$K^+\Lambda$ Photo- and Electroproduction off Proton

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Motivation

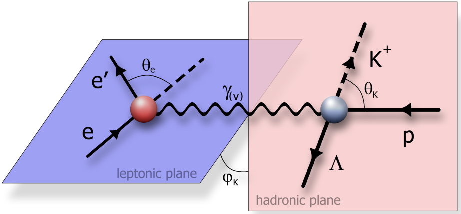
- We aim at understanding of baryon spectrum and production dynamics of particles with strangeness at low energies.
- Constituent Quark Model predicts a lot more N^* states than was observed in pion production experiments $\rightarrow$ “missing” resonance problem.
- Models for the description of elementary 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.
- 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

Electroproduction process

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

- 6 channels: $N = p,\ n$; $K = K^+,\ K^0$; $Y = \Lambda,\ \Sigma^0,\ \Sigma^+$
- 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

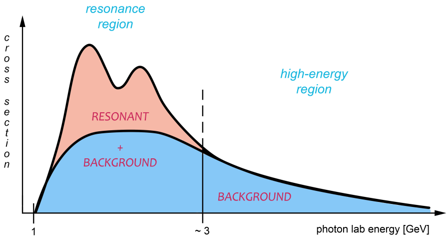
$$\frac{d^3\sigma^{\mathrm{unpol}}}{dE_{e'}\,d\Omega_{e'}\,d\Omega_K^{c.m.}} = \Gamma\left[\sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos(2\varphi_K) + \sqrt{2\varepsilon_L(\varepsilon+1)}\sigma_{LT}\cos\varphi_K\right]$$

Introduction

Photoproduction process

$p + \gamma \rightarrow K^+ + \Lambda$

- 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) $\rightarrow$ we assume a large number of nucleon resonances with mass $< 2\,\text{GeV}$



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

Isobar model

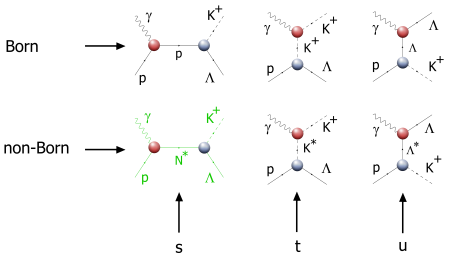
- Single-channel approximation
- Use of effective hadron Lagrangian
- Satisfactory agreement with the data in the energy range $E_\gamma^{lab} = 0.91 - 2.5\,\mathrm{GeV}$
- Coupling constants and $SU(3)_f$ symmetry breaking (Rev.Mod.Phys. **35**, 916 (1963))

$$-4.4 \leq \frac{g_{K\Lambda N}}{\sqrt{4\pi}} \leq -3.0,$$

$$0.8 \leq \frac{g_{K\Sigma N}}{\sqrt{4\pi}} \leq 1.3.$$

- Hadron form factors introduced
- Shortcoming: too large Born contributions; solutions:
    - introduction of hyperon resonances in the u-channel (*e.g.* Saclay-Lyon model)
    - introduction of hadronic form factors (*e.g.* Kaon-MAID model)
    - ignoring the ranges for $g_{K\Lambda N}$ and $g_{K\Sigma N}$

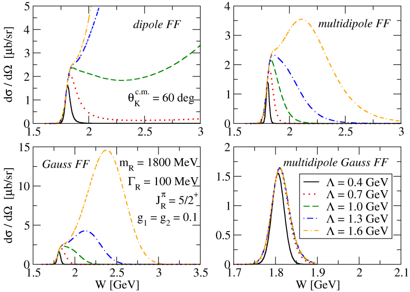
- Amplitude $\equiv$ a sum of tree-level Feynman diagrams (higher-order contributions neglected)
    - background part: Born terms involving an off-shell proton (s-channel), kaon exchange (t) and hyperon exchange (u); non-Born terms: the exchange of (axial) vector kaon resonances (t) and hyperon resonances (u)
    - resonant part: s-channel Feynman diagrams with nucleon resonances in the intermediate state



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 (PRC **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 (PRC **84**, 045201 (2011)):



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

- hff introduces a dependency on value of the cut-off parameter Λ

Davidson-Workman method used (PRC **63**, 025210 (2001))

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

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

Consistent formalism for high-spin resonances

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

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

  allows non physical contributions of lower-spin components

- non physical contributions can be removed by an appropriate choice of $\mathcal{L}_{int}$
  - consistent formalism for spin-3/2 fields (PRD **58** (1998) 096002)
  - generalization for arbitrary high-spin field (PRC **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 $Y^*(3/2)$

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:

  (PRC **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	0.55	0.37	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

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

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

Extension from photoproduction to electroproduction

Phenomenological form factors in the electromagnetic vertex

- GKex(02S) for nucleon, hyperons and their resonances (PRC **66**, 045501 (2002))
- VMD for kaon (PRC **46**, 1617 (1992))
- monopole em. f. f. for K^* and K_1 resonances (PRC **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 $\mathcal{F}^\beta = k^2\epsilon^\beta - k\cdot\epsilon\,k^\beta$

