

Machine learning in meson photoproduction

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Motivation for focusing on meson (kaon) photoproduction

- Understanding the baryon spectrum

- “Missing” resonance problem:
Constituent Quark Model predicts more N^* states than is observed in π production experiments.

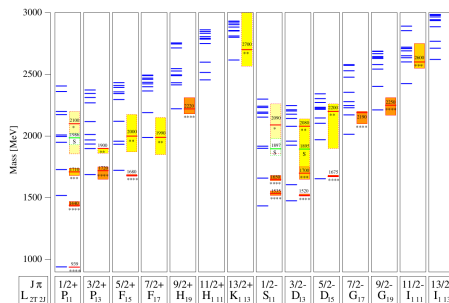
- Hypernuclear physics calculations:

PR C **106**, 044609 (2022),

PR C **108**, 024615 (2023),

PR C **112**, 024609 (2025)

- studies of charge-symmetry breaking, baryon-baryon interaction, ...



Bonn CQM [EPJ A10 (2001) 395–446]

- New good-quality photoproduction data:
CLAS, BGOOD, LEPS, GRAAL, MAMI, SAPHIR Collaborations

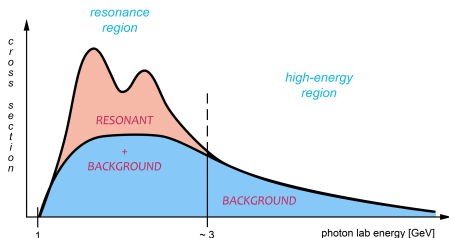
- Effective theories and models:
a remedy for not being able to use perturbative QCD at low energies.

Introduction

Photoproduction process



- Threshold: $E_\gamma^{lab} = 0.911 \text{ GeV}$, $W = 1.609 \text{ GeV}$
- In the lowest order, the reaction is described by the exchange of hadrons.
 - *The 3rd nucleon-resonance region:*
many resonant states and no dominant one in the kaon photoproduction
→ need to assume a large number of nucleon resonances with mass $< 2.5 \text{ GeV}$



- **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

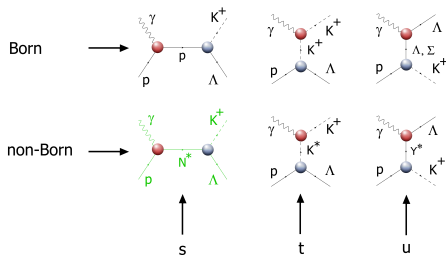
Photoproduction off protons with K^+ and Λ in the final state

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 and resonant part



- hadronic form factors account for the inner structure of hadrons

Free parameters (couplings, hff's cutoffs) adjusted to experimental data.

Satisfactory agreement with the data in the energy range $W = 1.6 - 2.5 \text{ GeV}$.

Isobar model

Calculation procedure

- Reaction amplitude: sum of s -, t -, and u -channel (non) Born amplitudes

$$\mathbb{M} = \sum_x \mathbb{M}_x, \text{ where } x \equiv s, t, u, N^*, K^*, Y^*$$

- Each contribution can be rewritten in a compact form

$$\mathbb{M}(p, p_\Lambda, k) = \bar{u}(p_\Lambda) \gamma_5 \left(\sum_{j=1}^6 \mathcal{A}_j(s, t) \mathcal{M}_j \right) u(p),$$

where $\mathcal{A}_j$ are (complex) scalar amplitudes and $\mathcal{M}_j$ are gauge-invariant operators,

$$\begin{aligned} \mathcal{M}_1 &= \frac{1}{2} [\not{k} \not{\epsilon} - \not{\epsilon} \not{k}], & \mathcal{M}_2 &= (\not{p} \cdot \epsilon) - (k \cdot p) \frac{(k \cdot \epsilon)}{k^2}, \\ \mathcal{M}_3 &= (\not{p}_\Lambda \cdot \epsilon) - (k \cdot p_\Lambda) \frac{(k \cdot \epsilon)}{k^2}, & \mathcal{M}_4 &= \not{\epsilon} (\not{k} \cdot p) - \not{k} (p \cdot \epsilon), \\ \mathcal{M}_5 &= \not{\epsilon} (k \cdot p_\Lambda) - \not{k} (p_\Lambda \cdot \epsilon), & \mathcal{M}_6 &= \not{k} (k \cdot \epsilon) - \not{\epsilon} k^2. \end{aligned}$$

[terms with $(k \cdot \epsilon)$ and k^2 appear only in electroproduction with virtual photons]

- When N diagrams contribute, then each of them contributes to $\mathbb{M}$ and

$$\mathcal{A}_j = \sum_{k=1}^N \mathcal{A}_j^k.$$

- Works for hadronic part of any EM pseudoscalar meson production amplitude!

