Role of the $N^*(2080)$ resonance in the $\vec{\gamma} p \to K^+ \Lambda(1520)$ reaction

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Outline

1. Introduction

2. Our approach

   Effective Lagrangian method.

   We will take into account the $t-$channel K exchange, the contribution of N and $N^*(2080)$ in the $s-$channel, and a contact term.

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4. Conclusions

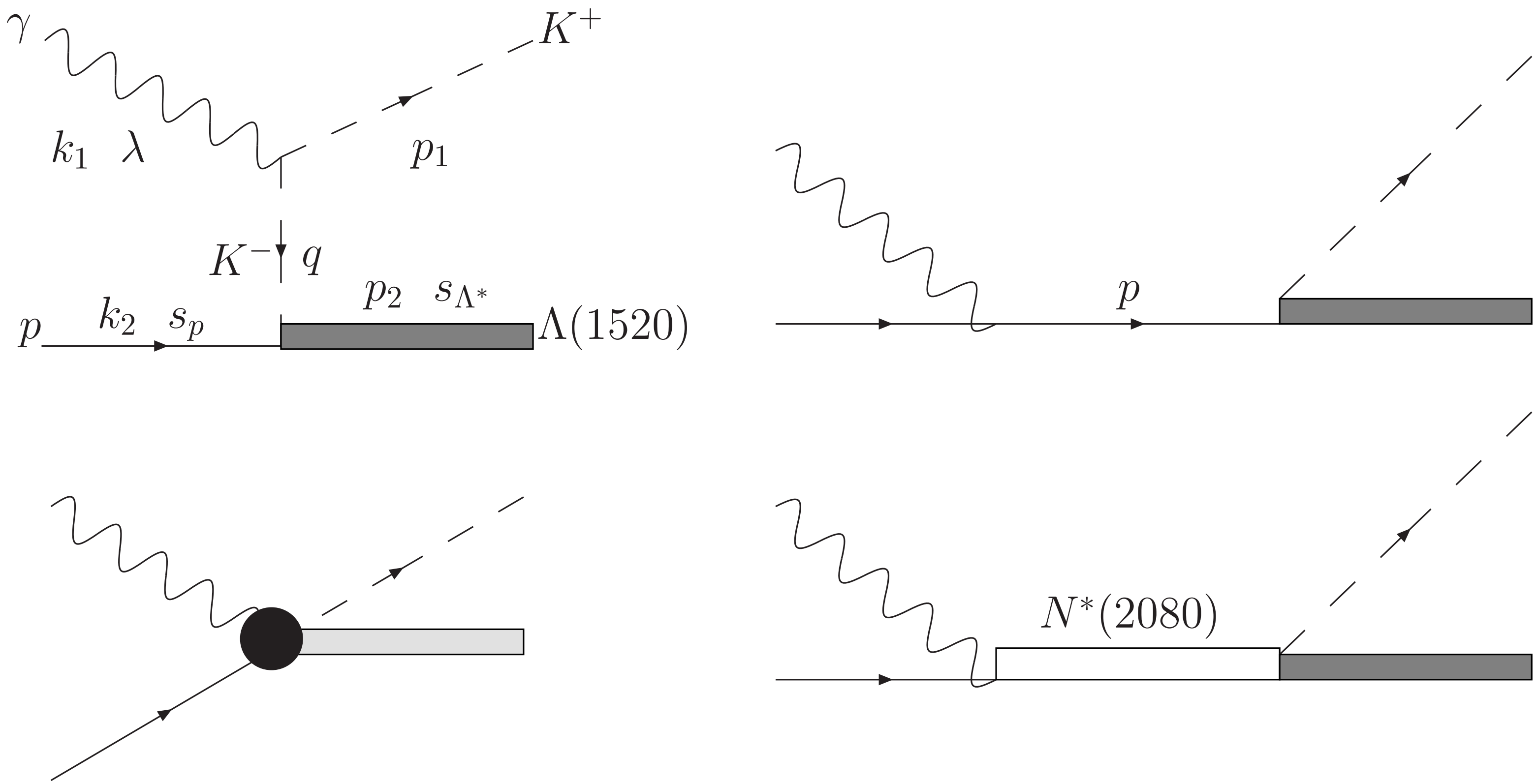
Introduction

1. The $\Lambda(1520)$ ($\equiv \Lambda^*$) photoproduction in the $\gamma p \rightarrow K^+\Lambda^*$ reaction is an interesting tool to gain a deeper understanding of the interaction among strange hadrons and also on the nature of baryon resonances.
2. This reaction has been examined at photon energies below 2.4 GeV in the Spring-8 LEPS experiment. For an invariant γp mass around 2.11 GeV, a bump structure in the differential cross section at forward K^+ angels was reported, which might hint to a sizable contribution from nucleon resonances in the $s-$channel. (**N. Muramatsu et al. (LEPS Collaboration), Phys. Rev. Lett. 103, 012001 (2009); H. Kohri et al. (LEPS Collaboration), Phys. Rev. Lett. 104, 172001 (2010).**)
3. Several phenomenological models, that used an effective hadron Lagrangian approach, can reproduce the high energy data reasonable well, but they fail to describe the bump structure in the new LEPS data.

Why $N^*(2080)$

1. The information about nucleon resonances in the relevant mass region (~ 2.1) GeV is scarce.
   1), $N^*(2080)$, $J^P = 3/2^-$, status: **;
   2), $N^*(2090)$, $J^P = 1/2^-$, status: *;
   3), $N^*(2100)$, $J^P = 1/2^+$, status: *.
