hardware trigger conditions, listed in table 1 were implemented for a broad range of experimental requirements. Trigger 4 was used for this analysis, where approximately 80 MeV minimum energy deposition was required in the BGO Rugby Ball and a signal in the SciFi and ToF detectors, described in table 1 as a Forward Track.
The efficiencies of the BGO Rugby Ball energy sum triggers, shown in fig. 3(a) were determined via a ratio of all events passing different trigger combinations. The high energy sum distribution was determined from the ratio of events passing both triggers 0 and 3, and all events passing trigger 3. The low energy sum was determined from the ratio of events passing both triggers 0 and 3, and all events passing trigger 3. These distributions were implemented in simulated data for an accurate determination of detection efficiencies.

The timing of the hardware triggers was not identical to measured times in the event reconstruction. Due to the comparatively large time range for forward going particles, the efficiency of trigger 4 also depended upon the particle $\beta$. Fig. 3(b) shows this efficiency, determined from a clean selection of forward going protons. For forward $K^+$ from $K^+\Lambda$, $\beta$ is approximately 0.65 and 0.90 at threshold and $W = 1900\text{MeV}$, corresponding to correction factors of 1.09 and 1.06 to the event yields respectively.

Shown in fig. 7, the detection efficiency was approximately 2.4% at threshold, rising smoothly to 5% at $1400\text{MeV}$.

This was determined using the well known $\gamma p \rightarrow \eta \eta$ differential cross section, the results of which are presented in ref. [46].
The efficiency also increases at more forward angles. These efficiencies also account for the π⁰ detection, the Λ → π⁰n branching ratio of 36%, and approximately 50% of K⁺ decaying in-flight. These three factors alone limit the detection efficiency to 13%.

**3.2 Systematic uncertainties**

Systematic uncertainties are divided into two components. The *scaling uncertainty*, the sources of which are listed in Table 2, is a constant fraction of the measured cross section. The position of the beam when impinging upon the target was the largest source due to the dependence of the measured production angle and forward acceptance. This was determined using simulated data. The absolute photon flux determination is the second largest uncertainty. This was estimated by measuring well known photoproduction cross sections, and comparing flux measurements using either Flumo or GIM detectors at low rates.

| Source                                      | % error |
|---------------------------------------------|---------|
| Beam spot alignment                         | 4.0     |
| Photon flux                                 | 4.0     |
| K⁺ selection                                | 2.0     |
| SciFi efficiency                            | 3.0     |
| Target wall contribution                    | 2.0     |
| Track time selection                        | 2.0     |
| Target length                               | 1.7     |
| ToF wall efficiency                         | 1.5     |
| MOMO efficiency                             | 1.0     |
| Drift chamber efficiency                    | 1.0     |
| Beam energy calibration                     | 1.0     |
| Modelling of hardware triggers              | 1.0     |
| π⁰ identification                           | 1.0     |
| Forward track geometric selection           | 1.0     |
| Summed in quadrature                        | 8.0     |

**Table 2.** Systematic uncertainties contributing to the constant fractional error.

The *fitting uncertainty* from extracting the number of events from the missing mass spectra permits the individual movement of data points. This was estimated by additionally including simulated γ⁺p → Δ⁺π⁺ events in the background distribution and by varying the fit range. Figure 8 shows the difference in the measured cross section for cos θ<sub>CM</sub> > 0.9 when additionally using this distribution to describe the missing mass spectra, with an exponential function to describe the data trend. Significant differences are observed only above approximately E<sub>γ</sub> = 1350 MeV. To check the consistency of the fitting procedure, the data was also binned into both 0.03 and 0.02 cos θ<sub>CM</sub> intervals, where the yield was summed and compared to the total over the full 0.1 cos θ<sub>CM</sub> interval. This showed good agreement within the systematic errors. The same fitting systematic uncertainty was assumed for the data binned in smaller cos θ<sub>CM</sub> intervals, where the lower statistics prevented an accurate determination.

