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Photoproduction of ω-Mesons at ELSA and the role of azimuthal asymmetries*

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Abstract Measurements of ω photoproduction of the Crystal-Barrel/TAPS experiment at the ELSA accelerator of Bonn University are presented which used linearly polarized tagged photon beam from threshold to $E_\gamma = 1700\,\mathrm{MeV}$. The azimuthal asymmetries Σ and Σ_π indicate s-channel resonance contributions on top of the established t-channel exchange processes. These findings are further enhanced by a very first measurement of the G-asymmetry which, in addition to the polarized photon beam, also requires a longitudinally polarized proton target. An intuitive interpretation of the specific sensitivity of the azimuthal asymmetries to the reaction mechanisms involved is given.

Key words baryon resonances, photoproduction, vector mesons, polarization

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1 Introduction

The spectrum of excited hadrons is manifestly determined by the non-perturbative sector of QCD. Lattice QCD provides a promising method to understand this regime from first principles and enormous improvements have been achieved over the last decade. Recently, a much regarded calculation using smeared link fermion action and a lattice size of $\simeq 3\,m_\pi^{-1}$ with pion mass down to $m_\pi = 190\,\mathrm{MeV}$ reproduced well the lowest lying baryon and meson masses[1]. However, columns of excited baryon states build on top of the ground states and it is unclear how LQCD will be able to address those. For the time being this remains the domain of models, which often attempt to incorporate basic symmetries and features of QCD, e.g. chiral symmetry and confinement. Representative for a prominent class of such models, namely constituent quark models, Fig. 1 shows the result of the Bonn Model[2] for excited N* of either parity. In Fig. 1 the masses of the states found in the model are represented as lines, grouped according to total spin and parity. The boxes indicate position and width of resonances according to the PDG. There are two obvious discrepancies between model and experiment: (1) The lowest(!) lying excitations of either parity, the $P_{11}(1440)$ (Roper) and the $S_{11}(1535)$ resonances are not well reproduced. It is characteristic for potential models that in particular the parity ordering of these states is wrong[3]. (2) Much more high-lying states are predicted than experimentally observed. This may be a model deficiency. But to exclude an experimental artifact it is important to investigate meson production channels which are complementary to single-meson nucleon final states. It is suspected that some of the higher lying "missing" states may predominantly couple to multiple pseudoscalar mesons or to vector mesons[4]. The photoproduction of ω mesons off the proton is well suited to investigate this issue. Ideally, the ω threshold is in the higher lying third resonance region of the nucleon as indicated in Fig. 1. Since the ω is isoscalar ($I = 0$), a s-channel process will only connect N* ($I = 1/2$) states with the nucleon ground state, but no Δ* with $I = 3/2$. This provides a great simplification to the complexity of the contributing excitation spectrum.

However, as other vector-meson channels, ω-photoproduction is dominated by t-channel processes. It is not sufficiently well understood to which extent s-channel nucleon resonances do contribute at all and it is a goal of the present experiments to investigate this.

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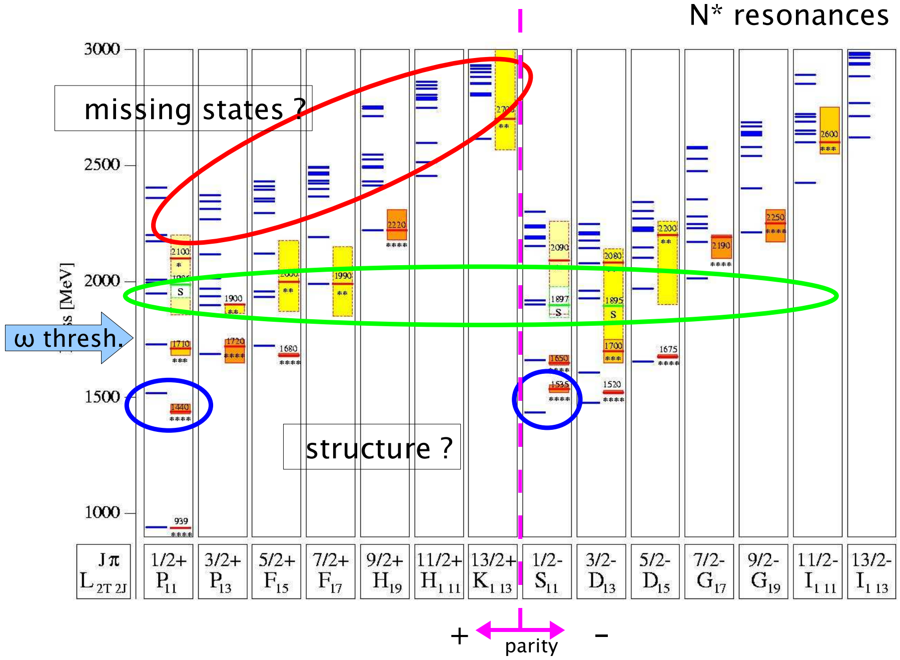