2. We rely on theoretical predictions based in a quark model (QM) for baryons. The two-star $D-$wave $J^P = 3/2^-$ $N^*(2080)$ ($\equiv N^*$) is predicted to have visible contributions to the $\gamma p \to K^+\Lambda^*$ reaction. (**S. Capstick, Phys. Rev. D 46, 2864 (1992); S. Capstick, and W. Roberts, Phys. Rev. D 58, 074011 (1998).**)
3. The evidence of its existence is poor or only fair. Its total decay width and branching ratios are not experimentally known, either. Thus, the LEPS measurements could be used to determine some of the properties of this resonance.

Our Model



We consider the K exchange in the $t-$channel, the contribution of N and $N^*(2080)$ in the $s-$channel, and a contact term.

Interaction Lagrangian Densities

$$
\begin{aligned}
\mathcal{L}_{\gamma KK} &= -ie(K^-\partial^\mu K^+ - K^+\partial^\mu K^-)A_\mu, & (1)\\
\mathcal{L}_{Kp\Lambda^*} &= \frac{g_{KN\Lambda^*}}{m_K}\bar{\Lambda}^{*\mu}(\partial_\mu K^-)\gamma_5 p + \text{h.c.}, & (2)\\
\mathcal{L}_{\gamma pp} &= -e\bar{p}\left(\not{A} - \frac{\kappa_p}{2M_N}\sigma_{\mu\nu}(\partial^\nu A^\mu)\right)p + \text{h.c.}, & (3)\\
\mathcal{L}_{\gamma Kp\Lambda^*} &= -ie\frac{g_{KN\Lambda^*}}{m_K}\bar{\Lambda}^{*\mu}A_\mu K^-\gamma_5 p + \text{h.c.}, & (4)\\
\mathcal{L}_{\gamma NN^*} &= \frac{ief_1}{2m_N}\bar{N}^*_\mu\gamma_\nu F^{\mu\nu}N - \frac{ef_2}{(2m_N)^2}\bar{N}^*_\mu F^{\mu\nu}\partial_\nu N + \text{h.c.}, & (5)\\
\mathcal{L}_{K\Lambda^*N^*} &= \frac{g_1}{m_K}\bar{\Lambda}^*_\mu\gamma_5\gamma_\alpha(\partial^\alpha K)N^{*\mu} + \\
& \frac{ig_2}{m_K^2}\bar{\Lambda}^*_\mu\gamma_5\left(\partial^\mu\partial_\nu K\right)N^{*\nu} + \text{h.c.}, & (6)
\end{aligned}
$$

