Photoproduction of kaons

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Photoproduction

$$\gamma + \mathrm{p} \longrightarrow \mathrm{K}^{+} + \Lambda$$

Electroproduction

$$\mathrm{e} + \mathrm{N} \longrightarrow \mathrm{e}' + \mathrm{K} + \mathrm{Y}, \qquad \mathrm{Y} = \Lambda, \Sigma$$

– in the one-photon approximation: $\gamma_{\mathrm{v}} + \mathrm{N} \longrightarrow \mathrm{K} + \mathrm{Y}$

– important ingredient in the DWIA calculations

$$\mathrm{e} + {}^{\mathrm{A}}\mathrm{Z} \longrightarrow \mathrm{e}' + \mathrm{K}^{+} + {}^{\mathrm{A}-1}_{\ \Lambda}(\mathrm{Z}-1)$$

Introduction

- production of open-strangeness ($s\bar{s}$) for $\sqrt{s} < 2.6$ GeV
  $\rightarrow$ which degrees of freedom – quarks and gluons or hadrons?
  $\rightarrow$ a reaction mechanism (e.g., resonant and non resonant parts of the amplitude)?
- the 3rd nucleon-resonance region ($\sqrt{s_{thr}} = 1.609$ GeV) – many resonances
  $\rightarrow$ a complicated description in comparison with π and η production
  $\rightarrow$ which resonant states are important?
  $\rightarrow$ missing resonances (predicted by quark models, not seen in π and η production)?
- open channels, e.g. π and η, coupled via the meson-baryon FSI
  $\rightarrow$ unitarity: *multi-channel* $\leftrightarrow$ *single-channel analysis*
- a phenomenological description in the resonance region – an isobar model
  $\rightarrow$ *an effective Lagrangian* with baryon, meson, and photon fields
  $\rightarrow$ frozen d.o.f. at small distances (partons) – *form factors*
  $\rightarrow$ *the tree-level approximation*
- crossing symmetry: description of $\Gamma(K^- p \longrightarrow \gamma\, \Lambda)$ (Saclay-Lyon model)
- many experimental data points after 2004 – more than 7000 data

Methods of description

- multi-channel analysis
  - unitary isobar approach (rescattering in the final state)
    – K-matrix approach: Giessen, Dubna-Mainz-Taipei, Bonn-Gatchina, Shyam and Scholten, Usov and Scholten
    – Hamiltonian formalism with Breit-Wigner forms: Julia-Diaz et al
  - chiral unitary framework (chiral Lagrangian, threshold region): Borasoy et al
- single-channel analysis
  - Isobar model (effective hadron Lagrangian)
    – Adelseck-Saghai (90), Williams-Ji-Cotanch (92), Saclay-Lyon (96), Kaon-MAID (99), Gent isobar (01), Maxwell (07)
  - Regge-plus-resonance model (hybrid isobar-Regge description)
    – Gent group: RPR-2007, RPR-2011
  - multipole analysis: Mart and Sulaksono
- Quark model (resonances included)
  - Zhenping Li; F.E. Close and Zhenping Li;
    Dinghui Lu, R.H. Landau, and S.C. Phatak (chiral color dielectric model)

Isobar model

- single-channel approximation – final-state interactions not included
  - the amplitude for $\Lambda K \longrightarrow \Lambda K$ not known experimentaly
  - violation of unitarity
  - fitted coupling constants can include a part of the FSI effects
  - energy dependent widths of N^* $\rightarrow$ *a partial restoration of unitarity*
- effective hadron Lagrangian
  - ground-state hadrons, N^*, Y^*, and K^* resonances $\rightarrow$ couplings
  - a set of relevant resonances has to be selected in the analysis
  - high-spin states: $N^*(3/2, 5/2)$ and $Y^*(3/2)$
  - missing nucleon resonances: $P_{11}(1880)$, $P_{13}(1900)$, $D_{13}(1875)$
  - hadron form factors included in a gauge-invariant way (a contact term)
  - tree-level expansion:
    s-channel exchanges (N^*– resonant contributions)
    t- and *u*-channel exchanges and a contact term (non resonant terms)
  - *too big contributions from the Born diagrams* – reduced
  - free parameters are fitted to data ($\approx$ 25 – 30 parameters $\Leftrightarrow$ 3400 data points)