**4 Results and discussion**

All presented data are tabulated in the appendix.
4.1 $\gamma p \rightarrow K^+\Lambda$ differential cross section

The differential cross section for $\cos \theta_{CM}^K > 0.9$ is shown in fig. [9] The interval range in $W$ is typically 15 MeV and determined by the width of the Photon Tagger channels. This is comparable to the previous data shown from the CLAS collaboration [12,22] and half the size of the SAPHIR collaboration data [18]. The comparatively small statistical errors resolve the discrepancies in the existing world data, where the SAPHIR data is consistently lower than the CLAS data, and the two CLAS datasets also exhibit deviations.

The isobar models of Skoupil and Bydžovský [26,27] BS1 and BS3 (green and blue lines), also plotted in fig. [9] show good agreement with the peak structure around $W = 1720$ MeV, however fail to reproduce the rising structure at $W = 1850$ MeV. A peak is evident in these models at this energy but at a more backward angle of $\cos \theta_{CM}^K = 0.94$ which is not covered by this new data. The Regge plus resonant (RPR) model of Skoupil and Bydžovský [26] (red line) fails to reproduce the bump at $W = 1720$ MeV, where it is considered that the $S_{11}(1650)$ would need to contribute more to describe the data. There is an improved agreement at $W = 1850$ MeV, where the rise can be described by the constructive interference of the $D_{13}(1700)$ and $D_{15}(1675)$. Neither resonances are included in the BS1 or BS3 isobar models, which may cause the discrepancies at these energies.

The Bonn-Gatchina BG2019 solution [24] when fitted to the CLAS data is also shown in fig. [9] as the magenta line. There is a reduced $\chi^2$ of 2.99 between the fit and this data. A new fit including this data is shown as the cyan line. The fit optimized all $K^+\Lambda$ and $K^+\Sigma^0$ couplings for the resonant contributions and $t$ and $u$ channel exchange terms.

The CLAS data is at the more backward angle of $\cos \theta_{CM}^K < 0.85$. The systematics uncertainties are in three components: The shaded blue and red bars are the scaling and fitting uncertainties respectively, described in sec. 3.2. The grey bars are the total. Previous data is shown of McCracken et al. (CLAS) [13] (blue open squares), Bradford et al. (CLAS) [12] (red open triangles) and Glander et al. (SAPHIR) [18] (green open diamonds). The Regge plus resonant model [22] and isobar models BS1 and BS3 [26,27] of Skoupil and Bydžovský are the red, green and blue lines respectively. The Bonn-Gatchina PWA [24] solutions with and without the inclusion of the new data are the cyan and magenta lines respectively.
s-channel dominating components of the reaction mechanism. As $W$ increases the cross section becomes more forward peaked consistent with increasing $t$-channel $K$ and $K^*$ exchange processes. In fig. 11, the peak at $W = 1720$ MeV remains approximately constant in strength over the $\cos \theta^K_{\text{CM}}$ range, however the rising peak towards 1900 MeV becomes stronger at the most forward angles, agreeing with the RPR model of Skoupil and Bydžovský [30].

![Fig. 10. $\gamma p \rightarrow K^+ \Lambda$ differential cross section versus $\cos \theta^K_{\text{CM}}$ for each centre of mass energy, $W$ labelled inset in MeV. Filled black circles are these data binned into 0.02 $\cos \theta^K_{\text{CM}}$ intervals, and other data points and model fits are the same as described in fig. 9.](image)

The data binned finely into 0.02 $\cos \theta^K_{\text{CM}}$ intervals was used to determine the differential cross section with respect to the Mandelstam variable, $t$. To account for the distribution of $t$ within each two dimensional $W$ and $\cos \theta^K_{\text{CM}}$ interval, a generated distribution assumed the differential cross section of the McCracken CLAS data [13]. For each interval, the mean average value of $t$ was used as the central value, and the width was determined as $\sqrt{12}$RMS. The differential cross section with respect to $t$ is shown for each $W$ interval in fig. 12. The function in eq. 1 was fitted to the data to interpolate the cross section to $t_{\text{min}}$ and $\cos \theta^K_{\text{CM}} = 1$, and to extract the slope parameter, $S$.