Rarita-Schwinger spinor for $\Lambda(1520)$ and $N^*(2080)$

$$\sum_s u_\rho(p,s)\bar{u}_\sigma(p,s) = \frac{\not{p}+M}{2M}P_{\rho\sigma}(p), \tag{7}$$

and,

$$P_{\rho\sigma}(p) = -g_{\rho\sigma} + \frac{1}{3}\gamma_\rho\gamma_\sigma + \frac{2}{3M^2}p_\rho p_\sigma + \frac{1}{3M}(\gamma_\rho p_\sigma - \gamma_\sigma p_\rho). \tag{8}$$

Scattering amplitudes

$$-iT_i = \bar{u}_\mu(p_2, s_{\Lambda^*}) A_i^{\mu\nu} u(k_2, s_p) \epsilon_\nu(k_1, \lambda) \tag{9}$$

The reduced $A_i^{\mu\nu}$ amplitudes read:

$$A_t^{\mu\nu} = -e\frac{g_{KN\Lambda^*}}{m_K}\frac{1}{q^2 - m_K^2} q^\mu (q^\nu - p_1^\nu)\gamma_5 f_\mathrm{c}, \tag{10}$$

$$\begin{aligned} A_s^{\mu\nu} &= -e\frac{g_{KN\Lambda^*}}{m_K}\frac{1}{s - M_N^2} p_1^\mu \gamma_5 \Big\{ \not{k}_1 \gamma^\nu f_\mathrm{s} + (\not{k}_2 + M_N)\gamma^\nu f_\mathrm{c} \\ &\quad + (\not{k}_1 + \not{k}_2 + M_N)\mathrm{i}\frac{\kappa_p}{2M_N}\sigma_{\nu\rho}k_1^\rho f_\mathrm{s}\Big\}, \end{aligned} \tag{11}$$

$$A_c^{\mu\nu} = e\frac{g_{KN\Lambda^*}}{m_K} g^{\mu\nu}\gamma_5 f_\mathrm{c}, \tag{12}$$

$$\begin{aligned} A_R^{\mu\nu} &= \gamma_5 \Big(\frac{g_1}{m_K}\not{p}_1 g^{\mu\rho} - \frac{g_2}{m_K^2} p_1^\mu p_1^\rho\Big) \frac{\not{k}_1 + \not{k}_2 + M_{N^*}}{s - M_{N^*}^2 + iM_{N^*}\Gamma_{N^*}} P_{\rho\sigma} \\ &\quad \Big(\frac{ef_1}{2m_N}(k_1^\sigma \gamma^\nu - g^{\sigma\nu}\not{k}_1) + \frac{ef_2}{(2m_N)^2}(k_1^\sigma k_2^\nu - g^{\sigma\nu} k_1 \cdot k_2)\Big) f_R, \end{aligned} \tag{13}$$

Form factors

We take the following parameterization for the four-dimensional form-factors

$$f_{\rm i} = \frac{\Lambda_i^4}{\Lambda_i^4 + (q_{\rm i}^2 - M_{\rm i}^2)^2}, \quad {\rm i} = {\rm s}, {\rm t}, {\rm R} \tag{14}$$

$$f_{\rm c} = f_{\rm s} + f_{\rm t} - f_{\rm s} f_{\rm t}, \quad \text{and} \begin{cases} q_{\rm s}^2 = q_{\rm R}^2 = s, \; q_{\rm t}^2 = q^2, \\ M_{\rm s} = M_N, \\ M_{\rm R} = M_{N^*}, \\ M_{\rm t} = m_K. \end{cases} \tag{15}$$

1. We respect gauge invariance.
2. Those form factors have been widely used in the literature. (**K. Ohta, Phys. Rev. C 40, 1335 (1989); H. Haberzettl et al., Phys. Rev. C 58, R40(1998).**)
3. We will consider different cut-off values for the background and resonant terms, i.e. $\Lambda_s = \Lambda_t \neq \Lambda_R$.

