Photoproduction of Kaons

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Introduction

Production of open strangeness for $W < 2.6\,\mathrm{GeV}$

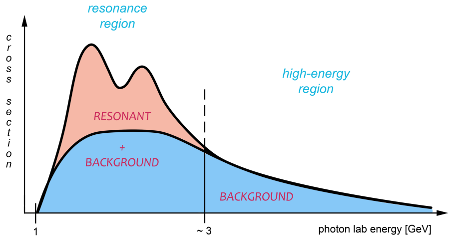
- introduction of effective models as perturbation theory in QCD is not suited for small energies
- choosing appropriate degrees of freedom (hadrons or quarks and gluons?)

New high-quality data became available

- LEPS, GRAAL, and (particularly) CLAS collaboration: $>$ 7000 data

The 3rd nucleon-resonance region $\Rightarrow$ many resonances

- complicated description in comparison with π or η production
- a need for selecting important resonant states
- presence of missing resonances (predicted by quark models, unnoticed in π or η production)



$p(\gamma, K^+)\Lambda$ process:

- resonance region dominated by resonant contributions (N^*)
- many non-resonant contributions (exchange of p, K, Λ; K^* and Y^*) $\Rightarrow$ background

Ways of describing the $p(\gamma, K^+)\Lambda$ process

Quark models

- quark d.o.f.; small number of parameters, contributions of resonances arise naturally: Zhenping Li, Hongxing Ye, Minghui Lu

Multi-channel analysis

- rescattering effects in the meson-baryon final-state system included, but the amplitude for *e.g.* $K^+\Lambda \to K^+\Lambda$ not known experimentally
- chiral unitary models (chiral effective Lagrangian, threshold region only): Borasoy *et al.*, Steininger *et al.*
- unitary isobar approach with rescattering in the final state

Single-channel analysis

- simplification: tree-level approximation; use of effective hadron Lagrangian, form factors to account for inner structure of hadrons
- isobar model
  - Saclay-Lyon, Kaon-MAID, Gent, Maxwell, Mart *et al.*, Adelseck and Saghai; Williams, Ji, and Cotanch
- Regge-plus-resonance model (hybrid description of both resonant and high-energy region; non resonant part of the amplitude modelled by exchanges of kaon trajectories)
  - group at Gent University: RPR-2007 (Phys. Rev. C 75, 045204 (2007)), RPR-2011 (Phys. Rev. C 86, 015212 (2012))

Isobar model

Single-channel approximation

- higher-order contributions (rescattering, FSI) partly included by means of effective values of coupling constants

Use of effective hadron Lagrangian

- hadrons either in their ground or excited states
- amplitude constructed as a sum of tree-level Feynman diagrams
  - **background part**: Born terms with an off-shell proton (*s*-channel), kaon (*t*), and hyperon (*u*) exchanges; non Born terms with (axial) vector K^* (*t*) and Y^* (*u*)
  - **resonant part**: *s*-channel Feynman diagram with N^* exchanges
- a number of contributing resonances leads to several versions; relevant resonances have to be chosen in the analysis
  - states with high spin, *e.g.* $N^*(3/2)$, $N^*(5/2)$, $Y^*(3/2)$
  - missing N^*: $D_{13}(1875)$, $P_{11}(1880)$, $P_{13}(1900)$
- hadron form factors account for internal structure of hadrons
  - included in a gauge-invariant way $\rightarrow$ need for a contact term
  - one can opt for many forms: dipole, multidipole, Gaussian, multidipole-Gaussian
- problem with overly large Born contributions
- $K\Lambda N$ vertex: pseudoscalar- or pseudovector-like coupling
- free parameters adjusted to experimental data

Satisfactory agreement with the data in the energy range $E_\gamma^{lab} = 0.91 - 2.5\,\text{GeV}$

