On Electromagnetic Production of Strange and Charm Mesons

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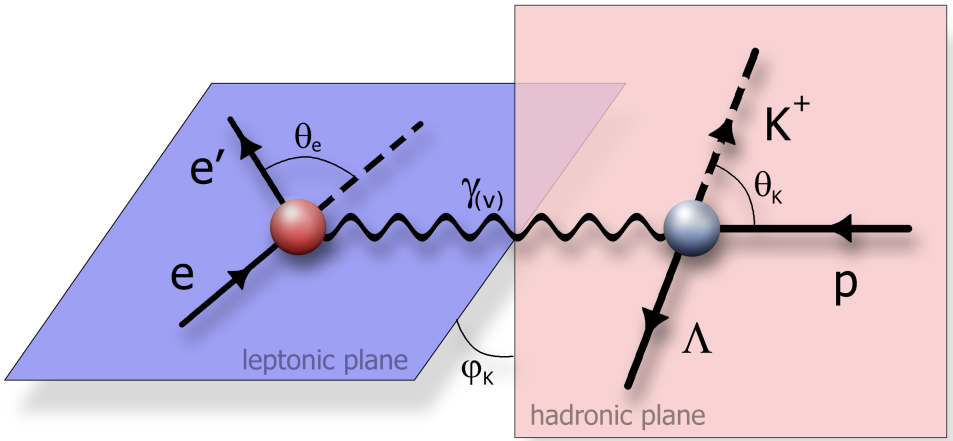
Introduction

Electroproduction process

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

- 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.
- $K^+\Lambda$ channel is the easiest one to study:
  - in other channels with Σ hyperons one needs to assume also exchanges of 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

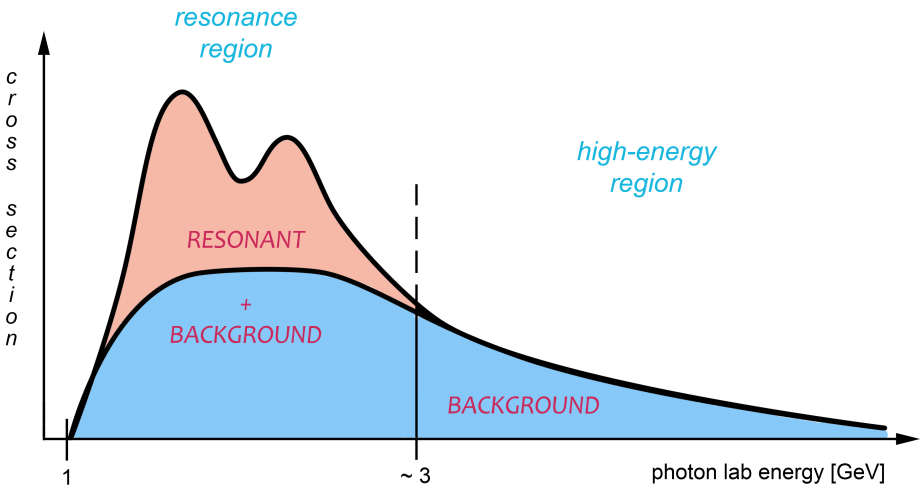
$$\frac{d^3\sigma^{\text{unpol}}}{dE_{e'}\,d\Omega_{e'}\,d\Omega_K^{c.m.}} = \Gamma\left[\sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos(2\varphi_K) + \sqrt{2\varepsilon_L(\varepsilon+1)}\sigma_{LT}\cos\varphi_K\right]$$

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 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

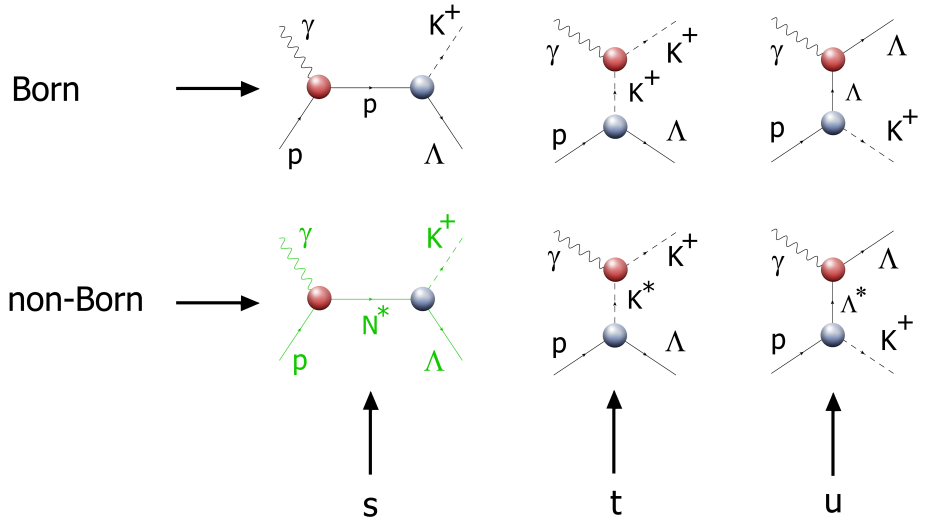
Isobar model

Single-channel approximation

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

Effective hadron Lagrangian

- hadrons either in their ground or excited states (inner structure → form factors)
- 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 $E_\gamma^{lab} = 0.91 - 2.8\,\mathrm{GeV}$