Parameters

1. $g_{KN\Lambda^*} = 10.5$, determined from the $\Lambda^* \to pK^-$ decay width.
2. $N^*N\gamma$ coupling constants f_1 and f_2, obtained from the N^* helicity amplitudes $A_{1/2}$ and $A_{3/2}$;

$$A^{p^*}_{1/2} = \frac{e\sqrt{6}}{12}\sqrt{\frac{k_\gamma}{M_N M_{N^*}}}\left(f_1 + \frac{f_2}{4M_N^2}M_{N^*}(M_{N^*}+M_N)\right), \quad (16)$$

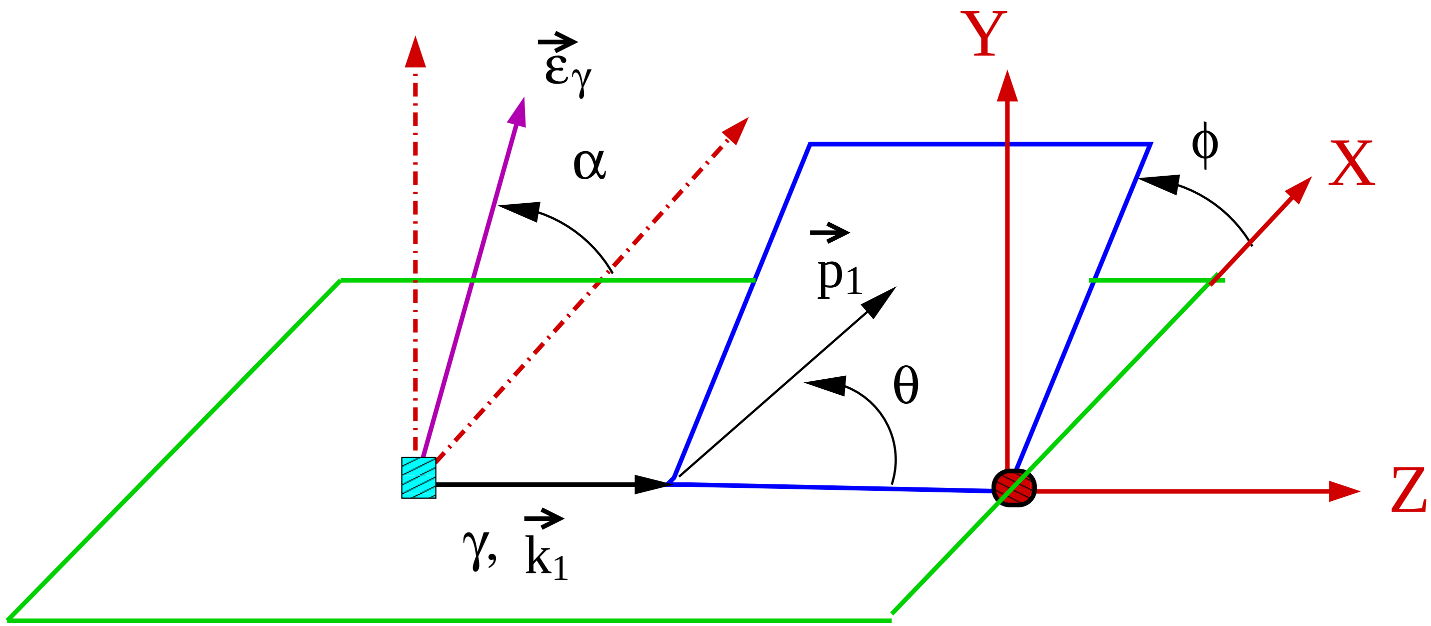
$$A^{p^*}_{3/2} = \frac{e\sqrt{2}}{4M_N}\sqrt{\frac{k_\gamma M_{N^*}}{M_N}}\left(f_1 + \frac{f_2}{4M_N}(M_{N^*}+M_N)\right), \quad (17)$$

   where $k_\gamma = (M^2_{N^*} - M^2_N)/(2M_{N^*})$.
3. The strong couplings g_1, g_2 and the cut-off parameters $\Lambda_s = \Lambda_t$ and Λ_R are free parameters, and we will fit them to the new LEPS data.