Isobar model – exchanges of the spin-3/2 and 5/2 nucleon resonances

- the Rarita Schwinger propagator for spin 3/2

$$S_{\mu\nu}(p) = \frac{\not{p} + m}{p^2 - m^2}\mathcal{P}^{3/2}_{\mu\nu} - \frac{2}{3m^2}(\not{p} + m)\mathcal{P}^{1/2}_{22,\mu\nu} + \frac{1}{\sqrt{3}m}(\mathcal{P}^{1/2}_{12,\mu\nu} + \mathcal{P}^{1/2}_{21,\mu\nu})$$

  allows (nonphysical) contributions of the lower spin components

- the nonphysical contributions can be removed by a suitable form of $\mathcal{L}_{int}$
  [V. Pascalutsa, P.R.D 58 (1998) 096002; T. Vrancx et al, P.R.C 84 (2011) 045201]

- invariance of $\mathcal{L}_{int}$ under local U(1) gauge transformation of the R.-S. field

  $\Rightarrow$ transverse interaction vertexes: $V^S_\mu p^\mu = V^{EM}_\mu p^\mu = 0$

  $\Rightarrow$ removes all nonphysical contributions: $V^S_\mu \, \mathcal{P}^{1/2,\mu\nu}_{ij} \, V^{EM}_\nu = 0$

- high momentum-power dependence from the vertexes (gauge invariance)
  $\rightarrow$ regularizes the contribution (the u-channel exchanges)
  $\rightarrow$ substantial growth of the cross section above the resonance region
  – strong form factors (multidipole Gauss) in the RPR model

Isobar model – exchanges of the spin-3/2 hyperon resonances

- a contribution to the invariant amplitude from $Y^*(3/2)$

$$\mathcal{M}^{3/2}_{Y^*} = \bar{u}(p_\Lambda)\, V^{EM,\mu} \frac{\not{p} + m}{u - m^2 + \mathrm{i} m\Gamma}\, \mathcal{P}^{3/2}_{\mu\nu}(p)\, V^{S,\nu}\, u(p_p),$$

with

$$\mathcal{P}^{3/2}_{\mu\nu}(p) = g^{\mu\nu} - \frac{1}{3}\gamma^\mu\gamma^\nu - \frac{1}{3p^2}(\not{p}p^\nu\gamma^\mu + p^\mu\gamma^\nu\not{p})$$

- $p^2 = u$ can be zero in the physical region
  → the contribution would be singular for $u = 0$
  → the transversality of the vertexes removes this term
  → moreover, the momentum power from the vertexes ($\sim p^2$) regularises such terms ⇒ the u-channel $Y^*(3/2)$ exchanges are regular
- similar properties hold also for exchanges of the spin-5/2 baryons
  [T. Vrancx et al, Phys. Rev. C 84 (2011) 045201]

Isobar model – fitting the photoproduction data

- considered resonances
  - t-channel: $K^*(892)$, $K_1(1272)$ with the vector and tensor couplings
  - s-channel: mass (1.5 – 2) GeV and spin $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ nucleon states from the Bayesian analysis (RPR) [L.De Cruz etal, Phys.Rev.C86(2012)015212] and five more states from PDG
  - missing resonances $D_{13}(1875)$, $P_{11}(1880)$, $P_{13}(1900)$
  - u-channel: nine hyperon states with spin $\frac{1}{2}$ and $\frac{3}{2}$
- hadron form fs.: dipole, multidipole, Gauss, and multidipole-Gauss
- constraints on the model parameters:
  - $SU(3)_f$ symmetry: $-4.4 \leq g_{KN\Lambda}/\sqrt{4\pi} \leq -3.0 \qquad 0.8 \leq g_{KN\Sigma}/\sqrt{4\pi} \leq 1.3$
- experimental data for $W < 2.36$ GeV
  - cross sections: CLAS 2005, 2010; LEPS; old data (Adelseck,Saghai)
  - hyperon polarization: CLAS 2010
  - beam asymmetry: LEPS
  - all together $\approx$ 3400 data points
  - experimental uncertainty used in fitting: $\Delta\sigma_{tot} = \sqrt{\Delta\sigma_{stat}^2 + \Delta\sigma_{syst}^2}$