Isobar model

Novel features of our IM

Exchanges of high-spin resonant states

- non physical lower-spin components removed by appropriate choice of $\mathcal{L}_{int}$

$$V_S^{\mu}\,\mathcal{P}^{(1/2)}_{ij,\mu\nu}\,V_{EM}^{\nu} = 0$$

Energy-dependent decay widths of nucleon resonances $\rightarrow$ restoration of unitarity

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

Extension from photoproduction to electroproduction

- Phenomenological form factors in the electromagnetic vertex
- Longitudinal couplings of N^*'s to γ^* (crucial at small Q^2)

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

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

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

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
- t channel: $K^*(892)$, $K_1(1272)$
- u channel: $Y^*(1/2)$ and $Y^*(3/2)$

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

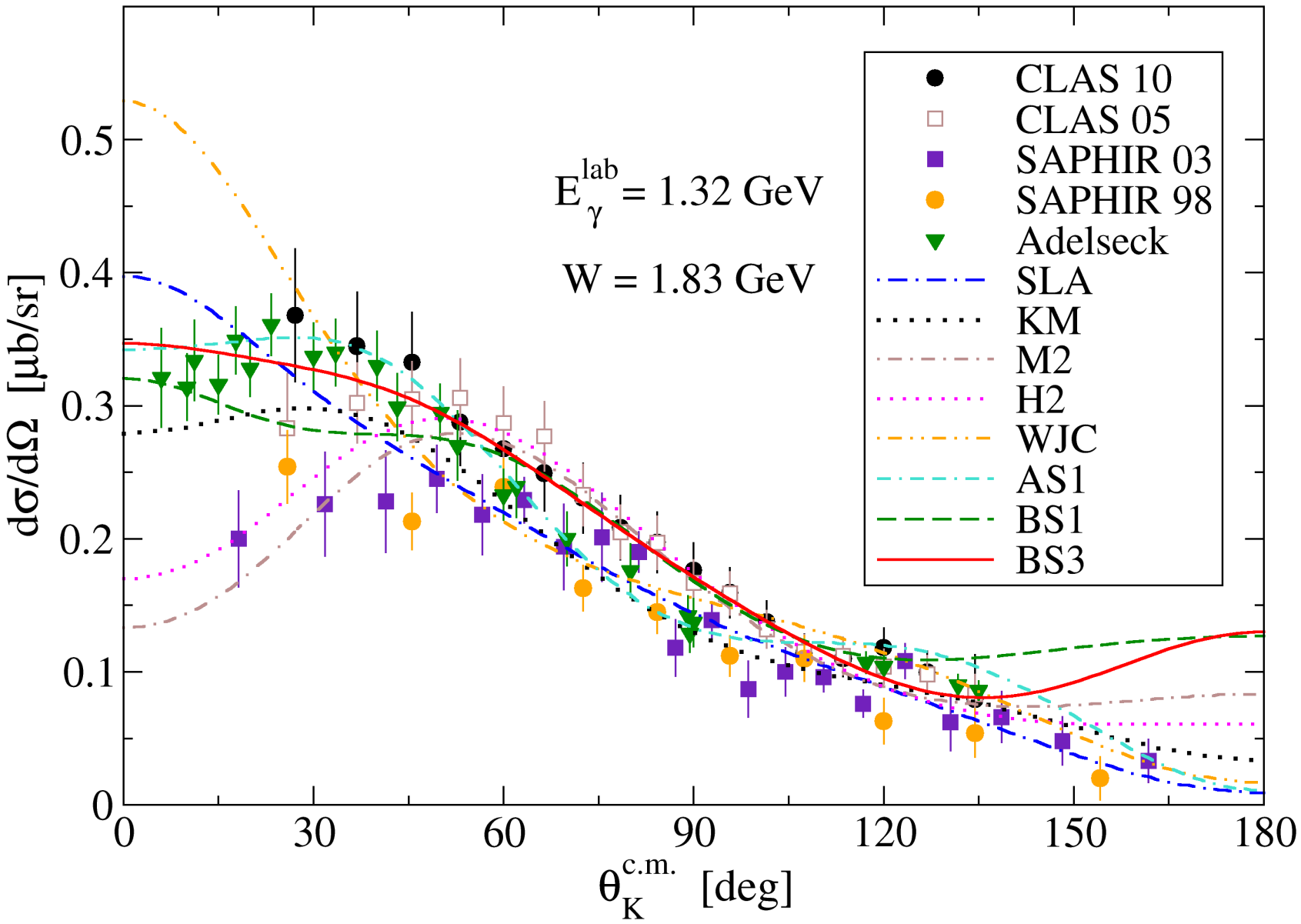
- cross section for $W < 2.355$ GeV (CLAS 2005 & 2010; LEPS, Adelseck-Saghai)
- hyperon polarisation for $W < 2.225$ GeV (CLAS 2010)
- beam asymmetry (LEPS)