Fig. 1. The spectrum of positive (left part) and negative parity (right part) nucleon states as obtained in the Bonn Model[2].

2 Mechanism and cross section of ω photoproduction

At high energies, the cross section of vector meson production off nucleons falls off exponentially with the squared recoil momentum, t. The slope corresponds to the range of the strong interaction within the vector meson and baryon system in a t-channel process. A universal t-dependence of the cross section is characteristic for "diffractive" production. It is associated with the exchange of natural parity quantum numbers (Fig. 2 left) related to the Pomeron, a composite gluonic or hadronic structure. At large $|t|$ deviations from pure diffraction show up[5]. Significant unnatural parity π^0 exchange (Fig. 2 middle) has been found at smaller energies[6] which is dominating close to threshold[7]. However, neither Pomeron nor π^0 exchange are able to reproduce the strong threshold energy dependence of the cross section and the ω decay angular distribution observed in exclusive photoproduction[8] and electroproduction[9]. This may hint for s-channel contributions (Fig. 2 right). Further experimental support for such a view is provided by first measurements of the photon beam asymmetry, Σ, through the GRAAL collaboration[10]. Recent coupled-channel analyses yielded however inconclusive results[11, 12].

Using linearly polarized photon beams we investigated the reaction $\gamma\,\mathrm{p} \rightarrow \mathrm{p}\,\omega$ in more detail by extending the energy range of the previous beam asymmetry measurements and by measuring for the first time the pion asymmetry Σ_π. The latter asymmetry is related to the $\omega \rightarrow \pi^0\gamma$ decay which was theoretically studied in Ref. [13]. This neutral decay mode is very well suited for the Crystal-Barrel/TAPS experimental setup.

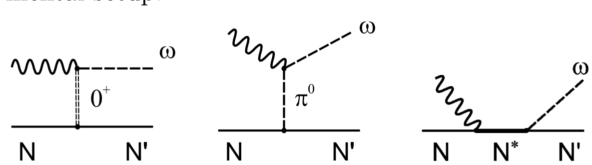

Fig. 2. Contributions to ω photoproduction: natural parity t-channel exchange (left), π^0 t-channel exchange (middle), s-channel intermediate resonance excitation (right).

Often in vector-meson photoproduction the cross section is written in terms of density matrix elements[14]. Equivalently, a notation very similar to the one used in pseudoscalar meson photoproduction can also be used, for the situation of the presented experiment:

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{\mathrm{d}\sigma_0}{\mathrm{d}\Omega}\,(1 - P_\gamma\,\Sigma_{(\pi)}\,\cos 2\Phi_{(\pi)})\,. \qquad (1)$$

The polarization independent cross section is denoted σ_0, the degree of linear polarization of the incident photon beam P_γ, and Φ is the azimuthal orientation of the reaction plane with respect to the plane of linear polarization. The kinematics of ω-photoproduction and the planes involved are depicted in Fig. 3. In ω-photoproduction three beam asymmetries can be naturally extracted, (1) the beam asymmetry of the ω meson calculated in the c.m.s. of the reaction, Σ (omega asymmetry), (2) the beam asymmetry of the final pion in the c.m.s. of the reaction, Σ_π (pion asymmetry), and (3) the beam asymmetry of the final pion in the rest frame of the ω, Σ_π^ω (pion-in-omega-rest-frame asymmetry) [15, 16]. Experimentally, the pion asymmetry is obtained if in Eq. (1) the azimuthal angle of the ω meson, Φ, is replaced by the angle Φ_π of the decay-π^0. This convention gives Σ_π a sign equivalent to Σ, but opposite to the (charged) decay asymmetry as defined in e.g.[14].

