Electromagnetic Production of Strange and Charm Mesons off Protons

Dalibor Skoupil
(with P. Bydžovský, A. Cieplý, and Y. Yamaguchi)

Nuclear Physics Institute, Czech Academy of Sciences, Řež, Czech Republic

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Motivation

- We aim at understanding the baryon spectrum and production dynamics of particles with strangeness at low energies.
- Constituent Quark Model predicts a lot more N^* states than was observed in pion production experiments $\rightarrow$ “missing” resonance problem.
- Models for the description of elementary hyperon electroproduction are a suitable tool for hypernuclear physics calculations.
- New good-quality photoproduction data from LEPS, GRAAL, MAMI and (particularly) CLAS collaborations allow us to tune free parameters of the models (not only in the $K^+\Lambda$ channel).
- As the α_s increases with decreasing energy, we cannot use perturbative QCD at low energies $\rightarrow$ the need for introducing effective theories and models.

Introduction

Methods of description of the $K^+\Lambda$ production

Quark models (Prog. Part. Nucl. Phys. **45**, S241 (2000))

- quark degrees of freedom; only a few free parameters
- contributions of resonances arise naturally as excited states of the quark system
- “missing” resonance problem

Multi-channel analysis

- rescattering effects in the meson-baryon final-state system included;
  but the experimental information on some amplitudes is missing, *e.g.* $K^+\Lambda \to K^+\Lambda$
- chiral unitary models (chiral $\mathcal{L}_{eff}$, threshold region only; Nucl. Phys. A **62** (1997) 297)
- unitary isobar approach with rescattering in the final state
  (Phys. Lett. B **57**, 101 (2001), Phys. Rev. C **59**, 460 (1999))

Single-channel analysis

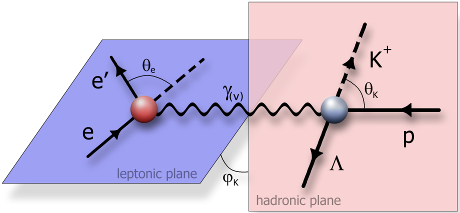
- simplification: tree-level approximation; use of $\mathcal{L}_{eff}$, inner structure of hadrons described with help of hadron form factors
- isobar model
  Saclay-Lyon, Kaon-MAID, Gent IM, Maxwell, Mart *et al.*; Adelseck, Saghai; Williams, Ji, Cotanch
- Regge-plus-resonance model
  RPR-2007 (Phys. Rev. C 75, 045204 (2007)), RPR-2011 (Phys. Rev. C 86, 015212 (2012))

Introduction

Electroproduction process

$e + N \to e' + K + Y$

- 6 channels: $N = p,\ n;\ K = K^+,\ K^0;\ Y = \Lambda,\ \Sigma^0,\ \Sigma^+, \Sigma^-$
- One-photon exchange approximation allows to separate the leptonic from the hadronic part of the process.
- We study only the $K^+\Lambda$ final state:
  - in other channels with Σ hyperons in the final state we would need to assume also Δ resonances
  - the $K^+\Lambda$ final state is the most abundant one in experimental data



Differential cross section of electroproduction for unpolarized electrons and baryons

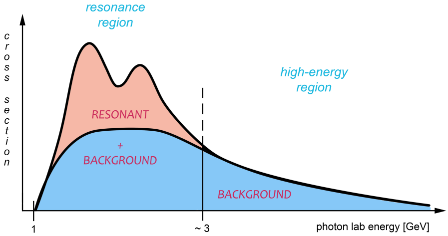
$$\frac{d^3\sigma^{\text{unpol}}}{dE_{e'}\,d\Omega_{e'}\,d\Omega_K^{c.m.}} = \Gamma\left[\sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos(2\varphi_K) + \sqrt{2\varepsilon_L(\varepsilon+1)}\sigma_{LT}\cos\varphi_K\right]$$

Introduction

Photoproduction process

$$p(p) + \gamma(k) \to K^+(p_K) + \Lambda(p_\Lambda)$$

- Photoproduction: a special case of electroproduction with $Q^2 = 0$, $\varphi_K = 0 \Rightarrow \sigma = \sigma_T$.
- Threshold: $E_\gamma^{lab} = 0.911\,\text{GeV}$, $W = 1.609\,\text{GeV}$; $p(\gamma, K^+)\Lambda$ occurs on the hadronic plane.
- In the lowest order, the reaction is described by the exchange of hadrons.
  - *The 3rd nucleon-resonance region:* many resonant states and none of them dominates the $K^+\Lambda$ production (unlike in π or η photoproduction) $\to$ we assume a large number of nucleon resonances with mass $< 2\,\text{GeV}$



- Resonance region:
  resonance contributions dominate (N^*)
- Background:
  - IM: a plenty of nonresonant contributions (p, K, Λ; K^* and Y^*)
  - RPR: exchange of kaon trajectories

Introduction

An overview of assumed resonances and their occurrence in models used for $p(\gamma, K^+)\Lambda$ description

	mass [MeV]	width [MeV]	spin	isospin	parity	*Kaon-MAID*	*Saclay-Lyon*	*Gent IM*	*BS1*	*BS2*	*BS3*	*RPR-2011*	*RPR fit*	*RPR-BS*	*RPR-BSpv*
$K^*(892)$	892	50	1	1/2	$-$	✓	✓	✓	✓	✓	✓				
$K_1(1270)$	1270	90	1	1/2	$+$	✓	✓	✓	✓	✓	✓				
$P_{11}(1440)$	1440	300	1/2	1/2	$+$		✓								
$S_{11}(1535)$	1535	150	1/2	1/2	$-$				✓	✓	✓	✓	✓	✓	✓
$S_{11}(1650)$	1655	150	1/2	1/2	$-$	✓		✓	✓	✓	✓	✓	✓	✓	✓
$D_{15}(1675)$	1675	150	5/2	1/2	$-$		✓						✓	✓	
$F_{15}(1680)$	1685	130	5/2	1/2	$+$				✓	✓	✓	✓	✓	✓	✓
$D_{13}(1700)$	1700	150	3/2	1/2	$-$								✓	✓	✓
$P_{11}(1710)$	1710	100	1/2	1/2	$+$	✓		✓	✓		✓				
$P_{13}(1720)$	1720	250	3/2	1/2	$+$	✓	✓	✓	✓	✓	✓	✓		✓	✓
$F_{15}(1860)$	1860	270	5/2	1/2	$+$				✓	✓	✓		✓	✓	✓
$D_{13}(1875)$	1875	220	3/2	1/2	$-$	✓		✓	✓	✓	✓	✓	✓	✓	✓
$P_{11}(1880)$	1870	235	1/2	1/2	$+$								✓		✓
$P_{11}(1900)$	1895	200	1/2	1/2	$+$							✓			
$P_{13}(1900)$	1900	250	3/2	1/2	$+$						✓	✓	✓	✓	✓
$F_{15}(2000)$	2000	140	5/2	1/2	$+$				✓	✓	✓	✓		✓	✓
$D_{13}(2120)$	2120	330	3/2	1/2	$-$						✓		✓		✓
$D_{15}(2570)$	2570	250	5/2	1/2	$-$									✓	
$\Lambda(1405)$	1405	50	1/2	0	$-$		✓			✓	✓				
$\Lambda(1520)$	1520	16	3/2	0	$-$				✓						
$\Lambda(1600)$	1600	150	1/2	0	$+$						✓				
$\Lambda(1800)$	1800	300	1/2	0	$-$				✓	✓					
$\Lambda(1810)$	1810	150	1/2	0	$+$		✓								
$\Lambda(1890)$	1890	100	3/2	0	$+$				✓		✓				
$\Sigma(1660)$	1660	100	1/2	1	$+$		✓		✓	✓					
$\Sigma(1670)$	1670	60	3/2	1	$-$						✓				
$\Sigma(1750)$	1750	90	1/2	1	$-$				✓						
$\Sigma(1940)$	1940	220	3/2	1	$-$				✓	✓					