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

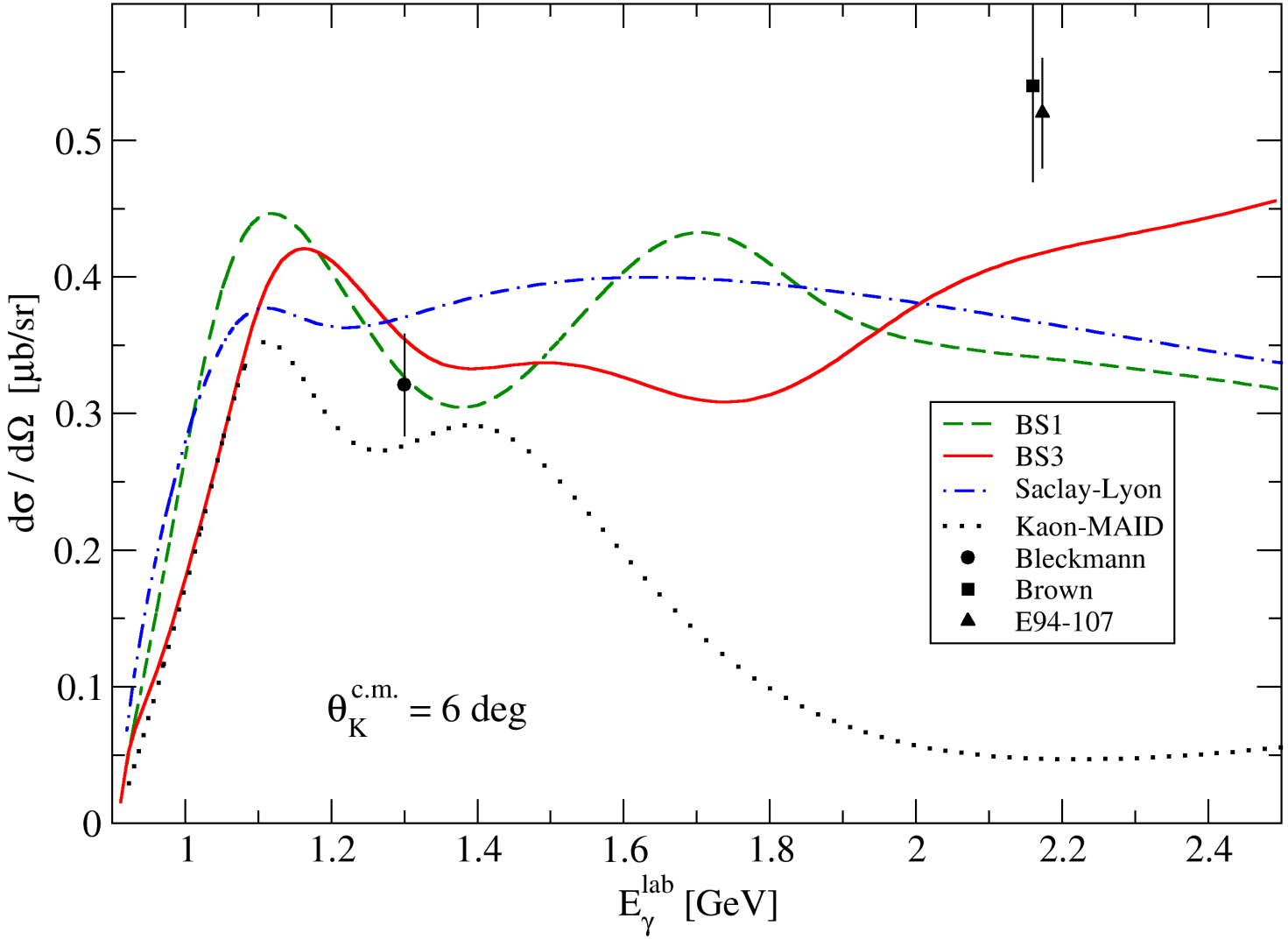
- $\sigma_U, \sigma_T, \sigma_L, \sigma_{LT'}, \sigma_K$

Solutions: BS1 and BS2, χ^2/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, χ^2/n.d.f. $= 1.74$ (energy-dependent widths of N^*'s; fit on $p(\gamma, K^+)\Lambda$ (χ^2/n.d.f. $= 1.51$) and $p(e, e' K^+)\Lambda$ data; PR C **97** (2018) 025202)