Σ_π provides new information on the mechanism of ω photoproduction. It is measured relative to the photon polarization plane and related to the usual decay asymmetry (in the vector-meson rest frame) by a corresponding Lorentz boost[15].

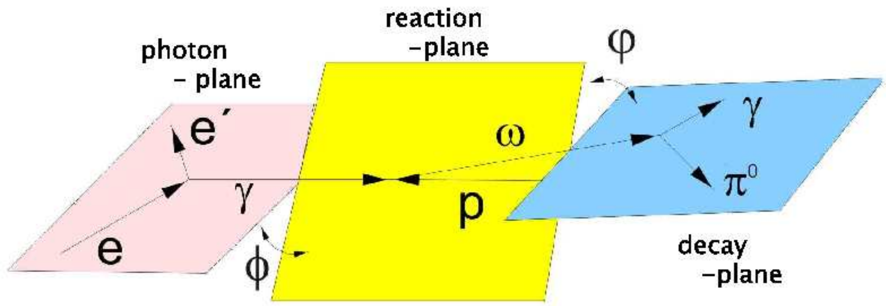

Fig. 3. The kinematics of ω-photoproduction. There are three different planes involved: (1) The plane of linear polarization of the photon beam (in electron scattering this corresponds, as indicated, to the electron scattering plane), (2) the reaction plane which is spanned by the recoil nucleon and the ω meson, and (3) the decay plane of the omega which in the present experiment is determined by decay-photon and π^0.

2.1 Role of beam-related asymmetries

The beam asymmetries are very sensitive to the mechanism of ω-photoproduction. This was theoretically investigated in the framework of the quark model by Zhao[17], and Titov and Lee[18]. More double polarization observables were recently studied in the framework of the Bonn-Gatchina PWA[15]. In combination, the beam asymmetry Σ and the pion asymmetry Σ_π can specifically distinguish s-channel from t-channel processes. The beam asymmetry is expected $\Sigma \simeq 0$ without s-channel resonance contributions, but clearly non-zero otherwise[18]. In contrast, $\Sigma_\pi \simeq -0.5$ is expected for a pure π^0 exchange mechanism, +0.5 for pure Pomeron exchange, while $\Sigma_\pi \simeq 0$ with s-channel resonances[15]. As discussed in the following, this result can be intuitively understood.

In general, the origin of azimuthal asymmetries is spin-orbit interaction, i.e. a correlation between spin and angular-momentum. For the case of the photon beam asymmetry in the simplest reaction, i.e. single pion photoproduction, this is illustrated in Fig. 4. Due to the strentgh of the correlation, spin and angular momentum of the final state meson and nucleon are preferentially aligned (or antialigned, in which case the remaining argumentation is the same). This situation is azimuthally symmetric, as is indicated in the left part of the figure. However, a linear polarization of the photon field in the x-z plane (i.e. corresponding B-field in y-direction) introduces a spin flip within the polarization plane (Fig. 4 middle). This leads to a cos 2Φ modulation of the cross section as is indicated in the right part of the figure. The origin of the asymmetry is the spin-orbit interaction involved. This is equivalent to the mechanism of the Boer-Mulders asymmetry in semi-inclusive deep inelastic scattering as discussed, e.g., in Ref. [19]. However, the degrees of freedom involved are different.

In the case of vector-meson photoproduction it is essential which hadron is subjected to the linearly polarized photon field, cf. Fig. 5: If it is the nucleon (ground or excited state) as in Fig. 4, then the beam asymmetry Σ will be non-zero. This is the case for a s-channel process. If, in contrast, it is the vector meson which couples to the photon field, then there will be no spin flip expected for the nucleon. The azimuthal distribution of the recoil nucleons remains unaffected and, consequently, $\Sigma \simeq 0$. This is to be expected for pure t-channel processes as is illustrated in Fig. 5.

The situation is reversed for the pion asymmetry in ω photoproduction. If the photon directly couples to the vector meson, then its spin will be subject to the precession in the polarization plane which, in turn, reflects in the decay distribution. Hence, an azimuthal asymmetry between the decay-π^0 and the photon polarization plane is introduced: $\Sigma_\pi \neq 0$. In a s-channel process the spin of the ω and hence the decay angular distribution remains unaffected, and hence $\Sigma_\pi \simeq 0$.