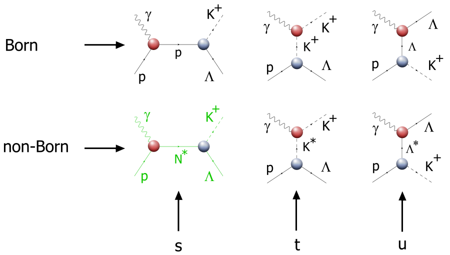
Isobar model

Single-channel approximation

- higher-order contributions (rescattering, FSI) included, to some extent, by means of effective values of the 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*) exchange
  - **resonance part**: *s*-channel Feynman diagram with N^* exchanges



Free parameters adjusted to experimental data

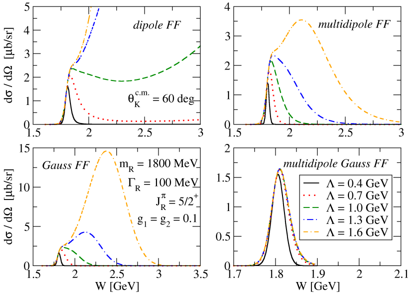
Satisfactory agreement with the data in the energy range $E_\gamma^{lab} = 0.91 - 2.8\,\text{GeV}$

Isobar model

Hadronic form factors

Hadrons have inner structure, vertices thus cannot be treated as point-like interactions

- dipole hff:
  $$F_d(x) = \frac{\Lambda^4}{\Lambda^4 + (x - m_x^2)^2}, \quad x = s, t, u$$
- multidipole hff (PR C **93**, 025204 (2016)):
  $$F_{md}(x) = F_d^{J+1/2}(x)$$
- Gaussian hff: $F_G(x) = \exp\left(-\frac{(x - m_x^2)^2}{\Lambda^4}\right)$
- multidipole-Gaussian hff (PR C **84**, 045201 (2011)):



$$F_{\mathrm{mdG}}(x) = \left[\frac{m_x^2 \tilde{\Gamma}^2}{(x - m_x^2)^2 + m_x^2 \tilde{\Gamma}^2}\right]^{J-1/2} F_G(x), \quad \tilde{\Gamma}(J) = \frac{\Gamma}{\sqrt{2^{1/2J} - 1}}$$

- hff introduces a dependency on value of the cut-off parameter Λ
- Davidson-Workman method used (PR C **63**, 025210 (2001))

$$\hat{F} = F_s(s) + F_t(t) - F_s(s) F_t(t)$$

$$F_s(s = m_p^2) = F_t(t = m_K^2) = 1, \quad \hat{F}(s = m_p^2, t) = \hat{F}(s, t = m_K^2) = 1$$

Isobar model

Exchanges of spin-3/2 and spin-5/2 resonant states

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

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

  allows non physical contributions of lower-spin components

$$P^{(1/2)}_{22,\mu\nu} = \frac{q_\mu q_\nu}{q^2}, \qquad P^{(1/2)}_{12,\mu\nu} = \frac{q^\rho q_\nu \sigma_{\mu\rho}}{\sqrt{3}q^2}, \qquad P^{(1/2)}_{21,\mu\nu} = \frac{q_\mu q^\rho \sigma_{\rho\nu}}{\sqrt{3}q^2}$$

- non physical contributions can be removed by an appropriate choice of $\mathcal{L}_{int}$
  (PR D **58** (1998) 096002, PR C **84** (2011) 045201)

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

- strong momentum dependence from the vertices ($\sim q^{2n}$ for spin-$(n+1/2)$ resonance)
  - helps regularize the amplitude
  - creates non physical structures in the cross section $\rightarrow$ strong HFF needed

- transversality of the vertices enables the inclusion of $Y^*(3/2)$

Isobar model

Energy-dependent decay widths of the N^*'s

- unitarity violated in a single-channel calculation
- energy-dependent width in the resonance propagator $\Rightarrow$ restoration of unitarity
- the energy dependence of the width Γ given by the possibility of a resonance to decay into various open channels
- prescrpition taken over from the Kaon-MAID model:

  (PR C **61** 012201(R) (1999))

	$N\pi$	$N\pi\pi$	$N\eta$	$K\Lambda$
$P_{11}(1440)$	0.64	0.35	0.01	0.00
$S_{11}(1535)$	0.50	0.08	0.42	0.00
$S_{11}(1650)$	0.56	0.20	0.16	0.08
$D_{15}(1675)$	0.45	0.53	0.01	0.01
$F_{15}(1680)$	0.65	0.35	0.00	0.00
$D_{13}(1700)$	0.12	0.75	0.10	0.03
$P_{11}(1710)$	0.10	0.50	0.30	0.10
$P_{13}(1720)$	0.11	0.81	0.03	0.05
$F_{15}(1860)$	–	–	–	–
$D_{13}(1875)$	0.08	0.90	0.01	0.01
$P_{11}(1880)$	0.06	0.50	0.32	0.02
$P_{13}(1900)$	0.08	0.73	0.08	0.11
$F_{15}(2000)$	0.08	0.88	0.04	0.00
$D_{13}(2120)$	0.10	0.90	0.00	0.00

Values from: Chin. Phys. C **40** (2016) 100001

$$\Gamma(\vec{q}) = \Gamma_{N^*}\frac{\sqrt{s}}{m_{N^*}}\sum_i x_i\left(\frac{|\vec{q}_i|}{|\vec{q}_i^{\,N^*}|}\right)^{2l+1}\frac{D(|\vec{q}_i|)}{D(|\vec{q}_i^{\,N^*}|)},$$

where

$$|\vec{q}_i^{\,N^*}| = \sqrt{\frac{(m_{N^*}^2 - m_b^2 + m_i^2)^2}{4m_{N^*}^2} - m_i^2},\quad |\vec{q}_i| = \sqrt{\frac{(s - m_b^2 + m_i^2)^2}{4s} - m_i^2},\quad D(\vec{q}) = \exp\left(-\frac{\vec{q}^{\,2}}{3\alpha^2}\right),$$

with $\alpha = 410\,\text{MeV}$.