\[
\frac{d\sigma}{dt} = \frac{d\sigma}{dt} \bigg|_{t_{\text{min}}} e^{S(t-t_{\text{min}})}
\]

Fig. 13 shows the differential cross section at $t_{\text{min}}$ and the slope parameter $S$ versus $W$. The shape of the cross section is similar to the most forward $\cos \theta^K_{\text{CM}}$ interval, with a dominant peak at 1720 MeV, and a rising structure to 1900 MeV. For the first 100 MeV above threshold, $S$ remains positive. At higher energies, $S$ becomes increasingly negative, indicating the onset of $t$-channel $K$ exchange dominating the reaction mechanism.

4.2 $\gamma p \rightarrow K^+ \Lambda$ recoil polarisation

The weak decay of the $\Lambda$ allows access to the recoil polarisation via the decay distribution. The $\pi^0$ four-momentum from $A \rightarrow \pi^0 \Lambda$ was boosted into the $\Lambda$ rest frame and the $\pi^0$ direction relative to the reaction plane was determined (denoted $N_\uparrow/N_\downarrow$). The recoil polarisation was measured according to eq. 2. The $\Lambda$ decay parameter, $\alpha = 0.642 \pm 0.04$ [51],

\[
P_A = \frac{2 N_\uparrow - N_\downarrow}{\alpha N_\uparrow + N_\downarrow}
\]
Simulated data were used to determine the success rate of correctly determining $N_{\gamma/L}$ per event to measure dilution effects which may have occurred due to limited azimuthal angular resolution at forward angles. A small correction as a function of $E_\gamma$ was determined. This was 5% and 7% at $E_\gamma = 914$ MeV (threshold) and 1500 MeV respectively.

The recoil polarisation data is shown in fig. 14. Nearly all systematic uncertainties shown in table 2 cancel out. The remaining dominating uncertainty is the accuracy of $\alpha$ of 6.2%.

This is the first data for $P_A$ in this most forward $\cos \theta_{CM}^K$ interval (the previous data shown are at more backward angles described in the figure caption). $P_A$ is consistent with zero at threshold and at higher energies becomes negative, consistent with the isobar models, BS1 and BS3 [26,27]. The Bonn-Gatchina BG2019 solution prior to including this data gives a $\chi^2$ of 0.98 for the recoil asymmetry. When refitting using the new data as described above, $\chi^2$ changes to 0.95.

5 Conclusions

Differential cross sections for $\gamma p \rightarrow K^+ A$ for $\cos \theta_{CM}^K > 0.9$ have been measured with high polar angle resolution from threshold to $W = 1870$ MeV. Additionally, the recoil polarisation data for $K^+ A$ is the first data set at this most forward $\cos \theta_{CM}^K$ interval.

The high statistics cross section data allow a discrimination between existing conflicting data sets and provide constraints in determining dominating $t$-channel $K$ and $K^*$ exchange at forward angles and low momentum transfer.
transfer. The Bonn Gatchina PWA analysis demonstrated a consistency between this data and the more backward CLAS data of Bradford and McCracken et al. \cite{12,13}.

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### Appendix: Tabulated data