Isobar model

Calculation procedure

- CGLN amplitudes $f_i(k^2, s, t)$ (in cms) [PR **106**, 1345-1355 (1957)]

$$\mathbb{M} = \chi_\Lambda^\dagger \mathcal{F} \chi_p; \quad \mathcal{F} = f_1(\vec{\sigma} \cdot \vec{\varepsilon}) - i f_2(\vec{\sigma} \cdot \hat{p}_K)[\vec{\sigma} \cdot (\hat{k} \times \vec{\varepsilon})] + f_3(\vec{\sigma} \cdot \hat{k})(\hat{p}_K \cdot \vec{\varepsilon}) \\ + f_4(\vec{\sigma} \cdot \hat{p}_K)(\hat{p}_K \cdot \vec{\varepsilon}) + f_5(\vec{\sigma} \cdot \hat{k})(\hat{k} \cdot \vec{\varepsilon}) + f_6(\vec{\sigma} \cdot \hat{p}_K)(\hat{k} \cdot \vec{\varepsilon}),$$

where *e.g.*

$$f_1 = N^*[-(W - m_p)\mathcal{A}_1 + (k \cdot p)\mathcal{A}_4 + (k \cdot p_\Lambda)\mathcal{A}_5 - k^2\mathcal{A}_6]$$

- Response functions, *e.g.* **transverse cross section**

$$\frac{d\sigma}{d\Omega} = \sigma_T = C \left\{ |f_1|^2 + |f_2|^2 - 2 \operatorname{Re} f_1 f_2^* \cos \theta_K \right. \\ \left. + \sin^2 \theta_K \left[\frac{1}{2}(|f_3|^2 + |f_4|^2) + \operatorname{Re} (f_1 f_4^* + f_2 f_3^* + f_3 f_4^* \cos \theta_K) \right] \right\},$$

(for other response functions see Z. Phys. A **352** (1995) 327)

- **Single polarization asymmetries** $A(P, \Sigma, T)$ have the form

$$A = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-},$$

where $d\sigma$ denotes the differential cross section and the superscript (+ or -) the polarization state (parallel or antiparallel) with respect to the corresponding quantization axis

Isobar model

Important features of the isobar model

Exchanges of high-spin resonant states

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

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

- spin-3/2 projection operator: $\mathcal{P}_{\mu\nu}^{(3/2)} = g_{\mu\nu} - \frac{1}{3}\gamma_\mu\gamma_\nu - \frac{1}{3q^2}(\not{q}\gamma_\mu q_\nu + q_\mu\gamma_\nu \not{q})$.
- spin-1/2 projection operators: $\mathcal{P}_{22,\mu\nu}^{(1/2)} = \frac{q_\mu q_\nu}{q^2}$, $\mathcal{P}_{12,\mu\nu}^{(1/2)} = \frac{q^\rho q_\nu \gamma_{\mu\rho}}{q^2\sqrt{3}}$, $\mathcal{P}_{21,\mu\nu}^{(1/2)} = \frac{q_\mu q^\rho \gamma_{\rho\nu}}{q^2\sqrt{3}}$
- $\mathcal{L}_{int}$ invariant under local gauge transformation of the RS field [PR D 58, 096002 (1998)]
 - interaction vertices are transverse: $q_\mu \Gamma^\mu(q, \dots) = 0$
 $\Rightarrow$ spin-1/2 projection operators decouple in the amplitude:

$$\Gamma^\mu(q, \dots) S_{\mu\nu}(q) \Gamma^\nu(q, \dots) = \Gamma^\mu(q, \dots) \frac{\not{q} + m}{q^2 - m^2 + im\Gamma} \mathcal{P}_{\mu\nu}^{(3/2)} \Gamma^\nu(q, \dots).$$

... analogously in the case of higher-spin fields [PR C 84, 045201 (2011)]

Isobar model

Important features of the isobar model

Energy-dependent decay widths of nucleon resonances

→ (partial) restoration of unitarity

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

Extension from photoproduction to electroproduction

- Phenomenological form factors in the electromagnetic vertex [PR C 66, 045501 (2002)]
- Longitudinal couplings of N^* 's to γ^* (crucial at small Q^2)