Isobar model

Extension from photo- to electroproduction

Phenomenological form factors in the electromagnetic vertex

- GKex(02S) for nucleon, hyperons and their resonances (PR C **66**, 045501 (2002))
- VMD for kaon (PR C **46**, 1617 (1992))
- monopole em. f. f. for K^* and K_1 resonances (PR C **38**, 1965 (1988))
- not sufficient to describe data reliably near $Q^2 = 0$ (photoproduction point)

Longitudinal couplings of nucleon resonances to virtual photons

- balance strong Q^2 dependence from transverse couplings
- crucial for description at small Q^2

$$V^{EM}(N^*_{1/2}p\gamma) = -i\frac{g_3^{EM}}{(m_R+m_p)^2}\Gamma_\mp\,\gamma_\beta\,\mathcal{F}^\beta,$$

$$V^{EM}_\mu(N^*_{3/2}p\gamma) = -i\frac{g_3^{EM}}{m_R(m_R+m_p)^2}\gamma_5\Gamma_\mp\,(\not{q}\,g_{\mu\beta}-q_\beta\gamma_\mu)\,\mathcal{F}^\beta,$$

$$V^{EM}_{\mu\nu}(N^*_{5/2}p\gamma) = -i\frac{g_3^{EM}}{(2m_p)^5}\Gamma_\mp(q_\alpha q_\beta g_{\mu\nu}+q^2 g_{\alpha\mu}g_{\beta\nu}-q_\alpha q_\nu g_{\beta\mu}-q_\beta q_\nu g_{\alpha\mu})\,p^\alpha\,\mathcal{F}^\beta,$$

with $\Gamma_- = 1$ for negative and $\Gamma_+ = i\gamma_5$ for positive parity N^*'s and $\mathcal{F}^\beta = k^2\epsilon^\beta - k\cdot\epsilon\,k^\beta$

Isobar model

Fitting procedure: minimization of χ^2/n.d.f. with help of MINUIT code

Resonance selection

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

Hadron form factors: F_{md} and F_d preferred to F_{mdG}

Electromagnetic form factors:

- model GKex(02S) (PR C **66**, 045501 (2002)) for nucleon, hyperons and their resonances
- monopole shape for K^* and K_1 resonances

Free parameters ($\approx 30 + 10$):

- $SU(3)_f$: $-4.4 \leq g_{K\Lambda N}/\sqrt{4\pi} \leq -3.0$, $0.8 \leq g_{K\Sigma N}/\sqrt{4\pi} \leq 1.3$
- 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 hff
- 1 longitudinal coupling for each N^*
- 2 cut-off parameters for the emff of K^* and K_1

3383 $p(\gamma, K^+)\Lambda$ data

- 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)

171 $p(e, e'K^+)\Lambda$ data

- $\sigma_U, \sigma_T, \sigma_L, \sigma_{LT'}, \sigma_K$

Isobar model

Results of the fitting procedure

Solutions: BS1 and BS2, $\chi^2/\text{n.d.f.} = 1.64$ for both
(constant widths of N^*'s; fit on $p(\gamma, K^+)\Lambda$ data; detailed in PR C **93** (2016) 025204),
and BS3, $\chi^2/\text{n.d.f.} = 1.74$ (energy-dependent widths of N^*'s; fit on $p(\gamma, K^+)\Lambda$ ($\chi^2/\text{n.d.f.} = 1.51$) and $p(e, e' K^+)\Lambda$ data; PR C **97** (2018) 025202)

- χ^2's, fitted parameter values (smallness) and correspondence with data taken into account
- sets of N^*'s in BS models similar to N^* sets found by Gent group in Bayesian analysis
- sets of chosen Y^* differ in all BS models $\rightarrow$ different description of background
  - inclusion of Y^*: larger values of cutoff parameters
  - inclusion of $Y^*(3/2) \Rightarrow$ much lower coupling constants of $Y^*(1/2)$
- electromagnetic form factors of K^* and K_1: crucial for $Q^2 > 2\,(\text{GeV}/c)^2$

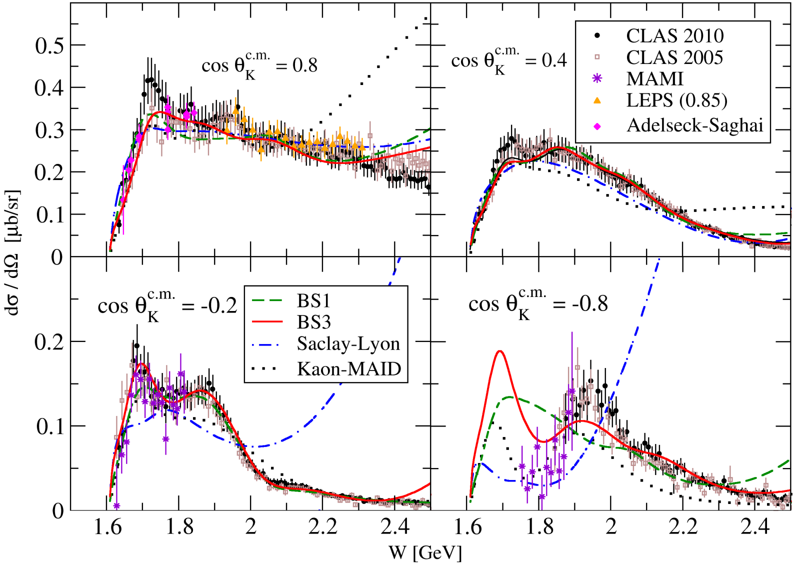
BS1 model

- $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{13}(1720)$, $F_{15}(1860)$, $D_{13}(1875)$, $F_{15}(2000)$;
- $K^*(892)$, $K_1(1272)$;
- $\Lambda(1520)$, $\Lambda(1800)$, $\Lambda(1890)$, $\Sigma(1660)$, $\Sigma(1750)$, $\Sigma(1940)$;
- multidipole form factor: $\Lambda_{bgr} = 1.88\,\text{GeV}$, $\Lambda_{res} = 2.74\,\text{GeV}$