| $\cos \theta_{CM}$ | $W_{\text{min}}$ | $W$ | $W_{\text{max}}$ | $d\sigma/d\Omega$ | $\delta_{\text{stat}}$ | $\delta_{\text{sys}}$ | $\delta_{\text{scaling}}$ | $\delta_{\text{fitting}}$ |
|------------------|------------------|-----|------------------|------------------|------------------|------------------|------------------|------------------|
| 0.95             | 1612.6           | 1624.1 | 1635.6            | 0.044             | 0.006            | 0.004            | 0.004            | 0.000            |
| 0.95             | 1635.6           | 1647.0 | 1658.3            | 0.117             | 0.009            | 0.009            | 0.009            | 0.000            |
| 0.95             | 1658.3           | 1669.4 | 1680.5            | 0.230             | 0.012            | 0.018            | 0.018            | 0.000            |
| 0.95             | 1680.5           | 1688.0 | 1695.4            | 0.331             | 0.019            | 0.027            | 0.027            | 0.000            |
| 0.95             | 1695.4           | 1702.8 | 1710.1            | 0.377             | 0.018            | 0.030            | 0.030            | 0.000            |
| 0.95             | 1710.1           | 1717.4 | 1724.7            | 0.399             | 0.020            | 0.032            | 0.032            | 0.000            |
| 0.95             | 1724.7           | 1732.0 | 1739.2            | 0.409             | 0.020            | 0.033            | 0.033            | 0.000            |
| 0.95             | 1739.2           | 1746.4 | 1753.6            | 0.407             | 0.020            | 0.033            | 0.033            | 0.000            |
| 0.95             | 1753.6           | 1760.8 | 1767.9            | 0.373             | 0.020            | 0.031            | 0.030            | 0.008            |
| 0.95             | 1767.9           | 1775.0 | 1782.0            | 0.337             | 0.019            | 0.029            | 0.027            | 0.010            |
| 0.95             | 1782.0           | 1789.0 | 1796.1            | 0.357             | 0.019            | 0.032            | 0.029            | 0.014            |
| 0.95             | 1796.1           | 1803.0 | 1810.0            | 0.334             | 0.019            | 0.032            | 0.027            | 0.017            |
| 0.95             | 1810.0           | 1816.9 | 1823.8            | 0.358             | 0.020            | 0.037            | 0.029            | 0.024            |
| 0.95             | 1823.8           | 1830.7 | 1837.5            | 0.366             | 0.019            | 0.044            | 0.029            | 0.033            |
| 0.95             | 1837.5           | 1844.3 | 1851.1            | 0.386             | 0.022            | 0.055            | 0.031            | 0.046            |
| 0.95             | 1851.1           | 1857.9 | 1864.6            | 0.406             | 0.021            | 0.071            | 0.033            | 0.063            |

Table 3. $\gamma p \rightarrow K^+ A$ differential cross section data ($d\sigma/d\Omega$) for $0 < \cos \theta_{CM}^K < 1.00$. The minimum, median and maximum centre of mass for each interval are labelled $W_{\text{min}}$, $W$ and $W_{\text{max}}$ respectively. The statistical, systematic, and the two components of the systematic error (scaling and fitting) are labelled $\delta_{\text{stat}}$, $\delta_{\text{sys}}$, $\delta_{\text{scaling}}$ and $\delta_{\text{fitting}}$ respectively.