Cross Sections

The differential cross section, in the center of mass frame (c.m.), for a polarized photon beam reads,

$$\left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{C.M.}} = \frac{|\vec{k}_1^{\,\mathrm{C.M.}}||\vec{p}_1^{\,\mathrm{C.M.}}|}{4\pi^2}\frac{M_N M_{\Lambda^*}}{(s-M_N^2)^2}\left(\frac{1}{2}\sum_{s_p,s_\Lambda^*}|T|^2\right)$$
$$= \frac{1}{2\pi}\frac{d\sigma}{d(\cos\theta_{\mathrm{C.M.}})}\{1-\Sigma\cos 2\,(\phi_{\mathrm{C.M.}}-\alpha)\} \qquad (18)$$



Input Parameters

We have performed three different fits.

	Fit A	Fit B	Fit C
$A^{p^*}_{1/2}$[GeV$^{-1/2}$]	-0.020 ± 0.008	-0.020 ± 0.008	$---$
$A^{p^*}_{3/2}$[GeV$^{-1/2}$]	0.017 ± 0.011	0.017 ± 0.011	$---$
ef_1	0.18 ± 0.07	0.18 ± 0.07	$---$
ef_2	-0.19 ± 0.07	-0.19 ± 0.07	$---$
M_{N^*}[MeV]	2080	$---$	$---$
Γ_{N^*}[MeV]	300	$---$	$---$