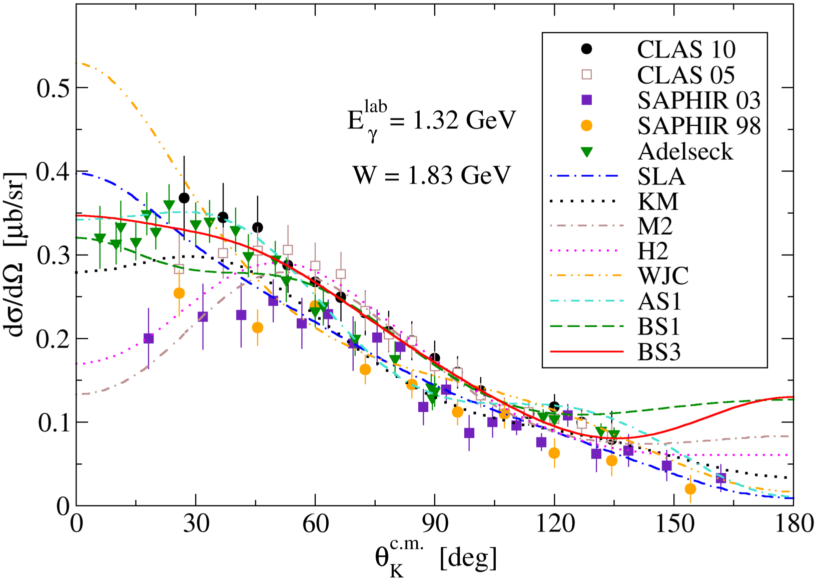
BS3 model

- $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{11}(1710)$, $P_{13}(1720)$, $F_{15}(1860)$, $D_{13}(1875)$, $P_{13}(1900)$, $F_{15}(2000)$, $D_{13}(2120)$;
- $K^*(892)$, $K_1(1272)$;
- $\Lambda(1405)$, $\Lambda(1600)$, $\Lambda(1890)$, $\Sigma(1670)$;
- dipole form factor: $\Lambda_{bgr} = 1.24\,\text{GeV}$, $\Lambda_{res} = 0.89\,\text{GeV}$

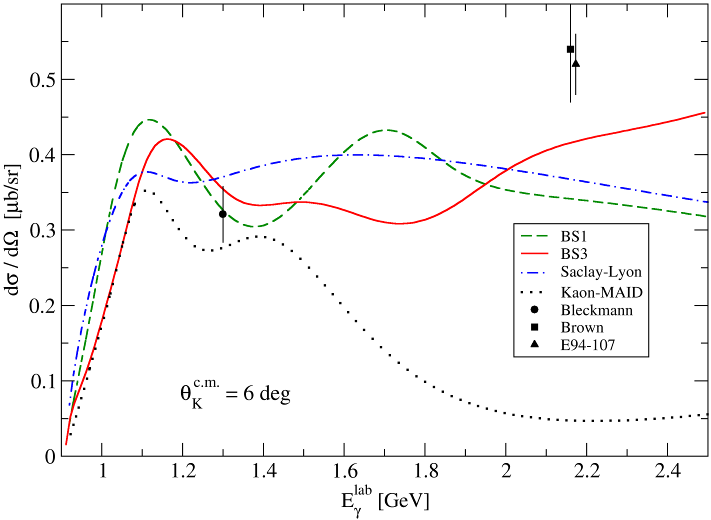
Energy dependence of the cross section for $p(\gamma, K^{+})\Lambda$



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

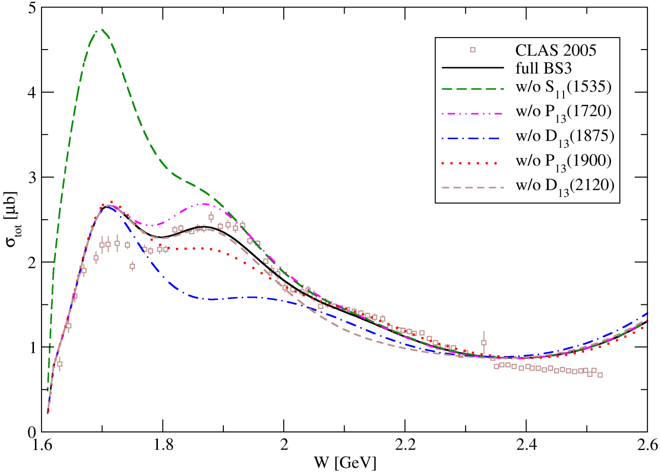


Predictions of $d\sigma/d\Omega$ for $p(\gamma, K^+)\Lambda$ at $\theta_K^{c.m.} = 6^\circ$



- Brown [$Q^2 = 0.18\,(\text{GeV}/c)^2$] & E94-107 [$Q^2 = 0.07\,(\text{GeV}/c)^2$]: data for $p(e, e'K^+)\Lambda$ but: $\sigma_L \sim Q^2$, $\sigma_{TT} \sim \sin^2\theta_K^{c.m.}$, and $\sigma_{LT} \sim \sqrt{Q^2}\sin\theta_K^{c.m.} \Rightarrow \sigma \approx \sigma_T$

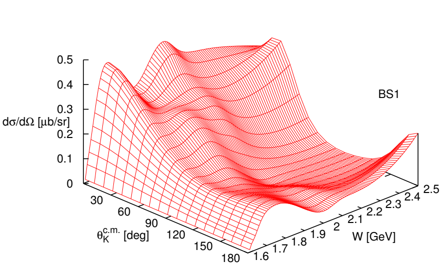
Total cross section prediction of the BS3 model

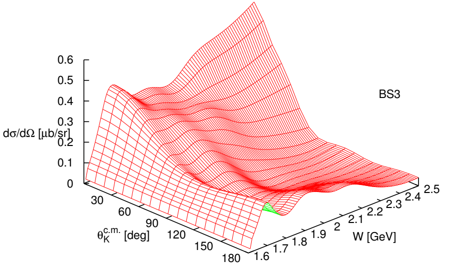


	$\Delta\chi^2$ [%]		$\Delta\chi^2$ [%]
$S_{11}(1535)$	331	$P_{13}(1900)$	826
$S_{11}(1650)$	81	$F_{15}(2000)$	30
$P_{11}(1710)$	43	$D_{13}(1875)$	844
$P_{13}(1720)$	188	$F_{15}(1860)$	82
$F_{15}(1680)$	202	$D_{13}(2120)$	125

$$\Delta\chi^2 = \frac{\chi^2_{N*} - \chi^2}{\chi^2} \cdot 100\%,$$

Description of the resonance region by BS1 and BS3 models





BS1 model

- $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{13}(1720)$, $F_{15}(1860)$, $D_{13}(1875)$, $F_{15}(2000)$;
- $K^*(892)$, $K_1(1272)$;
- $\Lambda(1520)$, $\Lambda(1800)$, $\Lambda(1890)$, $\Sigma(1660)$, $\Sigma(1750)$, $\Sigma(1940)$;
- multidipole form factor:

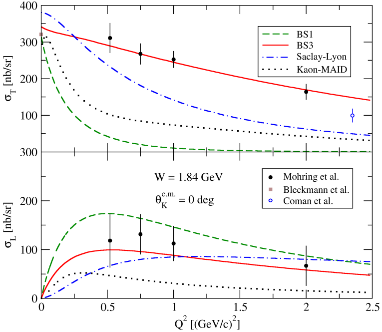
  $\Lambda_{bgr} = 1.88\,\text{GeV}$, $\Lambda_{res} = 2.74\,\text{GeV}$