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

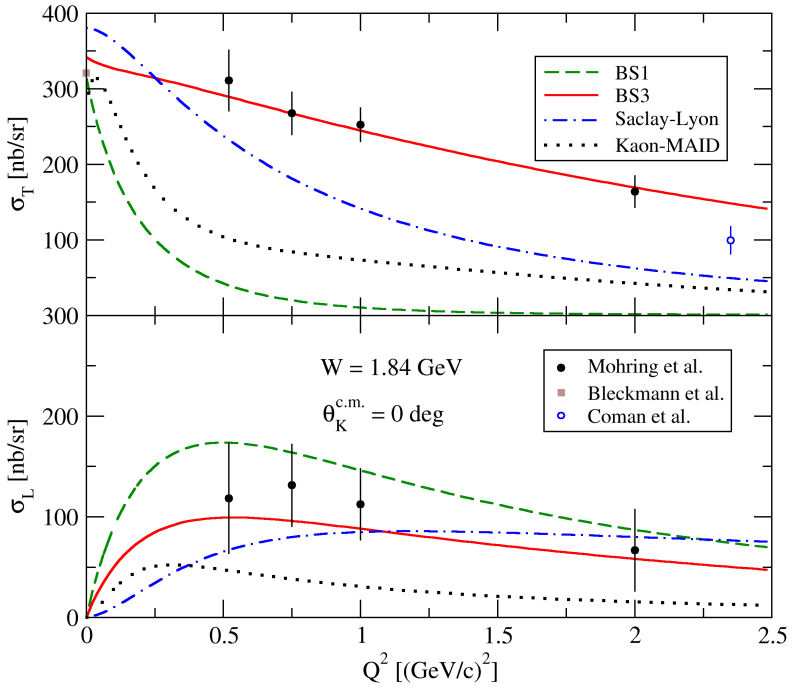


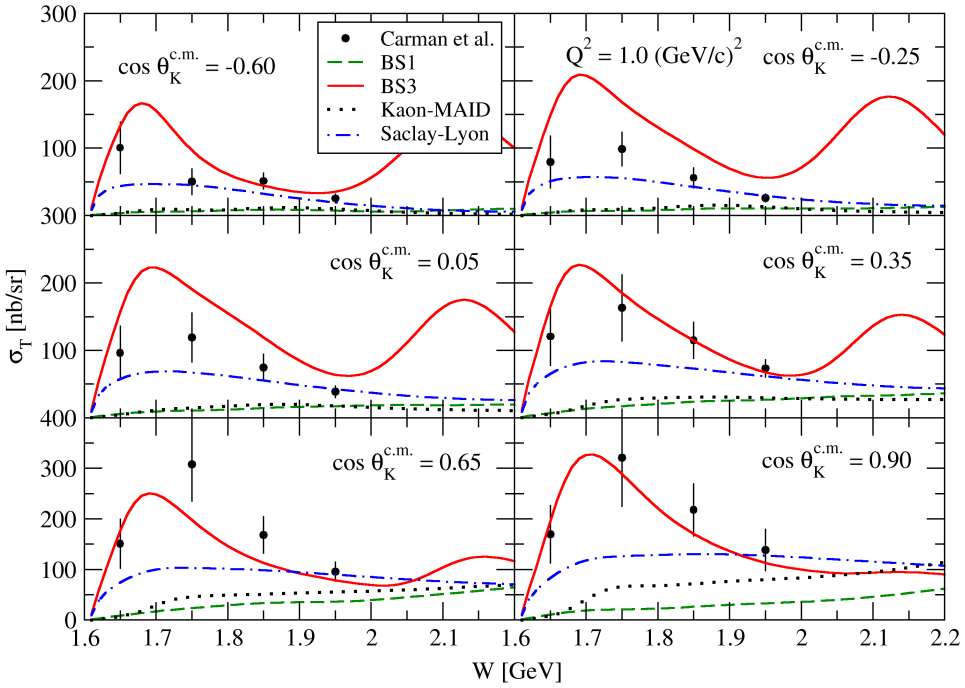
Predictions of $d\sigma/d\Omega$ for $p(\gamma, K^+)\Lambda$ at $\theta_K^{c.m.} = 6°$



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

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





Extension from photoproduction 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 description of data but with no dynamical foundation
    $\rightarrow$ 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