| $\cos \theta_{CM}$ | $W_{\text{min}}$ | $W$ | $W_{\text{max}}$ | $d\sigma/d\Omega$ | $\delta_{\text{stat}}$ | $\delta_{\text{sys}}$ | $\delta_{\text{scaling}}$ | $\delta_{\text{fitting}}$ |
|------------------|------------------|-----|------------------|------------------|------------------|------------------|------------------|------------------|
| 0.91             | 1612.6           | 1624.1 | 1635.6            | 0.058             | 0.019            | 0.005            | 0.005            | 0.000            |
| 0.91             | 1635.6           | 1647.0 | 1658.3            | 0.141             | 0.029            | 0.011            | 0.011            | 0.000            |
| 0.91             | 1658.3           | 1669.4 | 1680.5            | 0.204             | 0.033            | 0.016            | 0.016            | 0.000            |
| 0.91             | 1680.5           | 1688.0 | 1695.4            | 0.343             | 0.058            | 0.027            | 0.027            | 0.000            |
| 0.91             | 1695.4           | 1702.8 | 1710.1            | 0.381             | 0.052            | 0.031            | 0.031            | 0.000            |
| 0.91             | 1710.1           | 1717.4 | 1724.7            | 0.306             | 0.055            | 0.024            | 0.024            | 0.000            |
| 0.91             | 1724.7           | 1732.0 | 1739.2            | 0.404             | 0.057            | 0.032            | 0.032            | 0.000            |
| 0.91             | 1739.2           | 1746.4 | 1753.6            | 0.375             | 0.060            | 0.030            | 0.030            | 0.000            |
| 0.91             | 1753.6           | 1760.8 | 1767.9            | 0.315             | 0.053            | 0.027            | 0.025            | 0.008            |
| 0.91             | 1767.9           | 1775.0 | 1782.0            | 0.277             | 0.050            | 0.024            | 0.022            | 0.010            |
| 0.91             | 1782.0           | 1789.0 | 1796.1            | 0.309             | 0.059            | 0.028            | 0.025            | 0.014            |
| 0.91             | 1796.1           | 1803.0 | 1810.0            | 0.239             | 0.053            | 0.026            | 0.019            | 0.017            |
| 0.91             | 1810.0           | 1816.9 | 1823.8            | 0.327             | 0.060            | 0.036            | 0.026            | 0.024            |
| 0.91             | 1823.8           | 1830.7 | 1837.5            | 0.289             | 0.060            | 0.040            | 0.023            | 0.033            |
| 0.91             | 1837.5           | 1844.3 | 1851.1            | 0.319             | 0.058            | 0.052            | 0.026            | 0.046            |
| 0.91             | 1851.1           | 1857.9 | 1864.6            | 0.232             | 0.056            | 0.066            | 0.019            | 0.063            |

Table 4. $\gamma p \rightarrow K^+ A$ differential cross section data ($d\sigma/d\Omega$) for $0 < \cos \theta_{CM}^K < 0.92$. The notation is the same as in table 3.
| $\cos \theta_{CM}^K$ | $W_{\text{min}}$ | $W$ | $W_{\text{max}}$ | $d\sigma/d\Omega$ | $\delta_{\text{stat}}$ | $\delta_{\text{sys}}$ | $\delta_{\text{scaling}}$ | $\delta_{\text{fitting}}$ |
|---------------------|------------------|-----|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.93                | 1612.6           | 1624.1 | 1635.6          | 0.052           | 0.015           | 0.004           | 0.004           | 0.000           |
| 0.93                | 1635.6           | 1647.0 | 1658.3          | 0.131           | 0.024           | 0.010           | 0.010           | 0.000           |
| 0.93                | 1658.3           | 1669.4 | 1680.5          | 0.205           | 0.029           | 0.016           | 0.016           | 0.000           |
| 0.93                | 1680.5           | 1688.0 | 1695.4          | 0.316           | 0.048           | 0.025           | 0.025           | 0.000           |
| 0.93                | 1695.4           | 1702.8 | 1710.1          | 0.407           | 0.048           | 0.033           | 0.033           | 0.000           |
| 0.93                | 1710.1           | 1717.4 | 1724.7          | 0.352           | 0.045           | 0.028           | 0.028           | 0.000           |
| 0.93                | 1724.7           | 1732.0 | 1739.2          | 0.450           | 0.053           | 0.036           | 0.036           | 0.000           |
| 0.93                | 1739.2           | 1746.4 | 1753.6          | 0.330           | 0.043           | 0.026           | 0.026           | 0.000           |
| 0.93                | 1753.6           | 1760.8 | 1767.9          | 0.399           | 0.049           | 0.033           | 0.033           | 0.008           |
| 0.93                | 1767.9           | 1775.0 | 1782.0          | 0.340           | 0.045           | 0.029           | 0.029           | 0.010           |
| 0.93                | 1782.0           | 1789.0 | 1796.1          | 0.316           | 0.043           | 0.029           | 0.029           | 0.014           |
| 0.93                | 1796.1           | 1803.0 | 1810.0          | 0.287           | 0.041           | 0.029           | 0.029           | 0.017           |
| 0.93                | 1810.0           | 1816.9 | 1823.8          | 0.248           | 0.039           | 0.031           | 0.031           | 0.020           |
| 0.93                | 1823.8           | 1830.7 | 1837.5          | 0.302           | 0.042           | 0.041           | 0.041           | 0.024           |
| 0.93                | 1837.5           | 1844.3 | 1851.1          | 0.392           | 0.049           | 0.045           | 0.045           | 0.031           |
| 0.93                | 1851.1           | 1857.9 | 1864.6          | 0.338           | 0.043           | 0.069           | 0.069           | 0.027           |