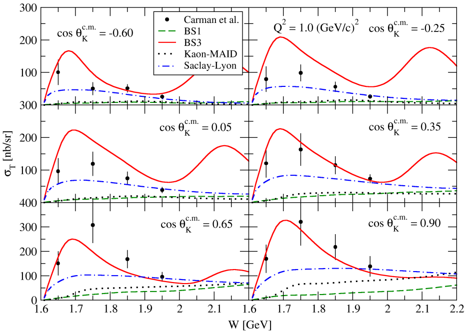
BS3 model

- $S_{11}(1535)$, $S_{11}(1650)$, $F_{15}(1680)$, $P_{11}(1710)$, $P_{13}(1720)$, $F_{15}(1860)$, $D_{13}(1875)$, $P_{13}(1900)$, $F_{15}(2000)$, $D_{13}(2120)$;
- $K^*(892)$, $K_1(1272)$;
- $\Lambda(1405)$, $\Lambda(1600)$, $\Lambda(1890)$, $\Sigma(1670)$;
- dipole form factor:

  $\Lambda_{bgr} = 1.24\,\text{GeV}$, $\Lambda_{res} = 0.89\,\text{GeV}$

Transverse, σ_T, and longitudinal, σ_L, cross sections of $p(e, e'K^+)\Lambda$





Extension from photo- to electroproduction

- BS1: naive extension by adding em. form factors only
- BS3: em. form factors and longitudinal couplings of N^*'s to γ^* added

Regge-plus-resonance model (PR C **73**, 045207 (2006))

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

- **background part**: exchanges of degenerate $K(494)$ and $K^*(892)$ trajectories

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

  - only 3 free parameters ($g_{K\Lambda N}$, $G^{(v)}_{K^*}$, $G^{(t)}_{K^*}$)
  - gauge-invariance restoration: "GLV method" - inclusion of the Reggeized electric part of the s-channel Born term (Nucl. Phys. A **627** (1997) 645-678)
  - strong criticism (PR C **92**, 055503 (2015)): "GLV method" successful in providing good descriptions of data, but there is no dynamical foundation for it
    $\rightarrow$ inclusion of contact term proposed

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

  - 6 free parameters ($g_{K\Lambda N}$, $G^{(v)}_{K^*}$, $G^{(t)}_{K^*}$, Λ_{bgr}, Λ_c, A_0)

- **resonant part**: inclusion of resonant s-channel diagrams with Feynman propagators

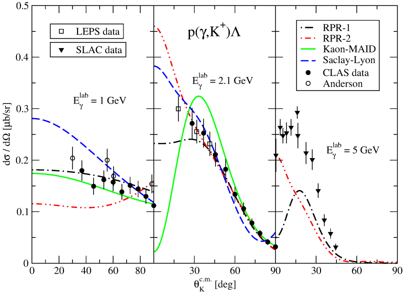
Fitting procedure

- less parameters to optimize (≈ 20) & more data available (≈ 4500) than in the isobar model

For details see: P. Bydžovský, D. Skoupil, Phys. Rev. C **100**, 035202 (2019)

Regge-plus-resonance model (GLV method for GI restoration)

Cross-section predictions on small $\theta_K^{c.m.}$

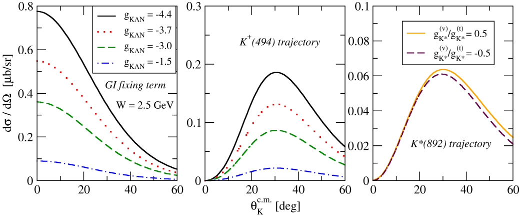


RPR-1 & RPR-2 (Nucl. Phys. A **914** (2013) 14-22)

- inconsistent formalism for $N^*(3/2)$ and $N^*(5/2)$
- fitted on LEPS and CLAS $d\sigma/d\Omega$ data:
  - RPR-1 fitted on all angles $\theta_K^{c.m.}$; $g_{K\Lambda N} = -1.45$, $g_{K^*}^{(v)}/g_{K^*}^{(t)} \approx -0.5$
  - RPR-2 fitted only on $\theta_K^{c.m.} < 90^\circ$; $g_{K\Lambda N} = -3.00$, $g_{K^*}^{(v)}/g_{K^*}^{(t)} \approx 0.5$

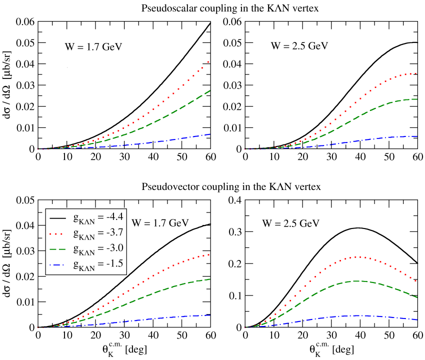
RPR-fit (D.S., PhD Thesis, 2016)

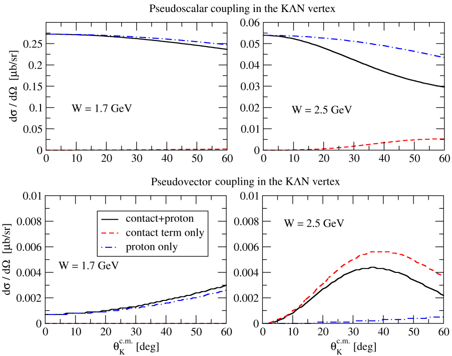
- consistent formalism for $N^*(3/2)$ and $N^*(5/2)$
- $\mathrm{d}\sigma/\mathrm{d}\Omega$ at small $\theta_K^{c.m.}$: the effect of $g_{K\Lambda N}$ much larger than the effect of $g_{K^*}^{(v)}/g_{K^*}^{(t)}$ ratio



Regge-plus-resonance model

Cross sections at small $\theta_K^{c.m.}$ within the new GI restoration scheme

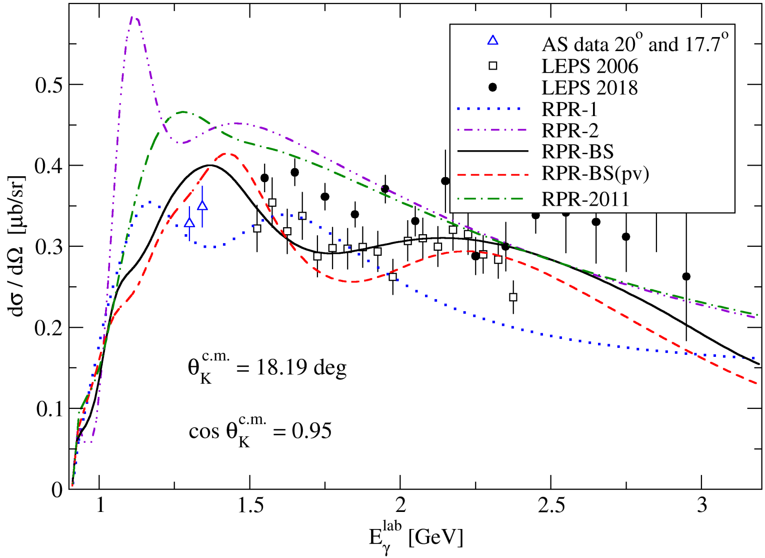




- left figure: Regge trajectories only; right figure: contact-term and proton-exchange contributions
- contributions of contact term in combination with proton exchange differ in PS and PV couplings
- proton exchange suppressed by the hff (hff not present in the GLV scheme)