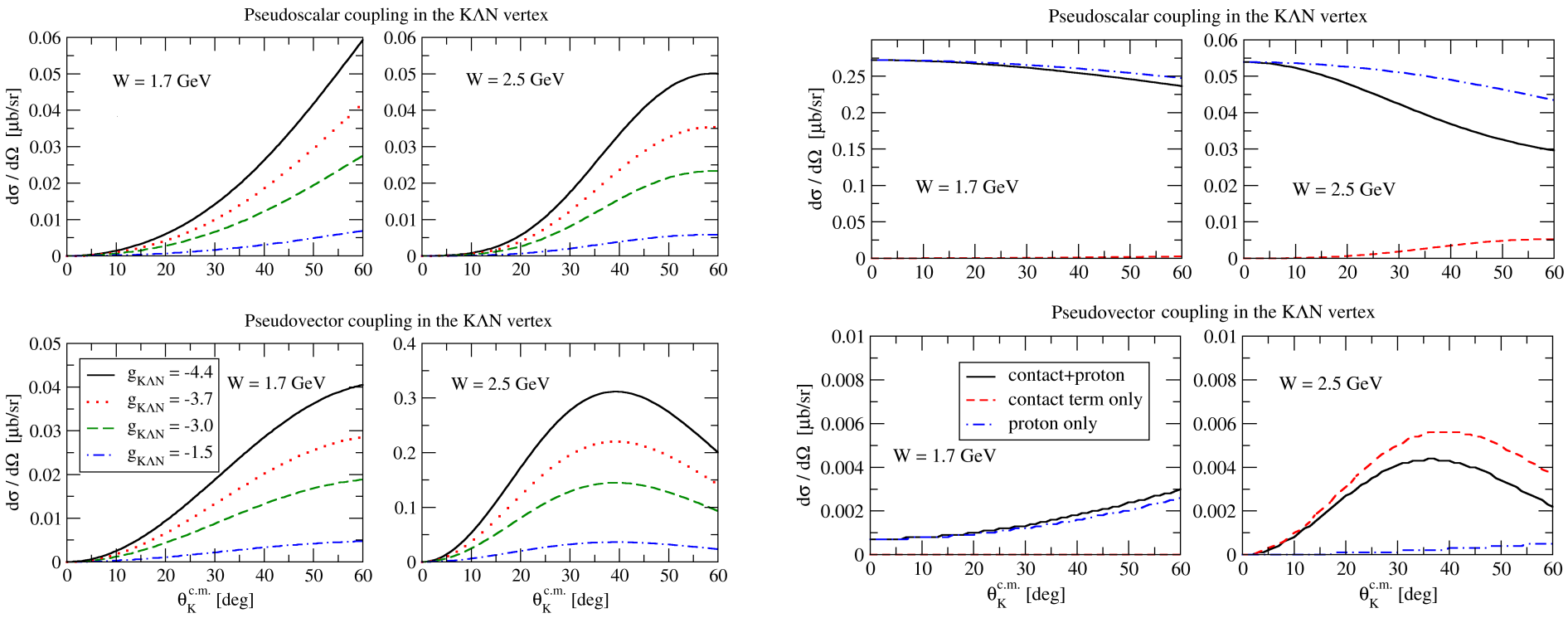
Fitting procedure

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

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

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)

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

P. Bydžovský, A. Cieplý, D. Petrellis, and D. Skoupil for CLAS Collaboration (to be submitted soon)

Fitting procedure

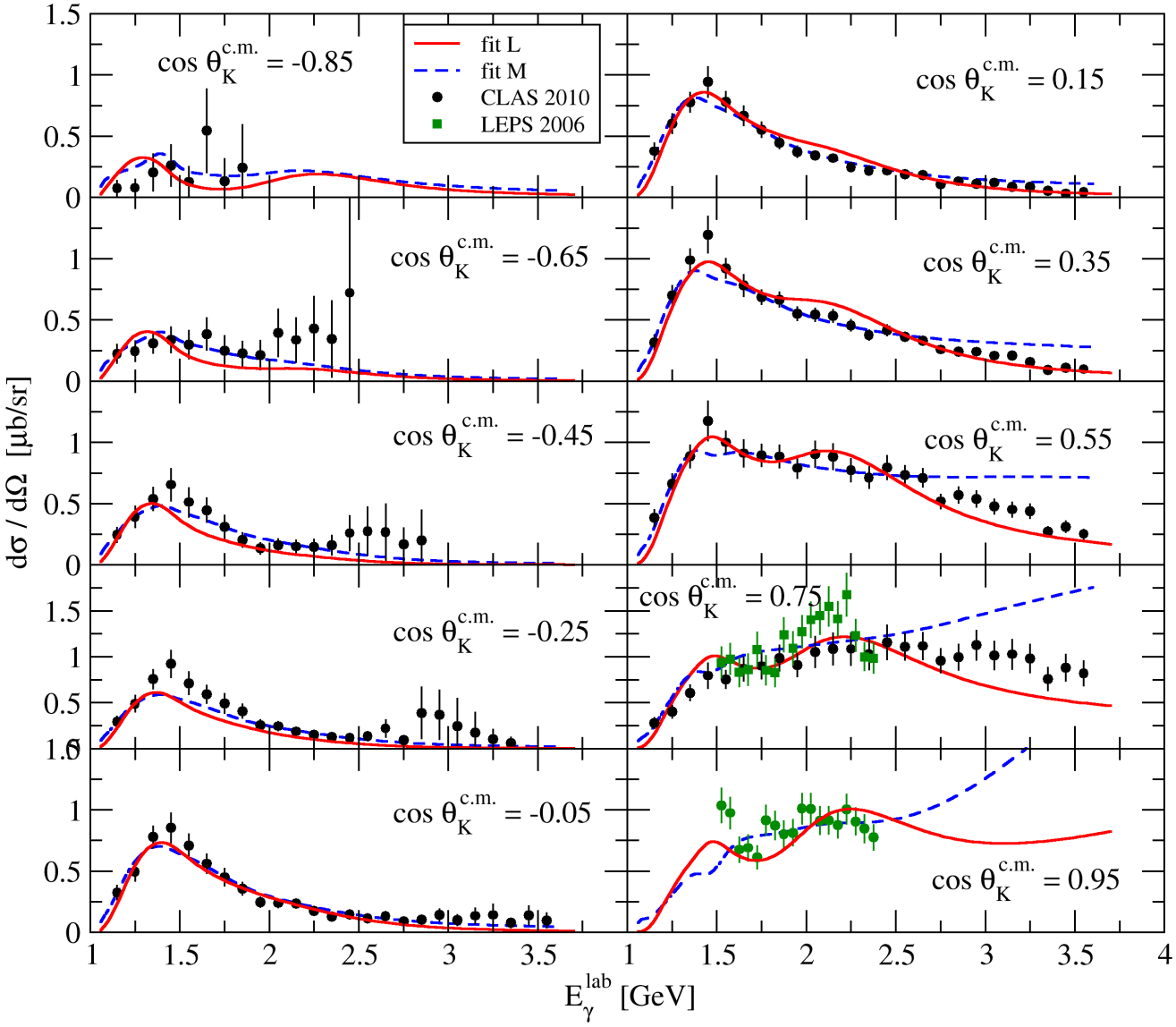
- non resonant part modelled by Born terms and exchanges of K^* and K_1 (t channel) and Σ^* (u channel)
- resonant part modelled by exchanges of nucleon and Δ resonances in the s channel (partly motivated by previous analyses)
- around 600 CLAS and LEPS data on $d\sigma/d\Omega$ and Σ (restricted up to $E_\gamma^{lab} = 2.6\,\mathrm{GeV}$) utilized to fit 24 free parameters
- the main coupling, $g_{K^+\Sigma^- n} = \sqrt{2} g_{K^+\Sigma^0 p} = 1.568$, taken from $K^+\Lambda$ channel
- a variant with the smallest $\chi^2/\mathrm{ndf} = 2.3 \rightarrow$ **fit M** (25 parameters, 14 resonances)
- **LASSO method** used: $\chi^2/\mathrm{ndf} = 3.4 \rightarrow$ **fit L** (17 parameters, 9 resonances)