Isobar model

Exchanges of high-spin resonant states

- Rarita-Schwinger (RS) propagator for the spin-3/2 field

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

  allows non physical contributions of lower-spin components

- non physical contributions can be removed by an appropriate form of $\mathcal{L}_{int}$
  - consistent formalism for spin-3/2 fields: V. Pascalutsa, Phys. Rev. D **58** (1998) 096002
  - generalisation for arbitrary high-spin field: T. Vrancx et al., Phys. Rev. C **84**, 045201 (2011)

- consistency is ensured by imposing invariance of $\mathcal{L}_{int}$ under U(1) gauge transformation of the RS field
  - interaction vertices are transverse: $V^S_\mu p^\mu = V^{EM}_\mu p^\mu = 0$
  - all non physical contributions vanish: $V^S_\mu \, \mathcal{P}^{1/2,\mu\nu}_{ij} \, V^{EM}_\nu = 0$

- strong momentum dependence from the vertices
  - helps regularize the amplitude
  - creates non physical structures in the cross section $\rightarrow$ strong form factors needed

- transversality of the vertices enables the inclusion of $Y^*(3/2)$
  - a term of $1/u$ in $\mathcal{P}^{(3/2)}_{\mu\nu}$ would be singular for $u=0$
  - this term however vanishes in consistent formalism

Isobar model

Fitting procedure

Resonance selection

- t channel: $K^*(892)$, $K_1(1272)$
- s channel: spin-1/2, 3/2, and 5/2 N^* with mass < 2 GeV; initial set from the Bayesian analysis (L. De Cruz, *et al.*, Phys. Rev. C **86** (2012) 015212) and varied throughout the procedure
  - missing resonances $D_{13}(1875)$, $P_{11}(1880)$, $P_{13}(1900)$
- u channel: $Y^*(1/2)$ and $Y^*(3/2)$

25 to 30 free parameters:

- $g_{K\Lambda N}$, $g_{K\Sigma N}$
- K^*'s have vector and tensor couplings
- spin-1/2 resonance $\rightarrow$ 1 parameter; spin-3/2 and 5/2 resonance $\rightarrow$ 2 parameters
- 2 cut-off parameters for the form factor

Around 3400 data points

- cross section for $W < 2.355$ GeV (CLAS 2005 & 2010; LEPS, Adelseck-Saghai)
- hyperon polarisation for $W < 2.225$ GeV (CLAS 2010)
- beam asymmetry (LEPS)

Two solutions: BS1 and BS2, $\chi^2/\text{n.d.f.} = 1.64$ for both

- Model BS1 (detailed in D.S., P. Bydžovský, Phys. Rev. C **93** (2016) 025204)
  - $K^*(892)$, $K_1(1272)$; $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{13}(1720)$, $F_{15}(1680)$, $D_{13}(1875)$, $F_{15}(2000)$; $\Lambda(1520)$, $\Lambda(1800)$, $\Lambda(1890)$, $\Sigma(1660)$, $\Sigma(1750)$, $\Sigma(1940)$
  - multidipole form factor with $\Lambda_{bgr} = 1.88$ GeV and $\Lambda_{res} = 2.74$ GeV

Regge-plus-resonance model

Amplitude: $\mathcal{M} = \mathcal{M}_{bgr}^{Regge} + \mathcal{M}_{res}^{isobar}$

- **background part**: exchanges of degenerate $K(494)$ and $K^*(892)$ trajectories $\rightarrow$ only 3 free parameters ($g_{K\Lambda N}$, $G_{K^*}^{(v)}$, $G_{K^*}^{(t)}$)

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

  - gauge-invariance restoration: inclusion of the Reggeized electric part of the s-channel Born term
  - the Regge propagator with rotating phase,