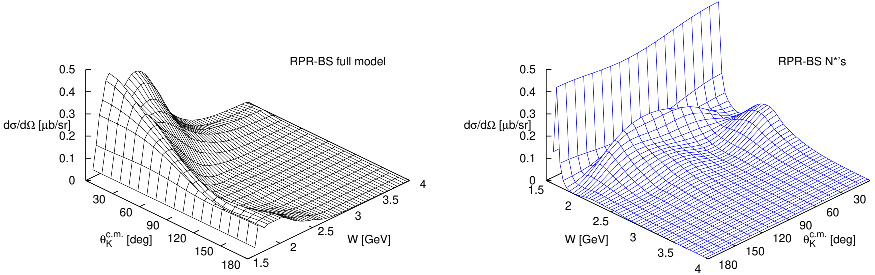
Regge-plus-resonance model

Cross sections at small $\theta_K^{c.m.}$ and the LEPS data



Regge-plus-resonance model: RPR-BS

Detailed in Phys. Rev. C **100**, 035202 (2019)



RPR-BS model

- selected N^*'s: $S_{11}(1535)$, $S_{11}(1650)$, $D_{13}(1700)$, $P_{13}(1720)$, $D_{15}(1875)$, $F_{15}(1680)$, $P_{13}(1900)$,$F_{15}(2000)$, $D_{13}(1875)$, $F_{15}(1860)$, $D_{15}(2570)$
- fixed decay widths of nucleon resonances
- multidipole hadron form factor: $\Lambda_{bgr} = 1.96\,\text{GeV}$, $\Lambda_N = 1.97\,\text{GeV}$
- 4358 data points for adjusting 26 free parameters
- $\chi^2/\text{n.d.f.} = 1.69$

Preliminary calculations of $K^0\Lambda$ production on the neutron

s channel

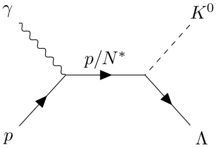
- $V^\mu_{EM}(k) = F^n_1(k)\gamma^\mu + i\frac{F^n_2(k)}{2m_n}\sigma^{\mu\nu}k_\nu$
- $F^n_1(0) = 0,\ F^n_2(0) = \kappa_n\ \Rightarrow$ electric part vanishes; magnetic interaction only

t channel

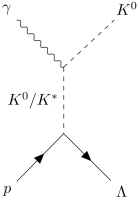
- $V^\mu_{EM} = -iQ_{K^0}(2p_K - k)^\mu$
- $Q_{K^0} = 0\ \Rightarrow$ no *t*-channel exchange contribution

u channel

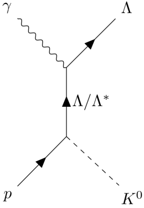
- $V^\mu_{EM}(k) = F^\Lambda_1(k)\gamma^\mu + i\frac{F^\Lambda_2(k)}{2m_\Lambda}\sigma^{\mu\nu}k_\nu$
- exchange of a neutral Λ baryon $\Rightarrow\ F^\Lambda_1(0) = 0,\ F^\Lambda_2(0) = \kappa_\Lambda\ \Rightarrow$ magnetic interaction only



s channel



t channel



u channel

Preliminary calculations of $K^0\Lambda$ production on the neutron

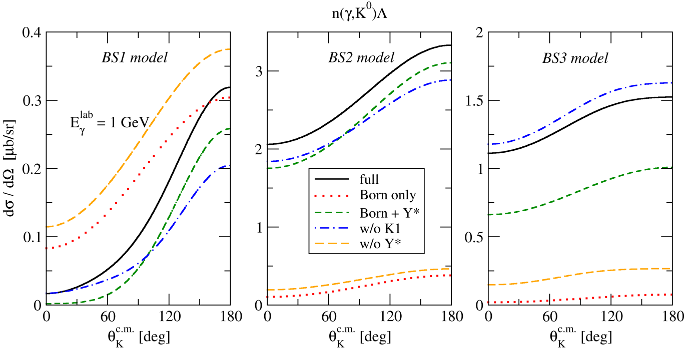
SU(2) isospin symmetry in the strong vertex

- $g_{K^{(*)+}\Lambda p} = g_{K^{(*)0}\Lambda n}$, $g_{K^{*(0)}\Lambda N^{*0}} = g_{K^{(*)+}\Lambda N^{*+}}$

Relations between electromagnetic couplings stem from experimental information

- helicity amplitudes $\mathcal{A}^N_{1/2}$, $\mathcal{A}^N_{3/2}$

Unknown parameter $r_{K_1 K\gamma} = g_{K_1^0 K^0 \gamma}/g_{K_1^+ K^+ \gamma}$ fitted to the data (KM: $r_{K_1 K\gamma} = -0.45$)



New fits for $K^+\Sigma^-$ channel

P. Bydžovský, A. Cieplý, D. Skoupil for CLAS Collaboration

Fitting procedure

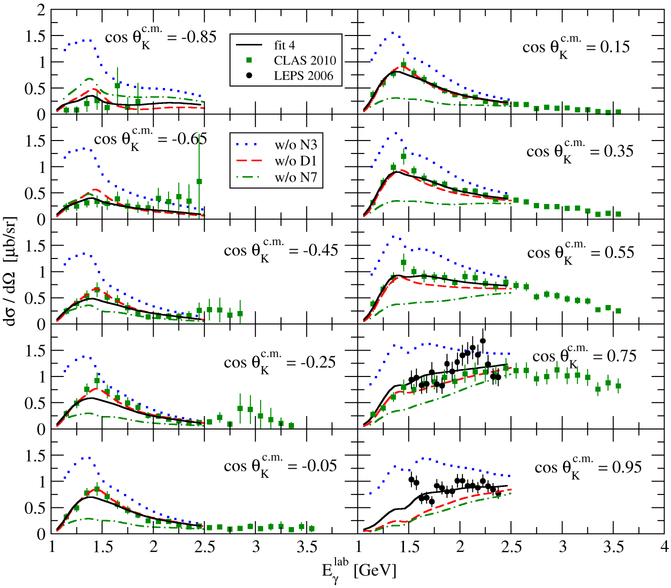
- non resonant part modelled by Born terms and exchanges of K^* and K_1 (t channel) and Σ^* (u channel)
- resonant part modelled by exchanges of nucleon and Δ resonances in the s channel (partly motivated by previous analyses)
- around 600 CLAS and LEPS data on $d\sigma/d\Omega$ and Σ (restricted up to $E_\gamma^{lab} = 2.6\,\mathrm{GeV}$) utilized to fit 24 free parameters
- the main coupling, $g_{K^+\Sigma^-n} = \sqrt{2}g_{K^+\Sigma^0p} = 1.568$, taken from $K^+\Lambda$ channel
- a variant with the smallest $\chi^2/\mathrm{ndf} = 2.39$ and reasonable values of parameters was selected