Models 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

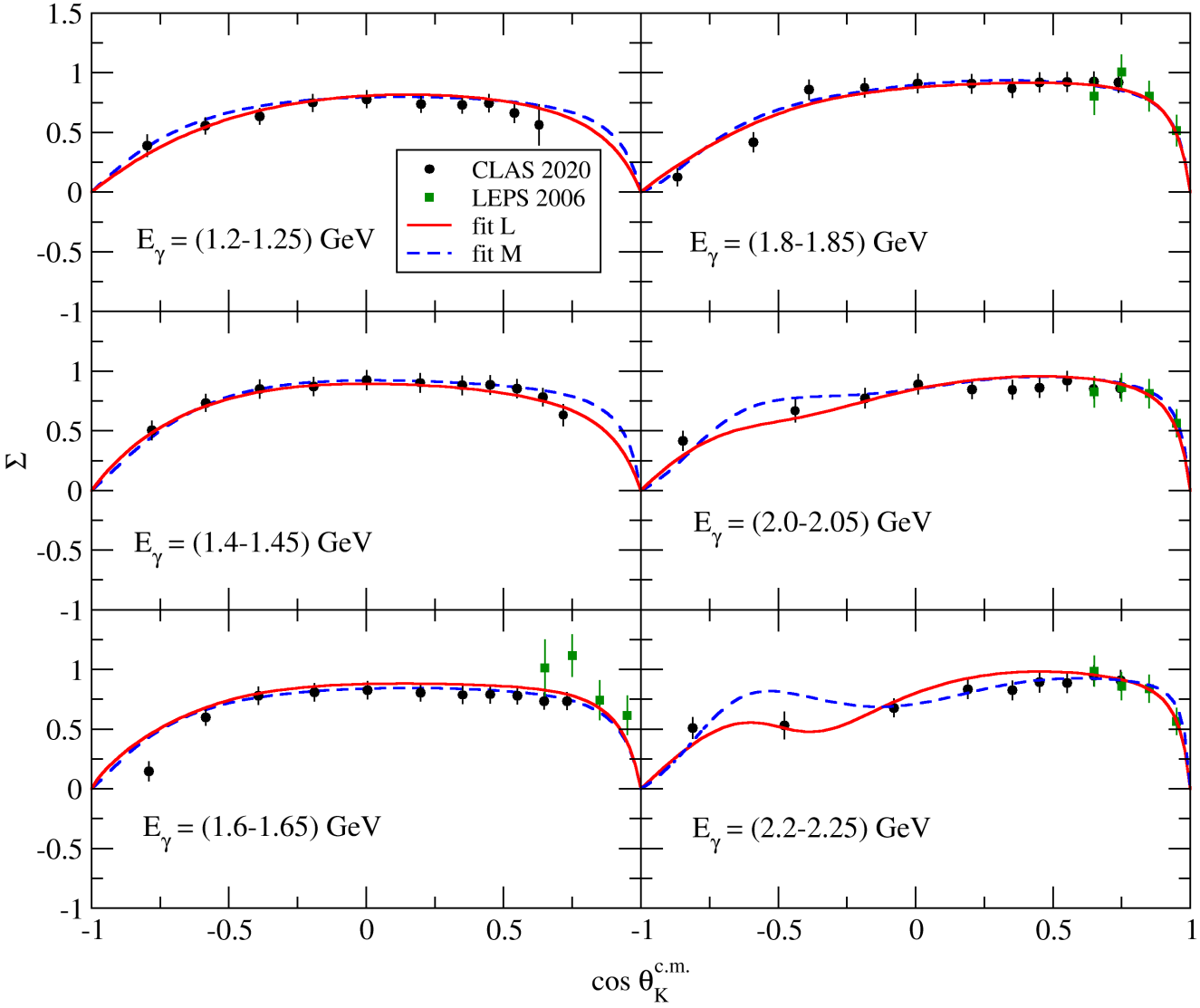
New fits for $K^+\Sigma^-$ channel

Differential cross section in dependence on the photon lab energy



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

Beam asymmetry in dependence on the kaon center-of-mass angle (CLAS 2020 data still preliminary)