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

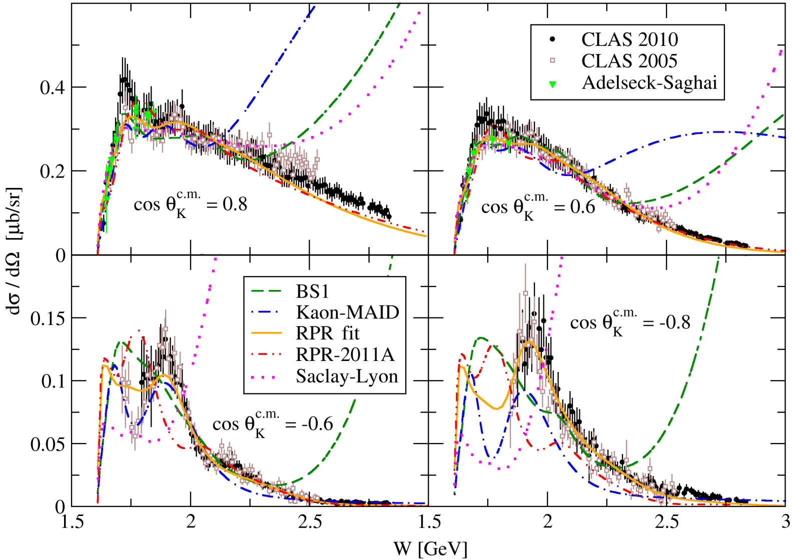
  coincides with the Feynman one: $\mathcal{P}_{Regge}(s,t) \rightarrow (t - m_K^2)^{-1}$ for $t \rightarrow m_K^2$

- **resonant part**: inclusion of resonant s-channel diagrams with standard Feynman propagators, which vanishes beyond the resonant region

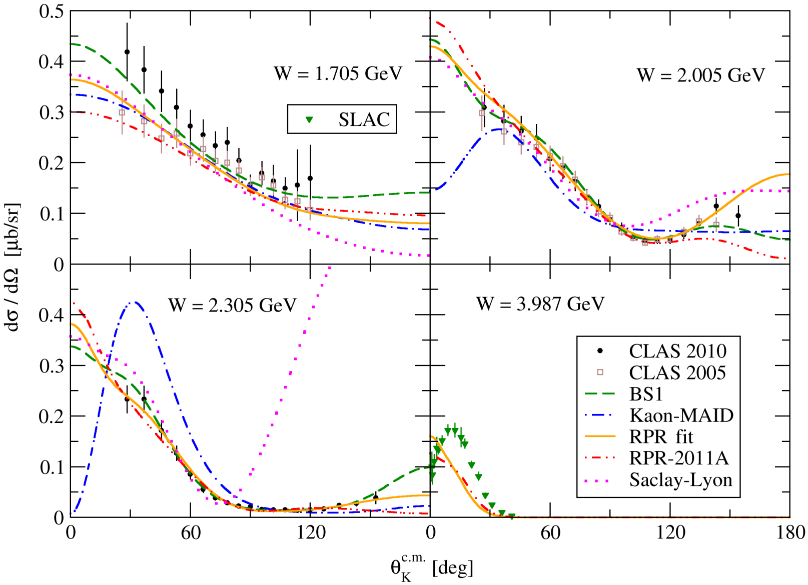
Fitting procedure

- less parameters to optimize (≈ 20) & more data available (≈ 5300) in comparison with the isobar model
- selected N^*: $S_{11}(1535)$, $S_{11}(1650)$, $D_{15}(1675)$, $F_{15}(1680)$, $D_{13}(1700)$, $F_{15}(1860)$, $P_{11}(1880)$, $D_{13}(1875)$, $P_{13}(1900)$, $D_{13}(2120)$