Fitted Parameters

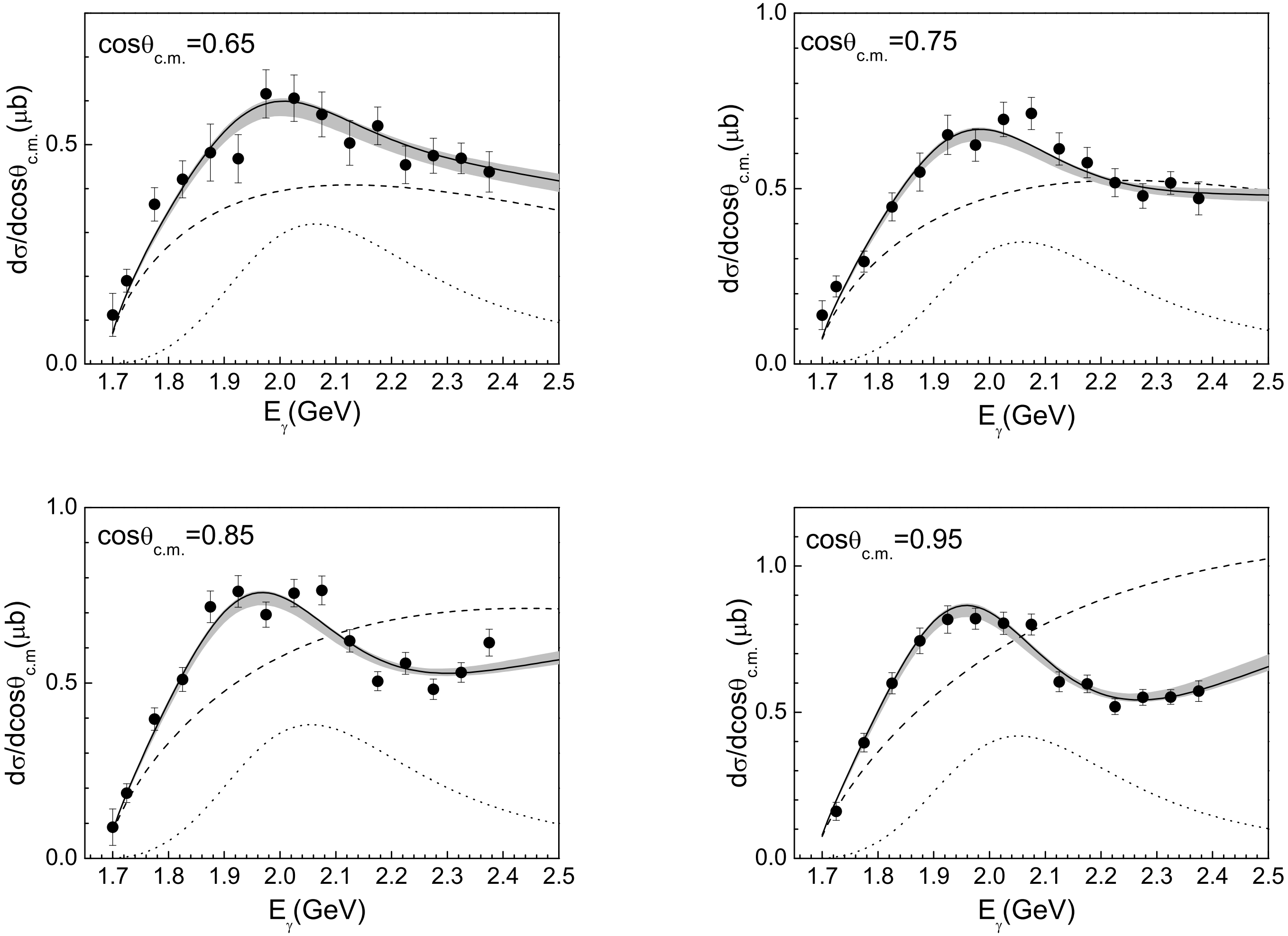
g_1	$5.0 \pm 0.2^{+2.8}_{-1.5}$	$2.0 \pm 0.1^{+1.4}_{-0.5}$	1.4 ± 0.3
g_2	$-9.7 \pm 2.0^{+6}_{-5}$	$-3.3 \pm 0.9^{+1.8}_{-3.4}$	5.5 ± 1.8
$\Lambda_s = \Lambda_t$ [MeV]	$613 \pm 2^{+5}_{-8}$	$613 \pm 2^{+1}_{-5}$	604 ± 2
Λ_R [MeV]	$990 \pm 50^{+30}_{-20}$	5.0 ± 3.9 *	909 ± 55
ef_1	$---$	$---$	0.177 ± 0.023
ef_2	$---$	$---$	-0.082 ± 0.023
M_{N^*}[MeV]	$---$	$2138 \pm 4^{+1}_{-21}$	2115 ± 8
Γ_{N^*}[MeV]	$---$	$168 \pm 10^{+19}_{-15}$	254 ± 24
χ^2/dof	2.4	1.4	1.2

Predicted Observables

$A^{p^*}_{1/2}$[GeV$^{-1/2}$]	$---$	$---$	0.0036 ± 0.0086
$A^{p^*}_{3/2}$[GeV$^{-1/2}$]	$---$	$---$	0.058 ± 0.021
$\Gamma_{N^* \to \Lambda^* K}$ [MeV]	$110 \pm 10^{+160}_{-50}$	$43 \pm 5^{+61}_{-20}$	19 ± 7
$\frac{\Gamma_{N^* \to \Lambda^* K}}{\Gamma_{N^*}}$[%]	$36 \pm 3^{+53}_{-18}$	$26 \pm 3^{+36}_{-12}$	7.5 ± 2.8