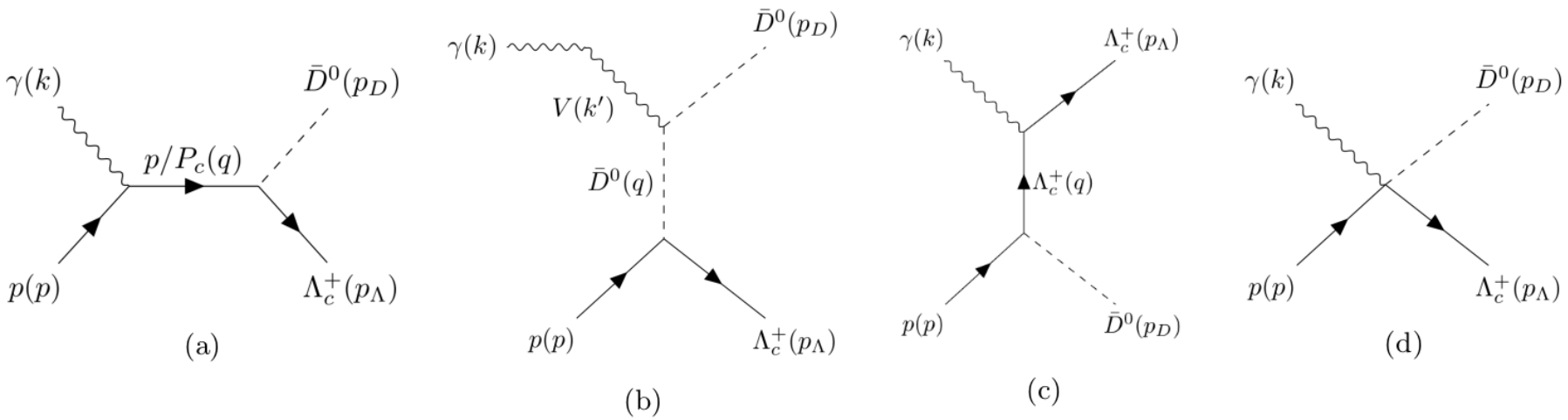


Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

D. Skoupil and Y. Yamaguchi; PR D **102**, 074009 (2020)

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, resp.
  - 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 both PS and PV couplings
  - 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