Table 5. $\gamma p \rightarrow K^+ \Lambda$ differential cross section data ($d\sigma/d\Omega$) for $0.92 < \cos \theta_{CM}^K < 0.94$. The notation is the same as in table 5.

| $\cos \theta_{CM}^K$ | $W_{\text{min}}$ | $W$ | $W_{\text{max}}$ | $d\sigma/d\Omega$ | $\delta_{\text{stat}}$ | $\delta_{\text{sys}}$ | $\delta_{\text{scaling}}$ | $\delta_{\text{fitting}}$ |
|---------------------|------------------|-----|------------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0.95                | 1612.6           | 1624.1 | 1635.6          | 0.054           | 0.016           | 0.004           | 0.004           | 0.000           |
| 0.95                | 1635.6           | 1647.0 | 1658.3          | 0.113           | 0.019           | 0.009           | 0.009           | 0.000           |
| 0.95                | 1658.3           | 1669.4 | 1680.5          | 0.231           | 0.026           | 0.018           | 0.018           | 0.000           |
| 0.95                | 1680.5           | 1688.0 | 1695.4          | 0.352           | 0.041           | 0.028           | 0.028           | 0.000           |
| 0.95                | 1695.4           | 1702.8 | 1710.1          | 0.397           | 0.037           | 0.032           | 0.032           | 0.000           |
| 0.95                | 1710.1           | 1717.4 | 1724.7          | 0.466           | 0.045           | 0.037           | 0.037           | 0.000           |
| 0.95                | 1724.7           | 1732.0 | 1739.2          | 0.381           | 0.039           | 0.030           | 0.030           | 0.000           |
| 0.95                | 1739.2           | 1746.4 | 1753.6          | 0.441           | 0.043           | 0.035           | 0.035           | 0.000           |
| 0.95                | 1753.6           | 1760.8 | 1767.9          | 0.385           | 0.040           | 0.032           | 0.031           | 0.008           |
| 0.95                | 1767.9           | 1775.0 | 1782.0          | 0.298           | 0.049           | 0.026           | 0.026           | 0.010           |
| 0.95                | 1782.0           | 1789.0 | 1796.1          | 0.386           | 0.041           | 0.034           | 0.034           | 0.014           |
| 0.95                | 1796.1           | 1803.0 | 1810.0          | 0.397           | 0.050           | 0.036           | 0.036           | 0.017           |
| 0.95                | 1810.0           | 1816.9 | 1823.8          | 0.377           | 0.039           | 0.039           | 0.039           | 0.024           |
| 0.95                | 1823.8           | 1830.7 | 1837.5          | 0.333           | 0.035           | 0.042           | 0.042           | 0.027           |
| 0.95                | 1837.5           | 1844.3 | 1851.1          | 0.371           | 0.058           | 0.054           | 0.054           | 0.030           |
| 0.95                | 1851.1           | 1857.9 | 1864.6          | 0.316           | 0.041           | 0.068           | 0.068           | 0.025           |