- free parameters
  - $g_{K\Lambda N}$, $g_{K\Sigma N}$
  - G_V and G_T for K^* and K_1
  - spin-1/2 resonances (N^* or Y^*) $\rightarrow$ 1 parameter
  - spin-3/2 and 5/2 resonances $\rightarrow$ 2 parameters
  - 2 cut-off parameters for the hadron form factors (resonant, background)
  - together about 30 free parameters
- two solutions: BS1 and BS2, both with $\chi^2/n.d.f = 1.64$
- selected resonances in model BS1
  - $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{13}(1720)$, $F_{15}(1860)$, $D_{13}(1875)$, $P_{13}(1900)$, $F_{15}(2000)$; $\Lambda(1520)$, $\Sigma(1660)$, $\Sigma(1750)$, $\Lambda(1800)$, $\Lambda(1890)$, $\Sigma(1940)$; $K^*(892)$, $K_1(1270)$
- model BS1:
  - multidipole form factors with $\Lambda_{bgr} = 1.88$ GeV and $\Lambda_{res} = 2.74$ GeV
  - $g_{KN\Lambda}/\sqrt{4\pi} = -3.00 \rightarrow$ the upper limit of the SU(3) violation (20%)
  - more details in D. Skoupil and P. B., Phys. Rev. C 93 (2016) 025204(20)

Regge-plus-resonance model [L.De Cruz *et al*, Phys.Rev.C**86** (2012) 015212]

Invariant amplitude: $\mathcal{M} = \mathcal{M}_{bgr}(Regge) + \mathcal{M}_{res}(isobar)$

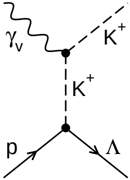
- the background part – exchanges of degenerate K and K* trajectories

$$\mathcal{M}_{bgr}(s,t) = \mathcal{P}^{K}_{Regge}(s,t) \times \beta_K(s,t) + \mathcal{P}^{K^*}_{Regge}(s,t) \times \beta_{K^*}(s,t)$$
$$+ \mathcal{M}^{p,elec}_{Feyn} \times \mathcal{P}^{K}_{Regge}(s,t) \times (t - m_K^2)$$

  - the Regge propagator with *the rotating phase*

$$\mathcal{P}^{x}_{Regge}(s,t) = \frac{(s/s_0)^{\alpha_x(t)}}{\sin \pi\, \alpha_x(t)} \frac{\pi\, \alpha'_x\, \mathrm{e}^{-i\pi\alpha_x(t)}}{\Gamma(1+\alpha_x(t))}, \qquad \alpha_x(t) = \alpha'_x(t - m^2), \quad x = \mathrm{K}, \mathrm{K}^*$$

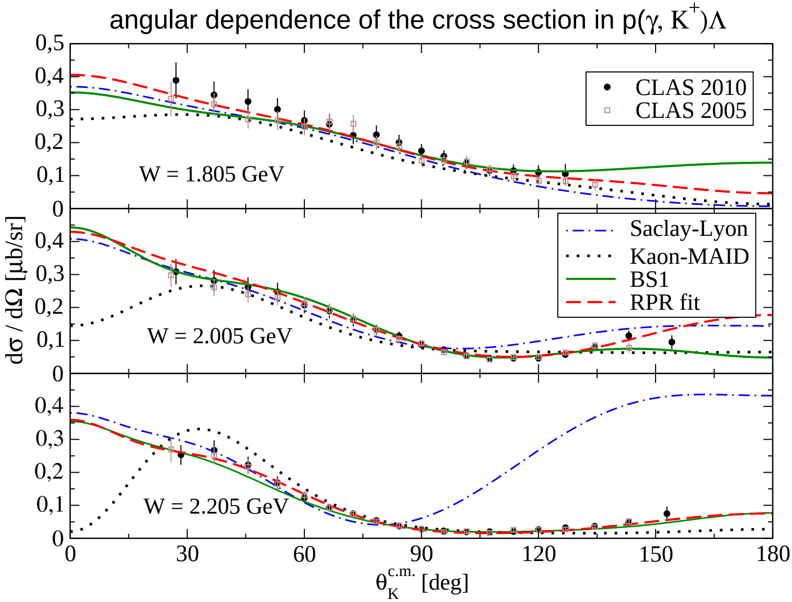
  - the residue of the lowest poles



for $t \to m_K^2 \qquad \mathcal{P}^{K}_{Regge}(s,t) \times \beta_K(s,t) \longrightarrow \dfrac{\beta_K(s,t)}{t - m_K^2}$