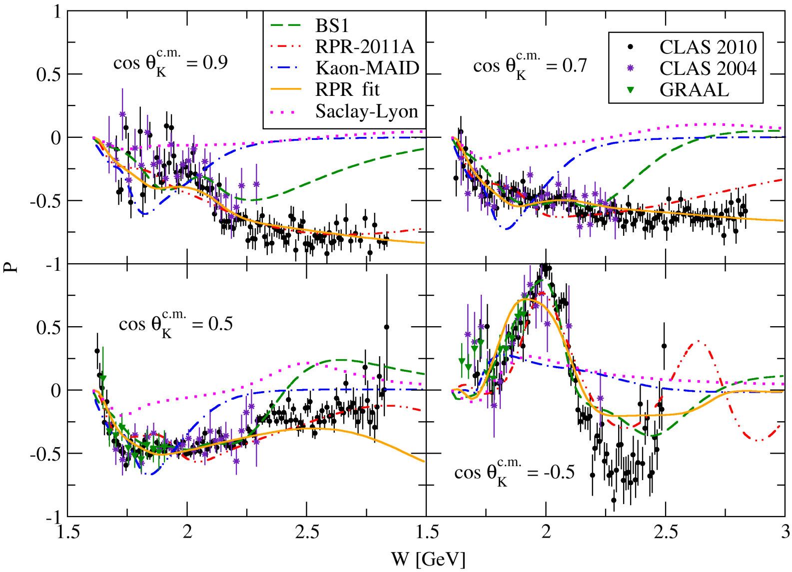
Energy dependence of the cross section for $p(\gamma, K^+)\Lambda$



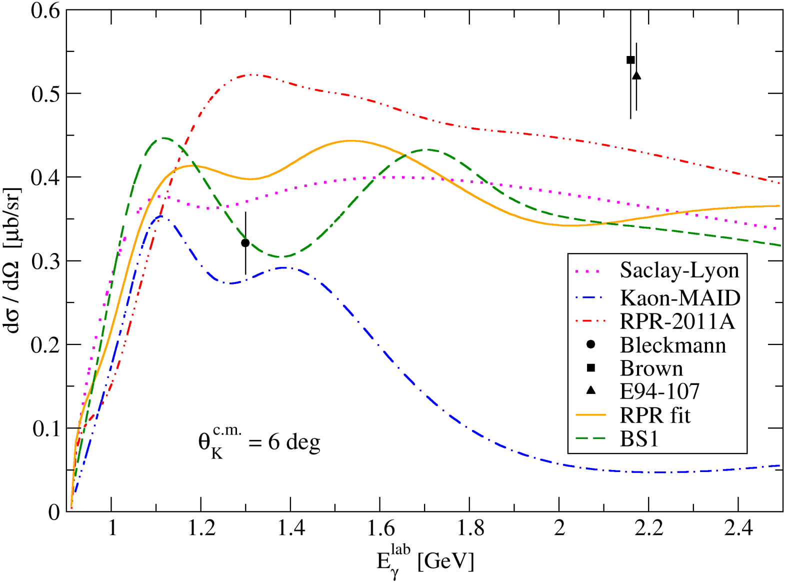
Angular dependence of the cross section for $p(\gamma, K^+)\Lambda$



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



Predictions of $d\sigma/d\Omega$ for $p(\gamma, K^+)\Lambda$ at $\theta_K^{c.m.} = 6^\circ$



Summary

- new isobar models BS1 and BS2 constructed using the consistent formalism for spin-3/2 and spin-5/2 resonances
- $Y^*(3/2)$ resonances were found to play an important role in depiction of the background part of the amplitude
- the set of N^* chosen in our analysis agrees well with the one selected in the robust Bayesian analysis with RPR model
    - missing resonances $P_{13}(1900)$ and $D_{13}(1875)$ are needed for data description in our models
    - we have found that $F_{15}(1860)$ is preferred to $P_{11}(1880)$
- preliminary fit with the RPR model including consistent high-spin formalism provides a reliable description of data in the resonant and high-spin region
- predictions of various models for the cross section at small kaon angles differ $\rightarrow$ the data still cannot fix the models fully

Outlook

- inclusion of energy-dependent widths of N^* (partial restoration of unitarity)
- extension of the isobar model towards the electroproduction of $K^+\Lambda$
- testing the models in the DWIA calculations exploiting data on hypernucleus production