Table 6. $\gamma p \rightarrow K^+ \Lambda$ differential cross section data ($d\sigma/d\Omega$) for $0.94 < \cos \theta_{CM}^K < 0.96$. The notation is the same as in table 5.
| $\theta_{CM}^K$ | $W_{min}$ | $W$ | $W_{max}$ | $d\sigma/d\Omega$ | $\delta_{stat}$ | $\delta_{sys}$ | $\delta_{scaling}$ | $\delta_{fitting}$ |
|------|------|------|------|--------------|-------------|-------------|----------------|----------------|
| 0.97 | 1612.6 | 1624.1 | 1635.6 | 0.059 | 0.017 | 0.005 | 0.005 | 0.000 |
| 0.97 | 1635.6 | 1647.0 | 1658.3 | 0.091 | 0.016 | 0.007 | 0.007 | 0.000 |
| 0.97 | 1658.3 | 1669.4 | 1680.5 | 0.269 | 0.026 | 0.022 | 0.022 | 0.000 |
| 0.97 | 1680.5 | 1688.0 | 1695.4 | 0.296 | 0.034 | 0.024 | 0.024 | 0.000 |
| 0.97 | 1695.4 | 1702.8 | 1710.1 | 0.374 | 0.037 | 0.030 | 0.030 | 0.000 |
| 0.97 | 1710.1 | 1717.4 | 1724.7 | 0.374 | 0.036 | 0.030 | 0.030 | 0.000 |
| 0.97 | 1724.7 | 1732.0 | 1739.2 | 0.441 | 0.039 | 0.035 | 0.035 | 0.000 |
| 0.97 | 1739.2 | 1746.4 | 1753.6 | 0.433 | 0.038 | 0.035 | 0.035 | 0.000 |
| 0.97 | 1753.6 | 1760.8 | 1767.9 | 0.321 | 0.034 | 0.027 | 0.026 | 0.008 |
| 0.97 | 1767.9 | 1775.0 | 1782.0 | 0.360 | 0.034 | 0.030 | 0.029 | 0.010 |
| 0.97 | 1782.0 | 1789.0 | 1796.1 | 0.372 | 0.034 | 0.033 | 0.030 | 0.014 |
| 0.97 | 1796.1 | 1803.0 | 1810.0 | 0.309 | 0.033 | 0.030 | 0.025 | 0.017 |
| 0.97 | 1810.0 | 1816.9 | 1823.8 | 0.446 | 0.039 | 0.043 | 0.036 | 0.024 |
| 0.97 | 1823.8 | 1830.7 | 1837.5 | 0.394 | 0.035 | 0.045 | 0.032 | 0.033 |
| 0.97 | 1837.5 | 1844.3 | 1851.1 | 0.426 | 0.051 | 0.057 | 0.034 | 0.046 |
| 0.97 | 1851.1 | 1857.9 | 1864.6 | 0.488 | 0.040 | 0.075 | 0.039 | 0.063 |

Table 7. $\gamma p \to K^+\Lambda$ differential cross section data ($d\sigma/d\Omega$) for $0.96 < \cos \theta_{CM}^K < 0.98$. The notation is the same as in table 6.

| $\theta_{CM}^K$ | $W_{min}$ | $W$ | $W_{max}$ | $d\sigma/d\Omega$ | $\delta_{stat}$ | $\delta_{sys}$ | $\delta_{scaling}$ | $\delta_{fitting}$ |
|------|------|------|------|--------------|-------------|-------------|----------------|----------------|
| 0.99 | 1612.6 | 1624.1 | 1635.6 | 0.049 | 0.016 | 0.004 | 0.004 | 0.000 |
| 0.99 | 1635.6 | 1647.0 | 1658.3 | 0.141 | 0.022 | 0.011 | 0.011 | 0.000 |
| 0.99 | 1658.3 | 1669.4 | 1680.5 | 0.214 | 0.025 | 0.017 | 0.017 | 0.000 |
| 0.99 | 1680.5 | 1688.0 | 1695.4 | 0.397 | 0.044 | 0.032 | 0.032 | 0.000 |
| 0.99 | 1695.4 | 1702.8 | 1710.1 | 0.418 | 0.039 | 0.033 | 0.033 | 0.000 |
| 0.99 | 1710.1 | 1717.4 | 1724.7 | 0.455 | 0.045 | 0.036 | 0.036 | 0.000 |
| 0.99 | 1724.7 | 1732.0 | 1739.2 | 0.447 | 0.040 | 0.036 | 0.036 | 0.000 |
| 0.99 | 1739.2 | 1746.4 | 1753.6 | 0.412 | 0.039 | 0.033 | 0.033 | 0.000 |
| 0.99 | 1753.6 | 1760.8 | 1767.9 | 0.377 | 0.041 | 0.031 | 0.030 | 0.008 |
| 0.99 | 1767.9 | 1775.0 | 1782.0 | 0.390 | 0.042 | 0.033 | 0.031 | 0.010 |
| 0.99 | 1782.0 | 1789.0 | 1796.1 | 0.370 | 0.036 | 0.033 | 0.030 | 0.014 |
| 0.99 | 1796.1 | 1803.0 | 1810.0 | 0.338 | 0.036 | 0.032 | 0.027 | 0.017 |
| 0.99 | 1810.0 | 1816.9 | 1823.8 | 0.409 | 0.040 | 0.041 | 0.033 | 0.024 |
| 0.99 | 1823.8 | 1830.7 | 1837.5 | 0.457 | 0.053 | 0.049 | 0.037 | 0.033 |
| 0.99 | 1837.5 | 1844.3 | 1851.1 | 0.420 | 0.051 | 0.057 | 0.034 | 0.046 |
| 0.99 | 1851.1 | 1857.9 | 1864.6 | 0.464 | 0.041 | 0.074 | 0.037 | 0.063 |