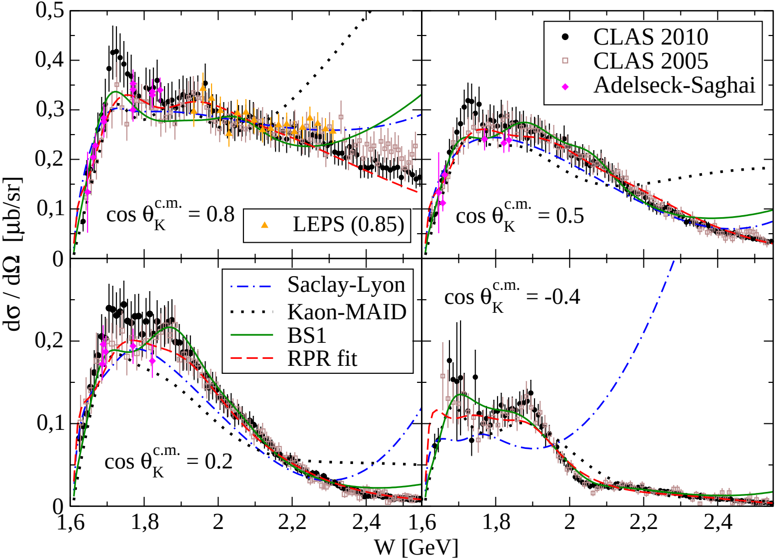
- only 3 parameters fixed mainly by high-energy data (W>2.6 GeV)
- the resonant part – selected N*: $S_{11}(1535)$, $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $F_{15}(1860)$, $P_{11}(1880)$, $D_{13}(1875)$, $P_{13}(1900)$, $D_{13}(2120)$

  – hadron form factors: multidipole

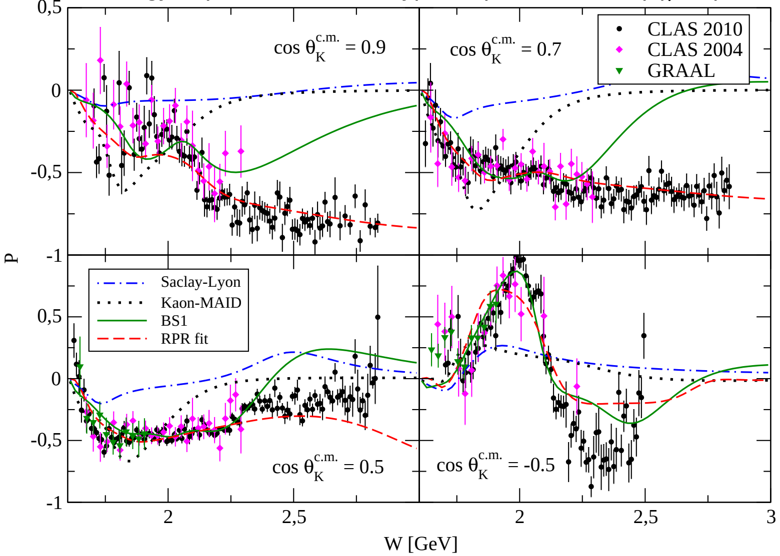


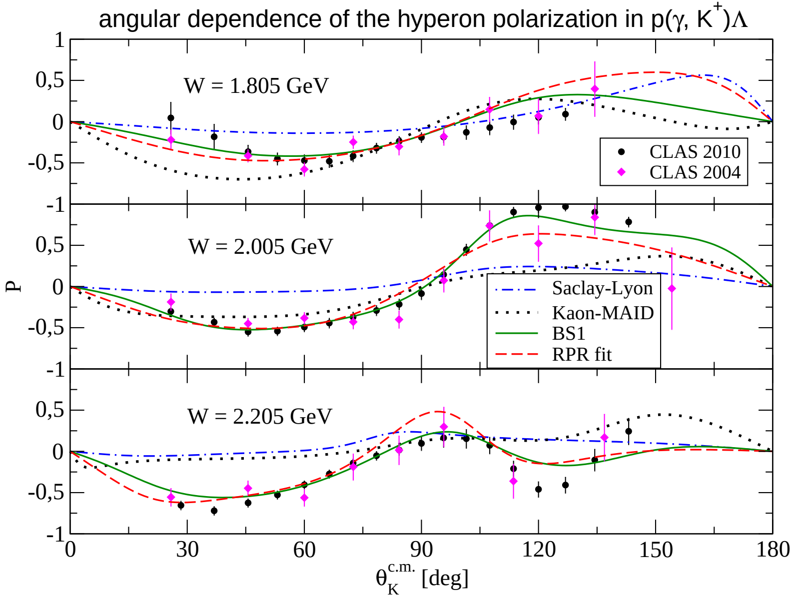
angular dependence of the cross section in p(γ, K+)Λ
0,5
0,4
0,3
0,2
0,1
0
CLAS 2010
CLAS 2005
W = 1.805 GeV
Saclay-Lyon
Kaon-MAID
BS1
RPR fit
W = 2.005 GeV
W = 2.205 GeV
dσ / dΩ [μb/sr]
0
30
60
90
120
150
180
θK c.m. [deg]