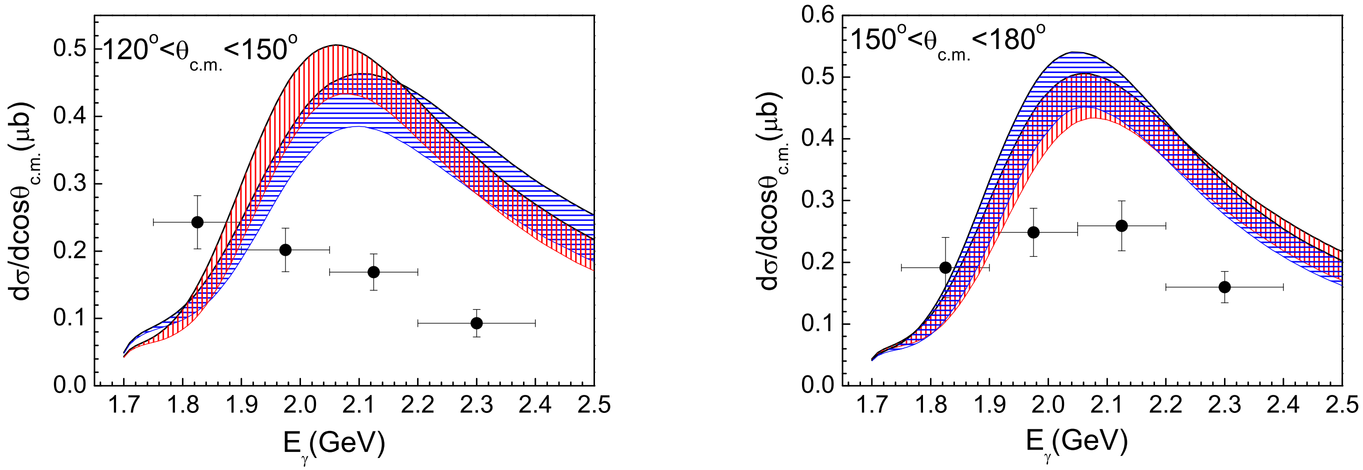
$$\Gamma_{N^* \to \Lambda^* K} = \frac{|\vec{p}_1^{\,\mathrm{C.M.}}| M_{N^*}(E_{\Lambda^*} - M_{\Lambda^*})}{18\pi M^2_{\Lambda^*}} \Big\{ |\vec{p}_1^{\,\mathrm{C.M.}}|^4 \frac{g_2^2}{m_K^4} + |\vec{p}_1^{\,\mathrm{C.M.}}|^2 (2E_{\Lambda^*} - M_{\Lambda^*}) \frac{(M_{N^*} + M_{\Lambda^*})}{M_{N^*}} \frac{g_1 g_2}{m_K^3} + \left(\frac{M_{N^*} + M_{\Lambda^*}}{M_{N^*}} \right)^2 (E^2_{\Lambda^*} - E_{\Lambda^*} M_{\Lambda^*} + \frac{5}{2} M^2_{\Lambda^*}) \frac{g_1^2}{m_K^2} \Big\} \quad (19)$$

Numerical Results



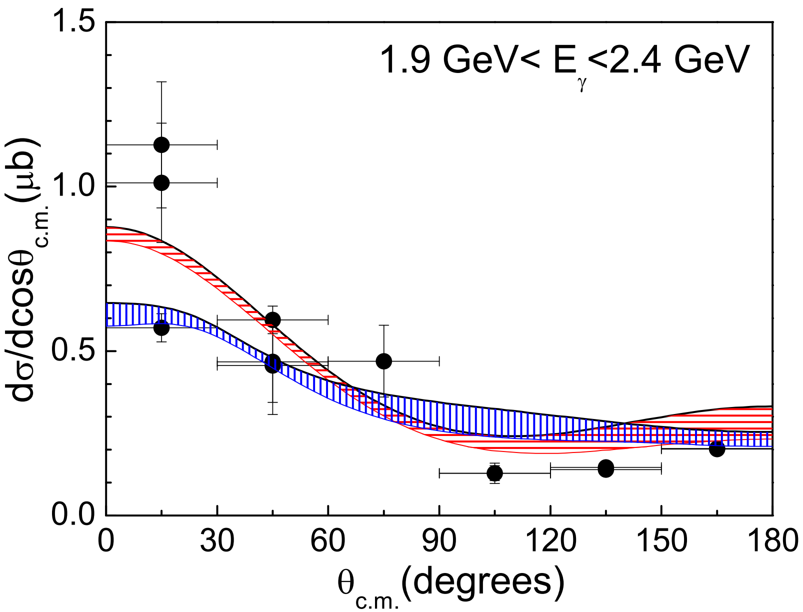
Results have been obtained from the eight–parameter fit C.