The beam-related asymmetries are inherent features of vector-meson photoproduction which do not require a polarized target. However, with target there are more asymmetries accessible. The combination of linear beam polarization and longitudinally polarized target yields G-type asymmetries, E-type asymmetries are occuring with circularly polarized beam and longitudinally polarized target[15], cf. also Ref. [20].

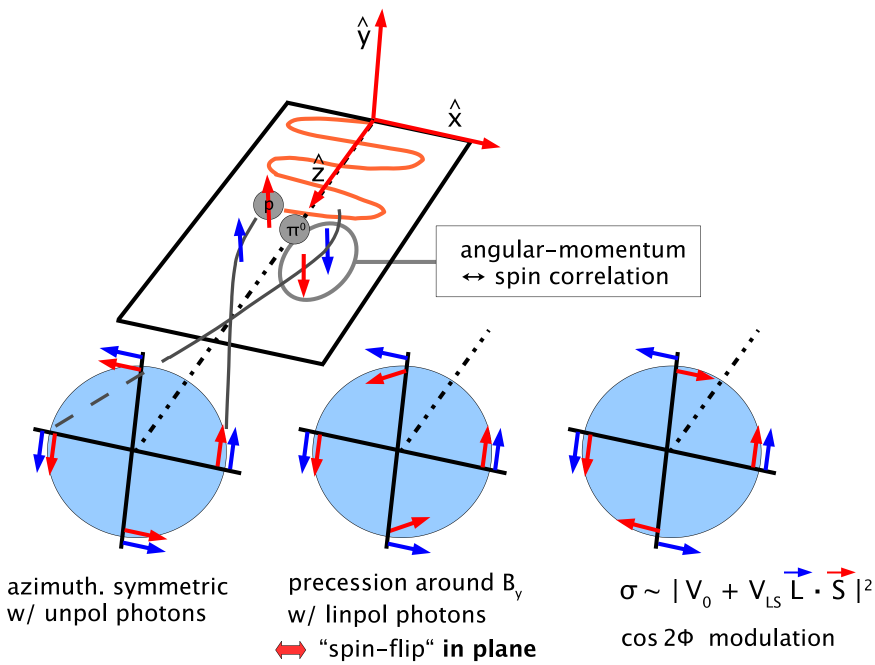

Fig. 4. Intuitive explanation for the photon beam asymmetry, Σ. The relative orientations of angular momentum in the nucleon-meson system and of nucleon spin (here for the case of pseudoscalar meson production) are represented by the arrows (left). Linear photon polarization in the depicted plane introduces nucleon spin flips within that plane (middle) which leads to a cos 2ϕ azimuthal asymmetry (right, see also text).

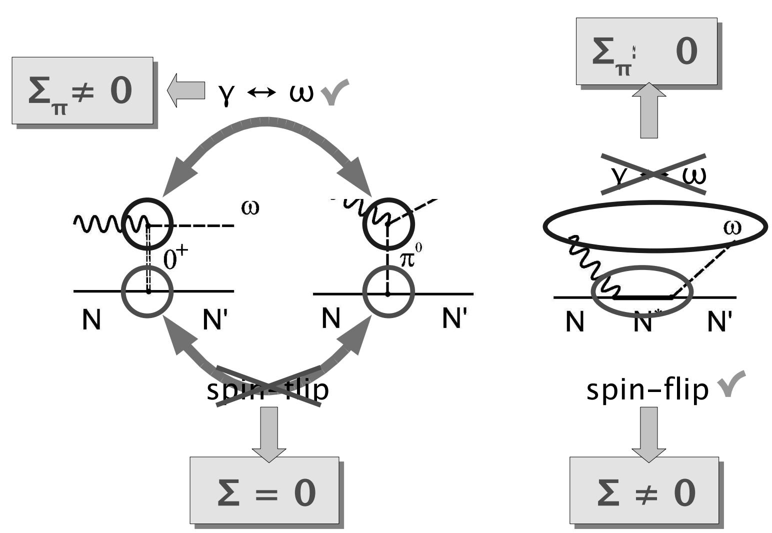

Fig. 5. The different impact of the spin-flip mechanism for the Σ and Σ_π asymmetries in ω-photoproduction (see also text).