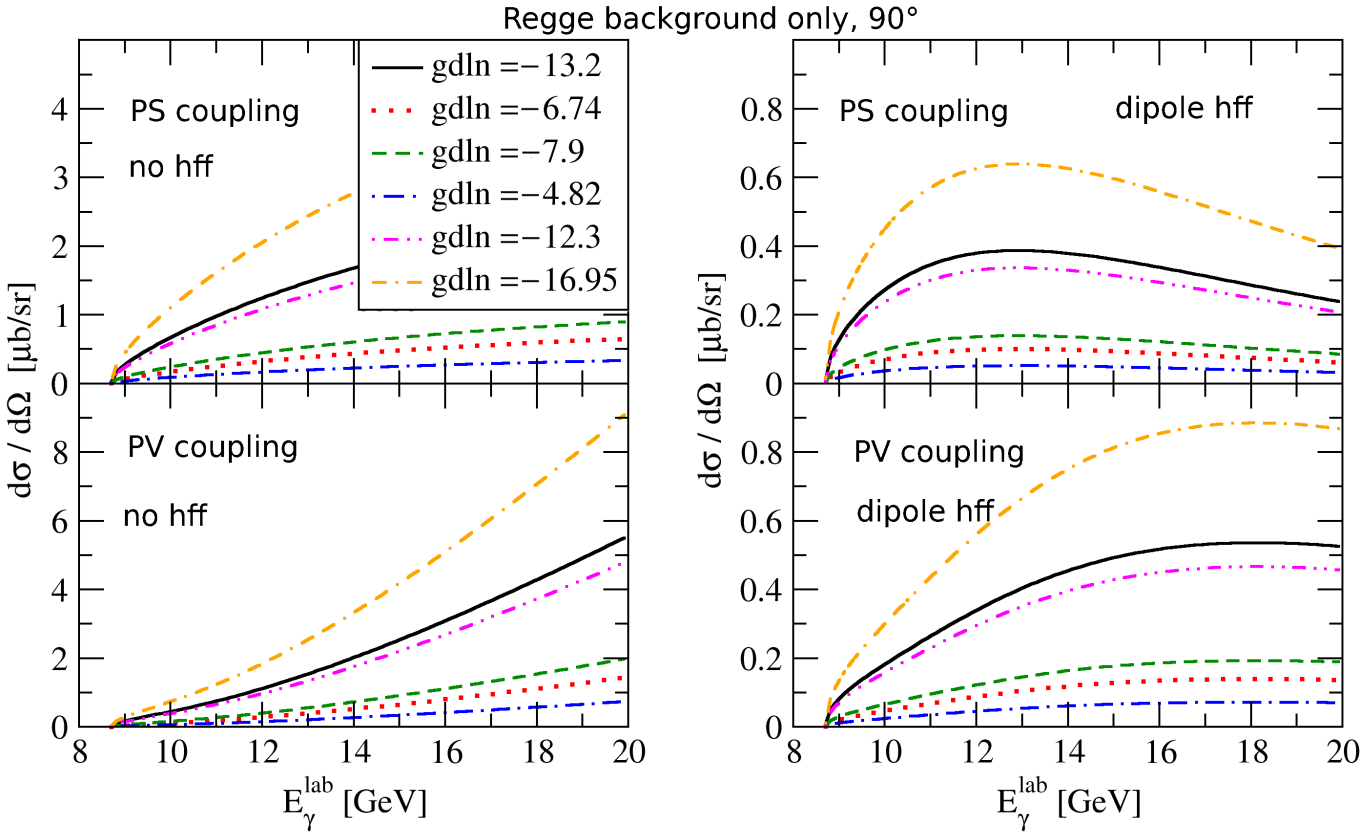


Photoproduction of $\bar{D}^0\Lambda_c^+$ within the RPR model

Model parameters

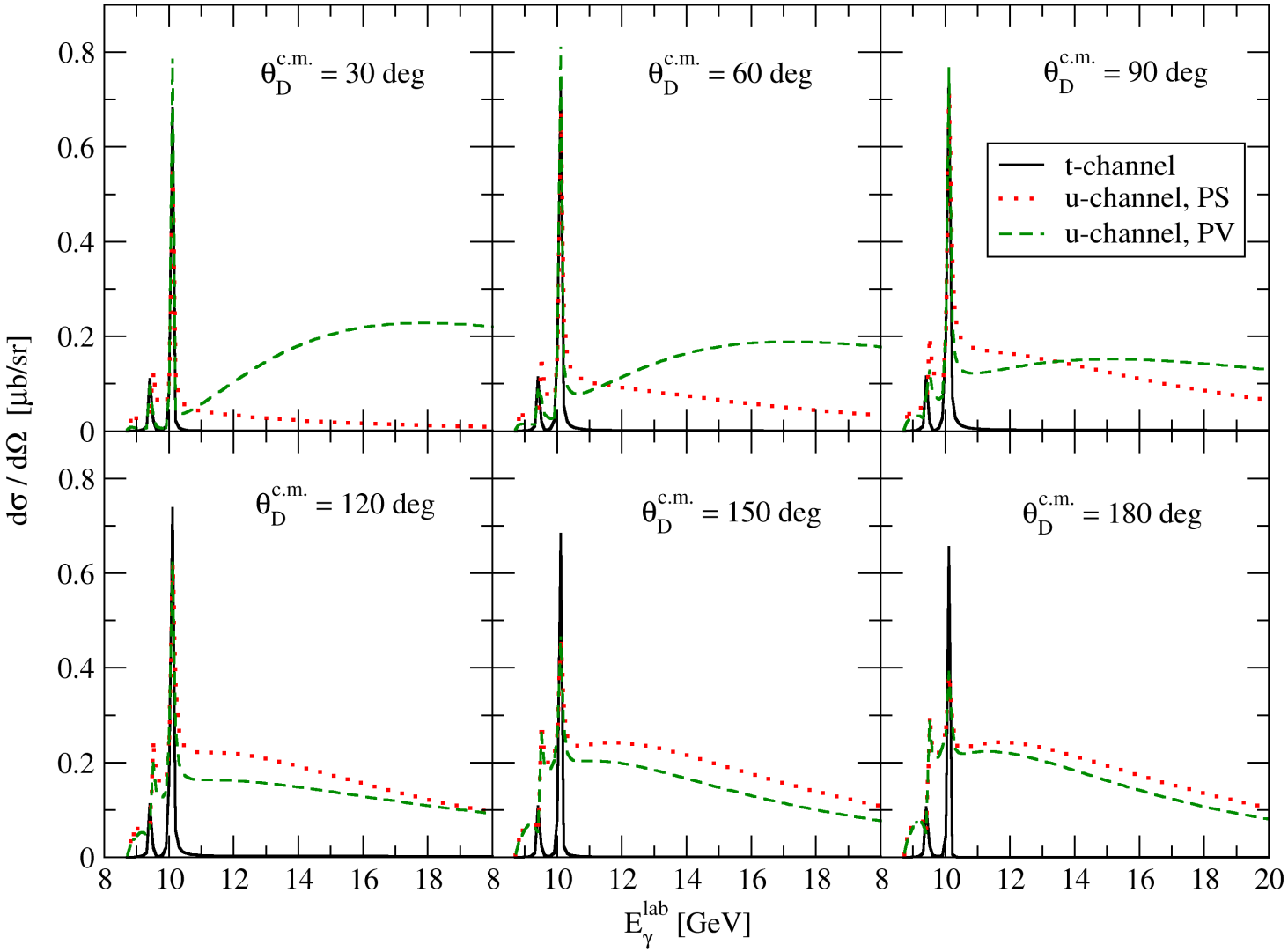
No experimental data available yet ⇒ no fitting possible

- 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
- Couplings of pentaquarks 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 in dependence on the photon lab energy



Summary

New versions of isobar model

- new amplitude constructed with the consistent formalism for high-spin resonances
- 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 (Σ production channels)

Thank you for your attention!