Numerical Results (Fit C)



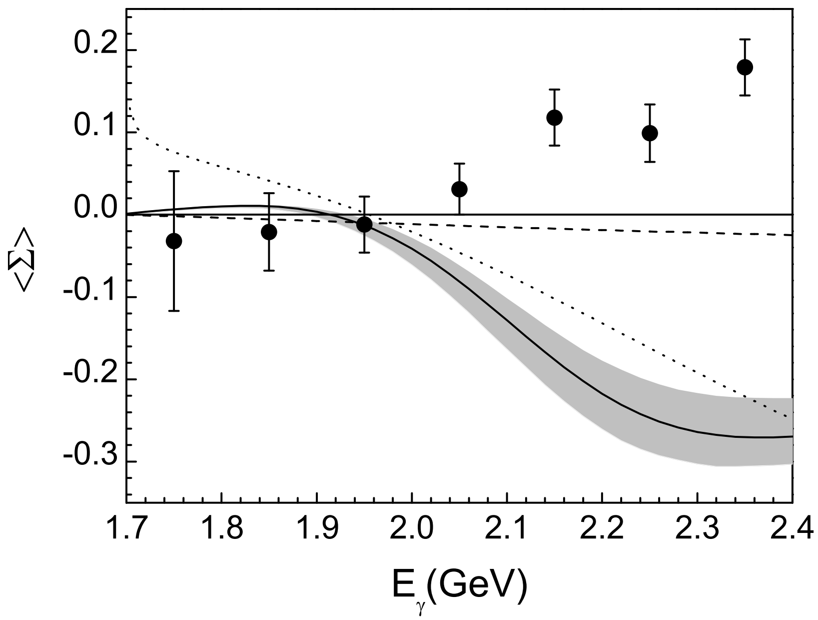
1. Blue horizontal line shaded region (right panel), $\theta_{\text{c.m.}} = 120^0$;
2. Blue horizontal line shaded region (left panel), $\theta_{\text{c.m.}} = 180^0$;
3. red vertical line shaded region in both panels, $\theta_{\text{c.m.}} = 150^0$.

Numerical Results (Fit C)



1. Red horizontal lines, $E_\gamma = 1.9$ GeV;
2. Blue vertical lines, $E_\gamma = 2.4$ GeV.

Polar angle average photon-beam asymmetry $\langle\Sigma\rangle$



$$\langle\Sigma\rangle = \frac{\int_{0.6}^{1.0} \frac{d\sigma}{d(\cos\theta_{\text{C.M.}})} \Sigma(\cos\theta_{\text{C.M.}}, E_\gamma) d(\cos\theta_{\text{C.M.}})}{\int_{0.6}^{1.0} \frac{d\sigma}{d(\cos\theta_{\text{C.M.}})} d(\cos\theta_{\text{C.M.}})}, \tag{20}$$

Conclusions

1. We have studied the $\vec{\gamma} p \to \Lambda^* K^+$ reaction at low energies within a effective Lagrangian approach. In particular, we have paid an special attention to a bump structure in the differential cross section at forward K^+ angles reported in the recent SPring-8 LEPS experiment. Starting from the background contributions studied in previous works, we have shown that this bump might be described thanks to the inclusion of the nucleon resonance $N^*(2080)$ (spin-parity $J^P = 3/2^-$). We have fitted its mass, width and hadronic $\Lambda^* K^+$ and electromagnetic $N^* N \gamma$ couplings to data.
2. We have found that this resonance would have a large decay width into $\Lambda^* K$, which will be compatible with the findings of the QM approach of Capstick and collaborators.
3. Our predictions for the backward angles and the polar angle average photon-beam asymmetry are not so good when compared with the experimental data.

Thank you very much for your attention!

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