3 Experiment and results

The experiment was performed at the tagged photon beam of the ELSA electron accelerator of the University of Bonn. Using electron beams of $E_0 = 3.2$ GeV coherent bremsstrahlung was produced from a 500 μm thick diamond crystal[21]. The plane of linear polarization was oriented in the vertical direction. The photon beam impinged on a 5.3 cm long liquid hydrogen target. A three layer scintillating fiber detector surrounded the target within the polar angular range from 15 to 165 degrees. It determined a point-coordinate for charged particles. Both, charged particles and photons were detected in the Crystal Barrel detector.

It was cylindrically arranged around the target with 1290 individual CsI(Tl) crystals of 16 radiation lengths in 23 rings, covering a polar angular range of 30° — 168°. The 5.8° — 30° forward cone was covered by the TAPS detector, set up in one hexagonally shaped wall of 528 BaF_2 modules at a distance of 118.7 cm from the target. The position of photon incidence could be resolved within 20 mm. To discriminate charged from neutral particles each TAPS module has a 5 mm plastic scintillator in front of it. More details on the double-polarization setup can be found in Refs. [20, 22].

The data analysis is described in some detail in Ref. [23]. Fig. 6 (top) shows the measured $\pi^0\gamma$ invariant mass distribution. In addition, results of Monte-Carlo simulations are presented. Here the distribution is decomposed into the ω signal and background. The major background originated from $2\pi^0$ production where one of the 4 decay photons remained undetected, mainly because it fell below the detection thresholds. Other backgrounds were described by a polynomial. A cut on the ω signal region yields azimuthal distributions an example of which is shown in Fig. 6 (bottom).

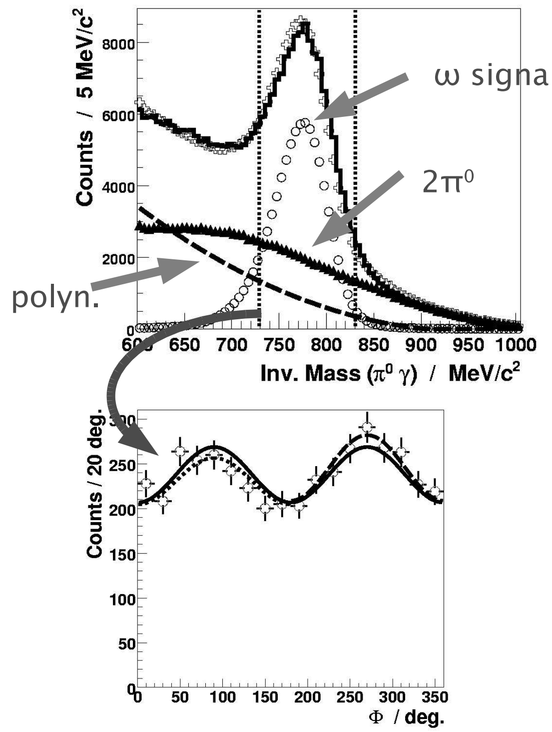

Fig. 6. $\pi^0\gamma$ invariant mass distribution ($E_\gamma =$ 1108 — 1700 MeV) and the simulated decompostion into ω signal and background (top). The latter is split into two parts which are distinguished by their origin from $2\pi^0$ photoproduction or from other sources (see text). In the bottom part is shown the azimuthal modulation within the signal area (indicated by the vertical lines) before background subtraction.