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 (PRC **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) (PRC **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

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

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

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 D.S., P. Bydžovský, PRC **93** (2016) 025204),
and BS3, $\chi^2/\text{n.d.f.} = 1.74$ (energy-dependent widths of N^*'s; fit on $p(\gamma, K^+)\Lambda$ and $p(e, e' K^+)\Lambda$ data; D.S.,P.B., PRC **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 in the 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 $p(\gamma, K^+)\Lambda$

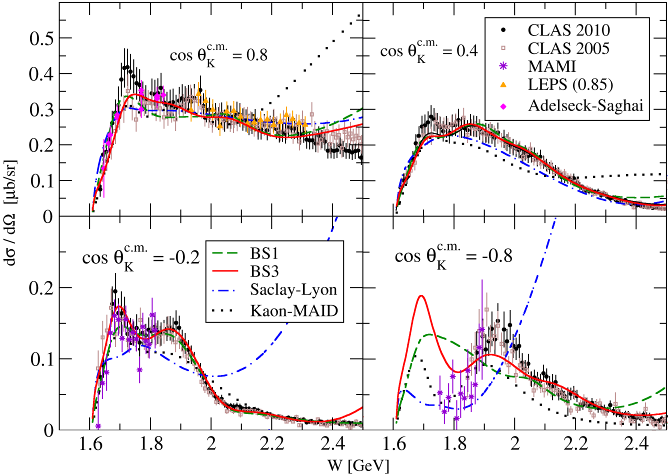


Figure 1 : Cross-section predictions of BS1 (dashed curve), BS3 (solid curve), Saclay-Lyon (dash-dotted curve), and Kaon-MAID (dotted curve) models are shown for four kaon center-of-mass angles. The data are from CLAS 2005 (PRC **73**,035202 (2006)), CLAS 2010 (PRC **81**,025201 (2010)), MAMI (Phys. Lett. B **735**, 112 (2014)), and LEPS (PRC **73**, 035214 (2006)) collaborations and from PRC **42**,108 (1990).

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

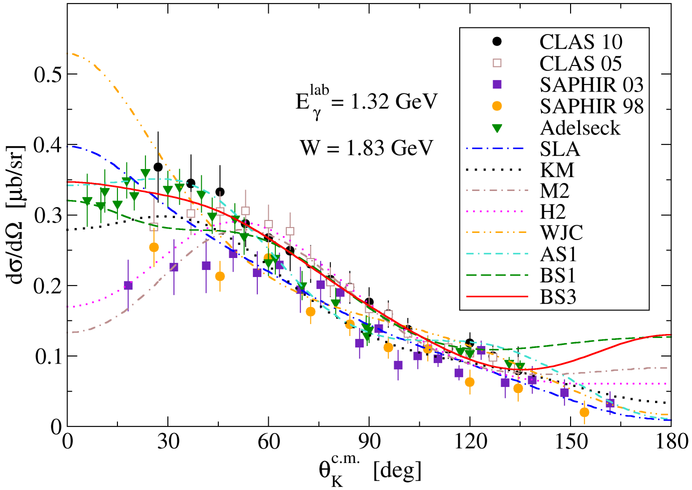


Figure 2 : Angular dependence of the $p(\gamma, K^+)\Lambda$ cross section. The discrepancy in the forward-angle region is remarkable. Data stem from CLAS 2005 (PRC **73**,035202 (2006)), CLAS 2010 (PRC **81**,025201 (2010)), SAPHIR 03 (EPJ A 19, 251 (2004)), SAPHIR 98 (Phys. Lett. B 445, 20 (1998)) and from PRC **42**,108 (1990).

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

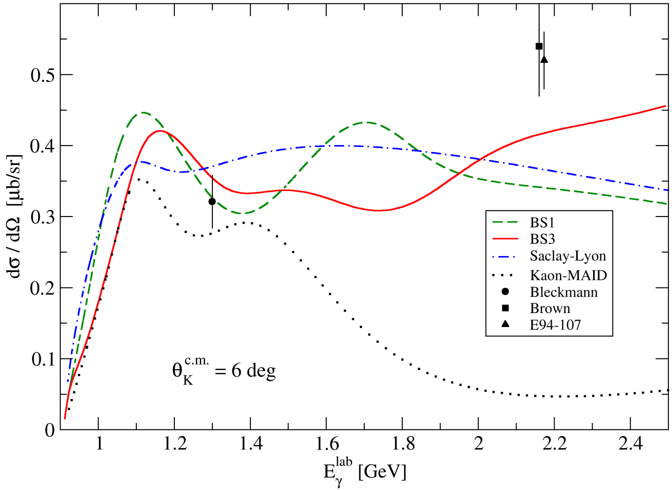


Figure 3 : Results for the differential cross section for $p(\gamma, K^+)\Lambda$ at $\theta_K^{c.m.} = 6^\circ$ are shown for several models. Data points of Brown (PRL **28**, 1086 (1972)) and E94-107 (Int.J.Mod.Phys. E **19**, 2383 (2010)) are for electroproduction with a very small value of the virtual-photon mass; the only photoproduction datum available in this region stems from Bleckmann *et al.* (Z. Phys. **239**, 1 (1970)).