Model characteristics

- only one Δ resonance introduced
- no hyperon resonances needed for reliable data description
- results in very good agreement with the cross-section and beam asymmetry data

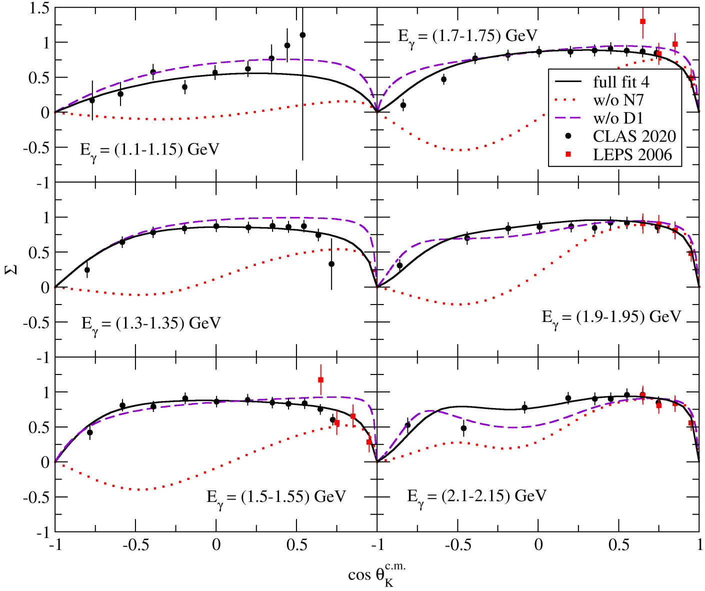
New fits for $K^+\Sigma^-$ channel

Differential cross section against kaon photon lab energy



New fits for $K^+\Sigma^-$ channel

Beam asymmetry against kaon center-of-mass angle

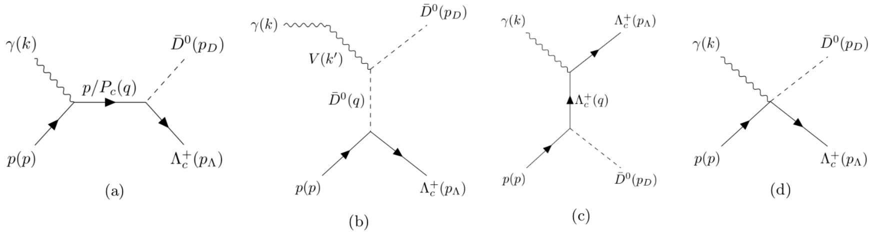


Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

D. Skoupil and Y. Yamaguchi; manuscript accepted for publication in Phys. Rev. D

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

- **background part**: exchanges of $\bar{D}^0(1864)$ or Λ_c^+ trajectories in the t or u channels, respectively
  - interchanging the Feynman propagator with the Regge one: $\mathbb{M}_{Regge} = \beta_X \mathcal{P}_R^X(\alpha_X(x))$
  - in the strong vertex we consider either PS or PV coupling
  - VMD in the γDD vertex: $V_\mu^{EM} = -iC^{(model)}(2p_D - k)_\mu,$
- **resonant part**: exchanges of P_c's in the s-channel diagrams with Feynman propagators; $P_c^+(4312)1/2^-$, $P_c^+(4440)3/2^-$, $P_c^+(4457)1/2^-$
- **gauge invariance**: introduction of the contact term and the proton exchange in the s channel



Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

Gauge invariance in the t channel

The gauge-breaking term in the t-channel $\bar{D}^0$-meson exchange (both PS and PV couplings)

$$\mathbb{M}_{\bar{D}^0} = \bar{u}(p_\Lambda)\gamma_5 f_t(t)\left[\mathcal{A}_2\mathcal{M}_2 + \mathcal{A}_3\mathcal{M}_3 - C^{(model)} g_{D\Lambda_c^+ N}\frac{k\cdot\varepsilon}{k^2}\right]u(p).$$

The minimal contact current, $\mathbb{M}^\mu_{int} = m^\mu_c f_t(t) + V_S C^\mu$, fulfils

$$k_\mu \mathbb{M}^\mu_{int} = Q_D F_t + Q_{\Lambda_c^+} F_u - F_s Q_p,$$

where $Q_D = C^{(model)}$, model = SU(4), QCDSR, QM, $Q_{\Lambda_c^+} = Q_p = e$.
F_x, $x = s, t, u$, denote the vertex factors in the s, t, and u channels, respectively.

- **PS coupling:** $F_t = F_u = F_s = g_{D\Lambda_c^+ N}\gamma_5$, thus

$$k_\mu \mathbb{M}^\mu_{int} = k_\mu m^\mu_c = C^{(model)} g_{D\Lambda_c^+ N}\gamma_5 \frac{k^\mu k_\mu}{k^2} \quad \Rightarrow \quad m^\mu_c \varepsilon_\mu(k) f_t(t) = C^{(model)} g_{D\Lambda_c^+ N} f_t(t)\gamma_5 \frac{k\cdot\varepsilon}{k^2}.$$

- **PV coupling:** $V^{PV}_S = -g'_{D\Lambda_c^+ N}\, \not{D}\gamma_5$; $F_t = -g'_{D\Lambda_c^+ N}(\not{p} - \not{p}_\Lambda)\gamma_5$ and $F_u = F_s = -g'_{D\Lambda_c^+ N}\, \not{p}_D\gamma_5$, where $g'_{D\Lambda_c^+ N} = g_{D\Lambda_c^+ N}/(m_\Lambda + m_p)$. Analogously to PS coupling:

$$m^\mu_c \varepsilon_\mu(k) f_t(t) = -C^{(model)} g'_{D\Lambda_c^+ N} f_t(t)(\not{p} - \not{p}_\Lambda)\gamma_5 \frac{k\cdot\varepsilon}{k^2}.$$

Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

Gauge invariance in the *u* channel

The gauge-breaking term in the *u*-channel Λ_c^+ exchange

- **PS coupling:** $\mathbb{M}_{\Lambda_c^+}^{PS,el} = -\frac{eg_{D\Lambda_c^+ N}}{u-m_\Lambda^2}\bar{u}(p_\Lambda)\gamma_5 f_u(u)\left[\cdots + (u-m_\Lambda^2)\frac{k\cdot\varepsilon}{k^2}\right]u(p)$
- **PV coupling:** $\mathbb{M}_{\Lambda_c^+}^{PV,el} = -\frac{eg'_{D\Lambda_c^+ N}}{u-m_\Lambda^2}\bar{u}(p_\Lambda)\gamma_5 f_u(u)\left[\cdots + (u-m_\Lambda^2)\frac{k\cdot\varepsilon}{k^2}(m_p + m_\Lambda + \not{k})\right]u(p)$

No VMD in the *t* channel assumed ($Q_D = 0$) $\rightarrow$ only *s* and *u* channels break GI

- The minimal contact current $\mathbb{M}_{int}^{\mu} = m_c^{\mu} f_t(t) + V_S C^{\mu}$
- The bare contact current: $k_\mu m_c^\mu = Q_{\Lambda_c^+} F_u - F_s Q_p = 0$ in PS and PV couplings
- The auxiliary current

$$C^\mu = -e\left[(2p_\Lambda - k)^\mu \frac{f_u - 1}{u - m_\Lambda^2} f_s + (2p + k)^\mu \frac{f_s - 1}{s - m_p^2} f_u\right].$$

Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

Gauge invariance in the u channel (continued)

- **PS coupling:**

$$\mathbb{M}_{int}^{PS} = \bar{u}(p_\Lambda)V_S^{PS}C^\mu\varepsilon_\mu(k)u(p)$$
$$= -eg_{D\Lambda_c^+N}\bar{u}(p_\Lambda)\gamma_5\left\{\left[2\mathcal{M}_3-(u-m_\Lambda^2)\frac{k\cdot\varepsilon}{k^2}\right]\frac{f_u-1}{u-m_\Lambda^2}f_s + \left[2\mathcal{M}_2+(s-m_p^2)\frac{k\cdot\varepsilon}{k^2}\right]\frac{f_s-1}{s-m_p^2}f_u\right\}u(p)$$

$$\mathbb{M}_p^{PS,el} = \frac{eg_{D\Lambda_c^+N}}{s-m_p^2}\bar{u}(p_\Lambda)\gamma_5 f_s(s)\left[\mathcal{M}_1+2\mathcal{M}_2+(s-m_p^2)\frac{k\cdot\varepsilon}{k^2}\right]u(p)$$

- **PV coupling:**

$$\mathbb{M}_{int}^{PV} = \bar{u}(p_\Lambda)V_S^{PV}C^\mu\varepsilon_\mu(k)u(p)$$
$$= -eg'_{D\Lambda_c^+N}\bar{u}(p_\Lambda)\gamma_5\left\{\cdots-(u-m_\Lambda^2)(m_\Lambda+m_p+\not{k})\frac{k\cdot\varepsilon}{k^2}\frac{f_u-1}{u-m_\Lambda^2}f_s + (s-m_p^2)(m_\Lambda+m_p+\not{k})\frac{k\cdot\varepsilon}{k^2}\frac{f_s-1}{s-m_p^2}f_u\right\}u(p).$$

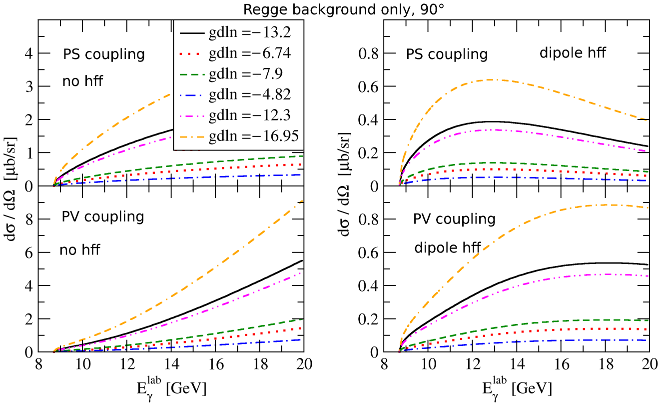
$$\mathbb{M}_p^{PV,el} = \bar{u}(p_\Lambda)\gamma_5\frac{eg'_{D\Lambda_c^+N}}{s-m_p^2}f_s(s)\left[\cdots+(s-m_p^2)(m_\Lambda+m_p+\not{k})\frac{k\cdot\varepsilon}{k^2}\right]u(p)$$

Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

Model parameters

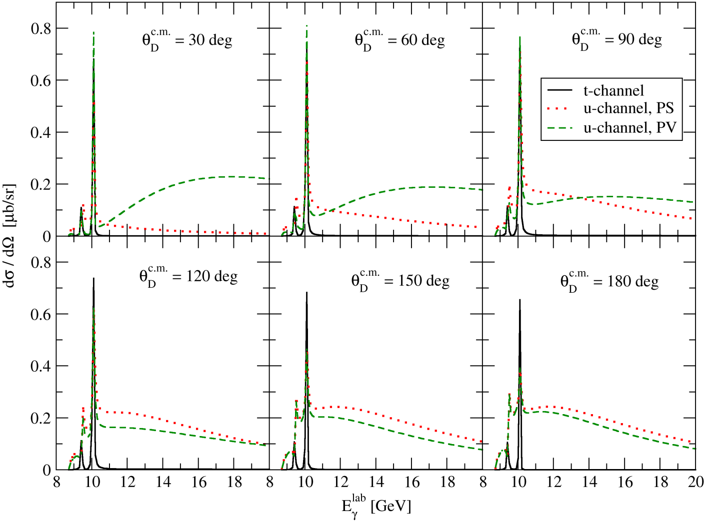
No experimental data available yet $\Rightarrow$ no fitting possible

- The main coupling, $g_{\bar{D}^0\Lambda_c N}$, obtained from SU(4) symmetry, QCD sum rules, Light-cone QCD sum rules, and Quark model
- P_c's couplings and hff cutoffs adjusted manually to get the estimated order of magnitude of cross sections



Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

Differential cross sections against photon lab energy



Summary

New versions of isobar model

- new amplitude constructed with the consistent formalism for spin-3/2 and spin-5/2 N^*'s and spin-3/2 Y^*'s
- multidipole hadron form factor introduced
- energy-dependent widths of N^* implemented
- extension of the isobar model towards the electroproduction of $K^+\Lambda$
- available for calculations online at: http://www.ujf.cas.cz/en/departments/department-of-theoretical-physics/isobar-model.html
- description extended to $K^0\Lambda$ (still in progress) and $K^+\Sigma^-$ production channels

New version of Regge-plus-resonance model

- a different scheme for gauge-invariance restoration applied, which plays significant role for cross sections at small $\theta_K^{c.m.}$
- RPR model used to predict $\bar{D}^0$-meson photoproduction

Outlook

- testing the models in the DWIA calculations exploiting data on hypernucleus production
- exploration of more reaction channels (*e.g.* $K^0\Lambda$ or $K^+\Sigma^0$)

Thank you for your attention!