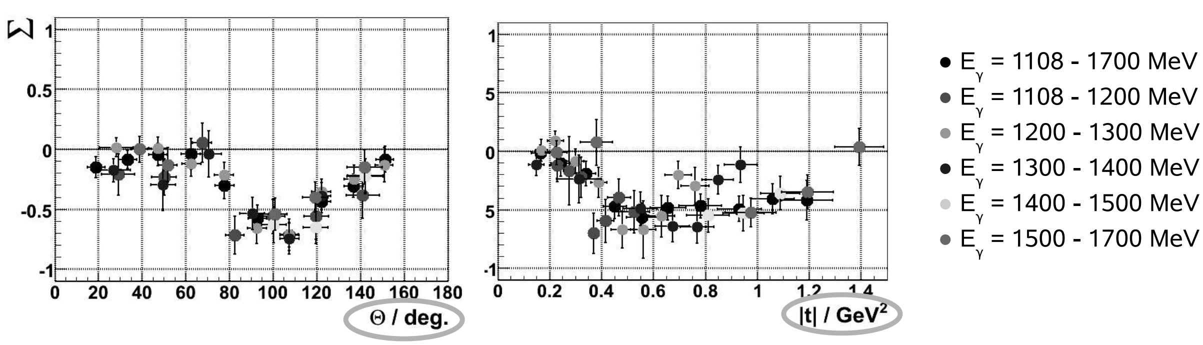

Fig. 7. Measured angular dependence of the photon beam asymmetry Σ for 5 different energy bins and for the total energy range.

After background subtraction and correction for the non-zero $2\pi^0$ asymmetries (cf. Ref. [23]) the photon beam asymmetries of Fig. 7 are obtained. They are clearly non-zero, which can be taken indicative for s-channel processes. This is further fostered through the pion asymmetries shown in Fig. 8, which are close to zero and stay off the indicated expectations for pure t-channel processes. Note that the most forward angular region, where t-channel processes are known to be dominating, is excluded in the figure. It is suppressed already on trigger level. The results of Figs. 7 and 8 are bin-wise compared to the Bonn-Gatchina PWA in Fig. 9. Both Σ and Σ_π agree well with the PWA if s-channel resonances are included. Based on the hitherto measured observables it is however premature to perform a detailed resonance analysis through the PWA. The agreement shown in Fig. 9 is obtained with a main contribution of the well known $P_{13}(1720)$ state. The error bars in the figures are purely statistical. The mean systematic error for beam and pion asymmetries is estimated to $\delta_{\rm sys}\Sigma = 0.08$ and $\delta_{\rm sys}\Sigma_\pi = 0.07$[23].

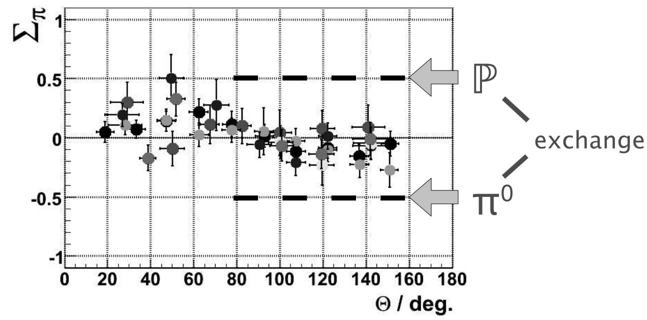

Fig. 8. Measured angular dependence of the pion asymmetry Σ_π for 5 different energy bins and for the total energy range. The expectations for pure pomeron exchange and for pure π^0 exchange are indicated. The symbols have the same meaning as in Fig. 7.

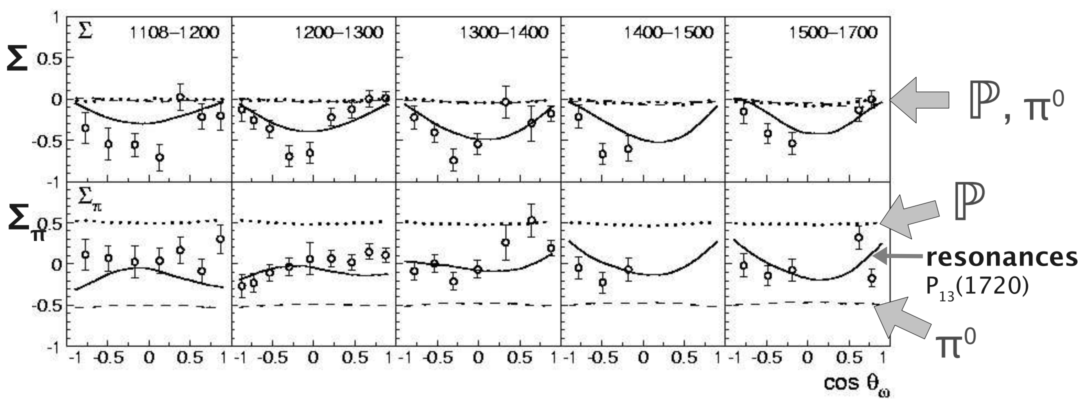

Fig. 9. Measured asymmetries in comparison to PWA results.