Table 8. $\gamma p \to K^+\Lambda$ differential cross section data ($d\sigma/d\Omega$) for $0.98 < \cos \theta_{CM}^K < 1.00$. The notation is the same as in table 6.
| $\cos \theta_{CM}^K$ | $W_{\min}$ [MeV] | $W$ [MeV] | $W_{\max}$ [MeV] | $P_\Lambda$ | $\delta_{\text{stat}}$ | $\delta_{\text{sys}}$ |
|---------------------|-----------------|----------|-----------------|------------|----------------|----------------|
| 0.95                | 1612.6          | 1624.1   | 1635.6          | 0.131      | 0.488          | 0.004          |
| 0.95                | 1635.6          | 1647.0   | 1658.3          | -0.086     | 0.176          | 0.003          |
| 0.95                | 1658.3          | 1669.4   | 1680.5          | -0.499     | 0.191          | 0.015          |
| 0.95                | 1680.5          | 1688.0   | 1695.4          | 0.034      | 0.155          | 0.001          |
| 0.95                | 1710.1          | 1717.4   | 1724.7          | -0.299     | 0.161          | 0.009          |
| 0.95                | 1724.7          | 1732.0   | 1739.2          | -0.249     | 0.152          | 0.007          |
| 0.95                | 1739.2          | 1746.4   | 1753.6          | -0.143     | 0.156          | 0.004          |
| 0.95                | 1753.6          | 1760.8   | 1767.9          | -0.255     | 0.191          | 0.008          |
| 0.95                | 1767.9          | 1775.0   | 1782.0          | -0.089     | 0.158          | 0.003          |
| 0.95                | 1782.0          | 1789.0   | 1796.1          | -0.355     | 0.156          | 0.011          |
| 0.95                | 1796.1          | 1803.0   | 1810.0          | -0.004     | 0.210          | 0.000          |
| 0.95                | 1810.0          | 1816.9   | 1823.8          | -0.672     | 0.160          | 0.020          |
| 0.95                | 1823.8          | 1830.7   | 1837.5          | -0.437     | 0.155          | 0.013          |
| 0.95                | 1837.5          | 1844.3   | 1851.1          | 0.076      | 0.178          | 0.002          |
| 0.95                | 1851.1          | 1857.9   | 1864.6          | -0.162     | 0.145          | 0.005          |
| 0.95                | 1864.6          | 1871.4   | 1878.1          | -0.157     | 0.153          | 0.005          |

**Table 9.** $\gamma p \rightarrow K^+ \Lambda$ recoil polarisation ($P_\Lambda$) for $0.90 < \cos \theta_{CM}^K < 1.00$. The other notation is the same as in table 5 with the exception that only the total systematic error is given.