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

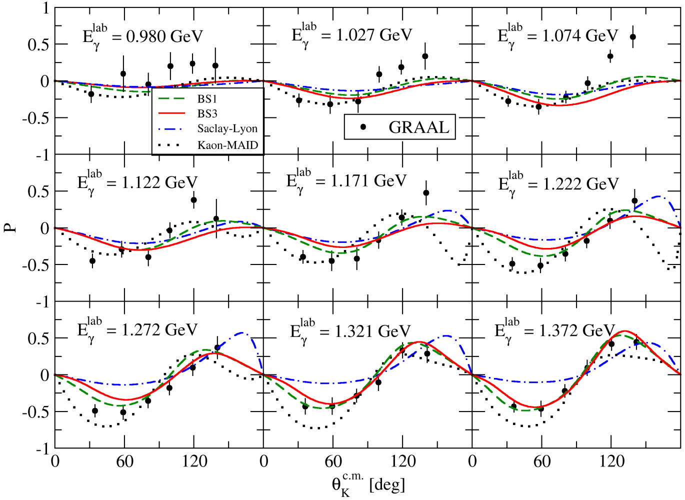


Figure 4 : Predictions of hyperon polarization P are shown for several values of energy E_γ^{lab}. Data stem from GRAAL collaboration (EPJ A **31**, 79 (2007)).

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

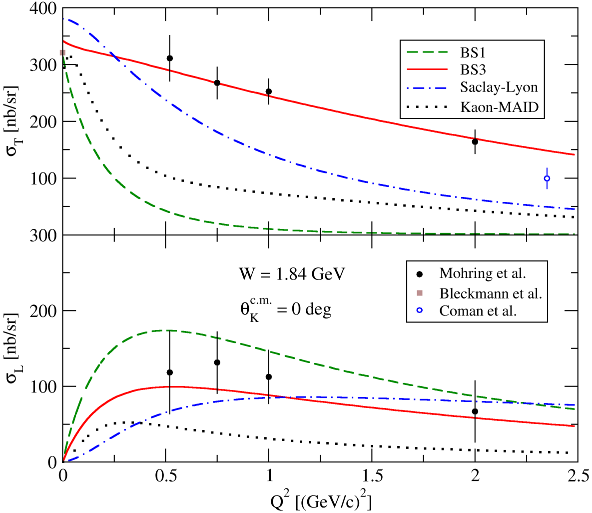


Figure 5 : Transverse, σ_T, and longitudinal, σ_L, cross sections for kaon electroproduction at $W = 1.84$ GeV and for zero kaon angle are shown as a function of Q^2. The result of the BS3 model and predictions of BS1, Saclay-Lyon, and Kaon-MAID models are compared with JLab (PRC **67**, 055205 (2003), PRC **81**, 052201(R) (2010)) and Bleckmann *et al.* (Z.Phys. **239**, 1 (1970)) data.

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

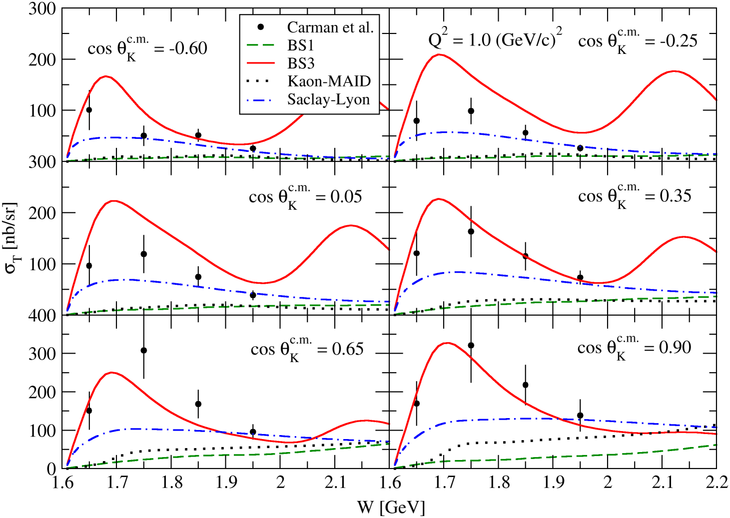


Figure 6 : Energy dependence of transverse cross section σ_T at $Q^2 = 1.0\,\text{GeV}c^2$ for several kaon c.m. angles $\theta_K^{c.m.}$. The result of the BS3 model and predictions of BS1, Saclay-Lyon, and Kaon-MAID models are compared with JLab data (PRC **79**, 065205 (2009)).

Summary

New versions of isobar model presented

- 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^*'s implemented
- extension of the isobar model towards the electroproduction of $K^+\Lambda$

Outlook

- testing the models in the DWIA calculations exploiting data on hypernucleus production
- exploration of different reaction channels (*e.g.* $K^0\Lambda$ production)
- work on gauge-invariance restoration in Regge-plus-resonance models (may influence prediction on forward angles)

Thank you for your attention!