energy dependence of the cross section in $p(\gamma, K^+)\Lambda$



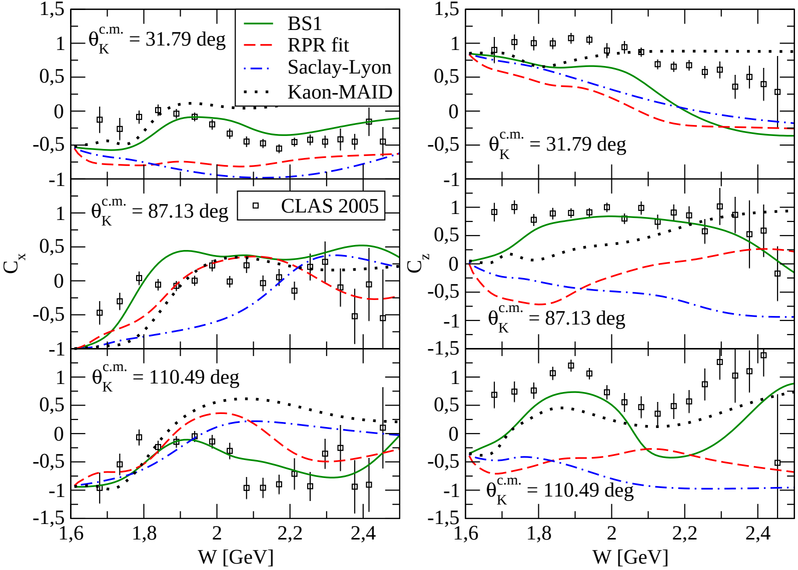
energy dependence of the hyperon polarization in $p(\gamma, K^+)\Lambda$



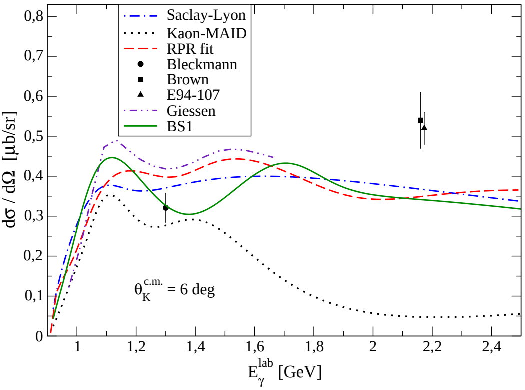


angular dependence of the hyperon polarization in p(γ, K+)Λ
W = 1.805 GeV
W = 2.005 GeV
W = 2.205 GeV
CLAS 2010
CLAS 2004
Saclay-Lyon
Kaon-MAID
BS1
RPR fit
P
θK c.m. [deg]
1
0,5
0
-0,5
-1
0
30
60
90
120
150
180

predictions for the double-polarization observables in $p(\gamma, K^+)\Lambda$



Predictions of the models at very small θ_K



Electroproduction data:

Brown72 [P.R.L.28(1972)1086]

$\sigma = \sigma_T + \epsilon\sigma_L$
W = 2.17 GeV
$Q^2 = 0.18$ (GeV/c)^2
$\theta_K^{c.m.} = 5.9^\circ$

E94-107 (JLab, Hall A)

σ_{full}
W = 2.2 GeV
$Q^2 = 0.07$ (GeV/c)^2
$\theta_K^{c.m.} = 6^\circ$

Giessen model: Shklyar etal, [Phys.Rev.C72(2005)015210]