3.1 First double polarization results

The setup described above was extended through the Bonn Frozen Spin polarized Target (BoFroST)[24] and some detector upgrades as decribed in more detail in the contributions of U. Thoma[22] and R. Beck[20], who also present first double polarization results in pseudoscalar meson photoproduction. Here I concentrate on the ω photoproduction channel and the very first, preliminary results obtained with linearly polarized photon beams in combination with longitudinally polarized proton target. This makes G-type observables accessible (cf. Ref. [20]). In complete analogy to the target-spin independent beam asymmetries Σ and Σ_π it is possible to extract the two asymmetries G and G_π[15]. The former is related to the azimuthal asymmetry of the ω, the latter to the asymmetry of the decay π^0, again in the $\pi^0\gamma$ decay channel. The observables and their sensitivities to the reaction mechanism are discussed in more detail in Ref. [15]. The very preliminary first measurement of the G-asymmetry[25] shown in Fig. 10 seems to indicate that G is non-zero. This is expected, if we have not a pure t-channel π^0 exchange mechanism close to threshold. Albeit a complete experiment with regard to the decomposition of the reaction amplitudes, which would require more than 23 independent observables to be measured, seems presently out of range, the different double polarization observables will still help to identify at least the leading s-channel contributions in ω-photoproduction.

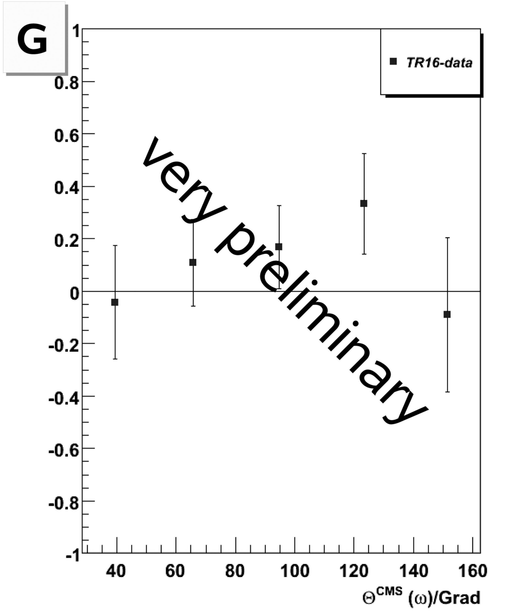

Fig. 10. Very preliminary first result for the G-asymmetry measured in ω-photoproduction with lineraly polarized beam and longitudinally polarized target. The errors are purely statistical. The data sample includes only a fraction of the total data set.

4 Summary and outlook

In summary, measurements of ω photoproduction of the Crystal-Barrel/TAPS experiment at the ELSA accelerator of Bonn University have been presented which used linearly polarized tagged photon beam from threshold to $E_\gamma = 1700\,\mathrm{MeV}$. The azimuthal asymmetries Σ and Σ_π indicate s-channel resonance contributions on top of the established t-channel exchange processes. These findings are further enhanced by a very first measurement of the G-asymmetry which, in addition to the polarized photon beam, also requires a longitudinally polarized proton target. G, G_π and further double polarization observables are indispensible to achieve a decompostion of, at least, the leading s-channel contributions. This will be essential to get a hand on "missing" resonances which may decouple from the pion-nucleon channel but contribute to ω photoproduction.

The present Crystal-Barrel/TAPS setup is ideally suited for multi-photon final states such as the p 3γ one associated with the $\omega \to \pi^0\,\gamma$ decay. The one order of magnitude more abundant decay of the ω-meson into $\pi^+\ \pi^-\ \pi^0$ remains practically unobservable due to the lack of charged pion identification. This will drastically improve with the new BGO-OpenDipole detector setup which is presently in preparation and shall be commissioned in 2010. It consists of a large acceptance magnetic dipole spectrometer for high resolution detection of charged particles in forward direction which is complemented by the BGO Ball of the former GRAAL experiment in the central angular region. This setup will be capable of detecting multiple meson final states, charged, neutral and mixed, including charged and neutral kaons, and hence significantly extend the present capabilities also with regard to the photoproduction of vector mesons, e.g. in final states involving vector meson and pseudoscalar meson(s) simultaneously[26, 27].

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