– electroproduction data but: $\sigma_L \sim Q^2$, $\sigma_{TT} \sim \sin^2\theta_K$, and $\sigma_{TL} \sim \sqrt{Q^2}\,\sin\theta_K$,

$$\sigma \;=\; \sigma_T + \epsilon\,\sigma_L + \epsilon\sigma_{TT} + \sqrt{2\epsilon(1+\epsilon)}\sigma_{TL}, \quad (\Phi_K = 0)$$

SL: $0.41 = 0.35 + 0.004 - 0.001 + 0.06$ $\quad(\epsilon{=}0.7,\ \theta_K{=}6^\circ,\ Q^2{=}0.07\ (\mathrm{GeV/c})^2)$

$\Rightarrow$ photoproduction dominates the unpolarized electroproduction cross section: $\sigma \approx \sigma_T$

The elementary models can be tested in the small-angle region calculating the hypernucleus-production cross sections in DWIA

$$e + {}^{A}Z \longrightarrow e' + K^{+} + {}^{A-1}_{\Lambda}(Z-1)$$

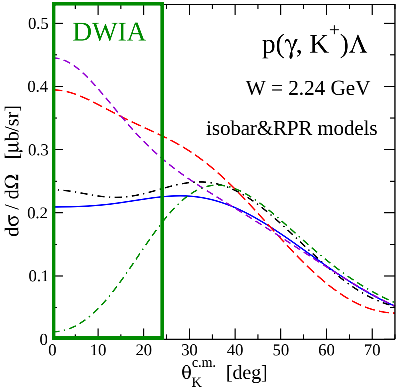
DWIA (in frozen-nucleon approx.):

$$\langle \Psi_H | \sum_i \chi_\gamma \chi_K^* \mathcal{J}^\mu(i) \, |\Psi_A\rangle$$

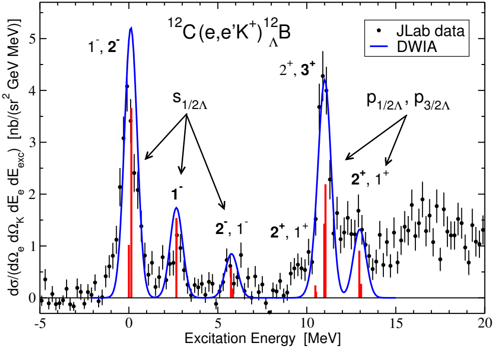
$\mathcal{J}^\mu$ – elementary hadron current in the laboratory frame

– the main contribution of $\mathcal{J}^\mu$ is from **a small θ_K region**

– $\mathcal{J}^\mu$ is determined mainly by the photoproduction data



Hypernucleus electroproduction cross sections



[M. Iodice *et al*, Phys. Rev. Lett. **99** (2007) 052501]

data: JLab Hall A
exp. E94-107

W = 2.21 GeV

$\theta_e^{lab} = \theta_K^{lab} = 6^o$

Q^2 is very small:
0.018 (GeV/c)^2

calculations with
the Saclay-Lyon model

– in DWIA the elementary hadron current contributes only for small θ_K

$\Rightarrow$ predictions of the elementary models can be tested for small θ_K and Q^2

Summary

- new isobar models BS1 and BS2 were constructed using a consistent description of the resonances with spin 3/2 and 5/2;
- $Y^*(3/2)$ resonances (not considered in older models, except for SLC) were found to play important role in description of the background part of amplitude;
- the selected set of N^* agrees well with that chosen in the Bayesian analysis with the Regge-plus-resonance model;
- we confirm importance of the missing resonances $P_{13}(1900)$ and $D_{13}(1875)$ for description of data in the $K^+\Lambda$ channel but, in our analysis, $P_{11}(1880)$ was replaced by $F_{15}(1860)$ recently included in PDG;
- our preliminary fit with the RPR model provides good description of data in the resonance region and above this region (CLAS 2010);
- predictions of the isobar and RPR models for the cross sections at small kaon angles differ – the data still cannot fully fix the models;
- the DWIA calculations of hypernucleus cross sections can be used to test the isobar and RPR models in the small θ_K and Q^2 kinematical region.

Outlook

- testing the isobar and Regge-plus-resonance models in the DWIA calculations (small θ_K) utilizing data on hypernucleus production;
- including energy dependent widths of N* (unitarity);
- extending the isobar model to electroproduction of $K^+\Lambda$;
- using the isobar model in photoproduction of K^0 on the neutron (deuteron data).

Thank you