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

$$V_{\mu}^{EM}(N_{3/2}^* p \gamma) = -i \frac{g_3^{EM}}{m_R(m_R + m_p)^2} \gamma^5 \Gamma_{\mp} (\not{q} g_{\mu\beta} - q_{\beta} \gamma_{\mu}) \mathcal{F}^{\beta},$$

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

Fitting the data in the $K^+\Lambda$ channel

Minimization of $\chi^2/\text{n.d.f.}$ with help of MINUIT library

Resonance selection

- s channel: spin-1/2, 3/2, and 5/2 N^* with mass < 2.5 GeV;
- t channel: $K^*(892)$, $K_1(1272)$
- u channel: $Y^*(1/2)$ and $Y^*(3/2)$

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

- $SU(3)_f$: $-4.4 \leq g_{KAN}/\sqrt{4\pi} \leq -3.0$,
 $0.8 \leq g_{K\Sigma N}/\sqrt{4\pi} \leq 1.3$
- 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

Experimental data

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

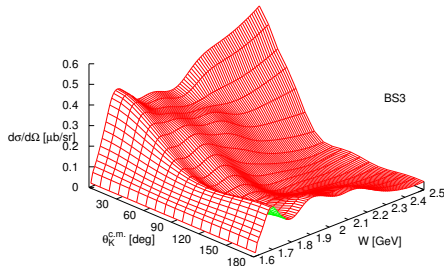
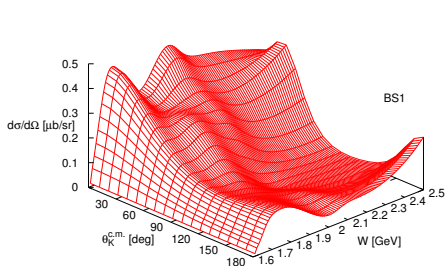
- cross section for $W < 2.355$ GeV
(CLAS 2005 & 2010; LEPS, Adelseck-Saghai)
- hyperon polarisation for $W < 2.225$ GeV
(CLAS 2010)
- beam asymmetry (LEPS)

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

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

Resulting models for the $K^+\Lambda$ photo- and electroproduction

BS models (BS = Bydžovský, Skoupil) [PR C **93**, 025204 (2016), PR C **97**, 025202 (2018)]



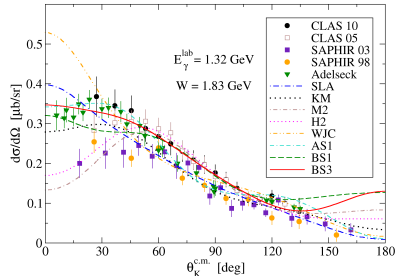
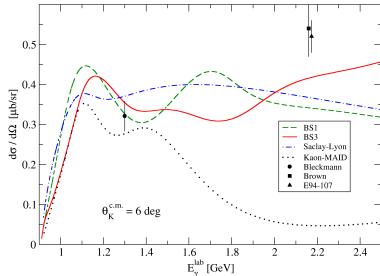
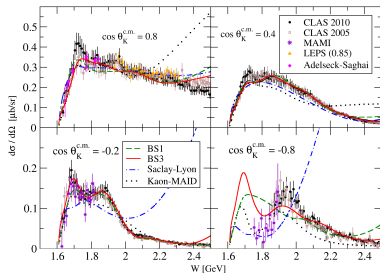
BS1 model ($\chi^2/n.d.f. = 1.64$)

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

BS3 model ($\chi^2/n.d.f. = 1.74$)

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

Cross sections of $p(\gamma, K^+)\Lambda$



← Brown [$Q^2 = 0.18$ (GeV/c) 2]

E94-107 [$Q^2 = 0.07$ (GeV/c) 2]:
data for $p(e, e' K^+) \Lambda$ with:

$$\sigma_L \sim Q^2,$$

$$\sigma_{TT} \sim \sin^2 \theta_K^{c.m.},$$

$$\sigma_{LT} \sim \sqrt{Q^2} \sin \theta_K^{c.m.} \Rightarrow \sigma \approx \sigma_T$$

Remedy for over-fitting: regularization

Least Absolute Shrinkage and Selection Operator (LASSO)

- penalty term: $\lambda \sum_{j=1}^K |w_j|$
- uses L1 norm (absolute values)
- shrinks coefficients and **can set some of them to zero**
- performs automatic feature selection and produces **sparser models**
- constraint region is a diamond with sharp corners $\rightarrow$ solution often ends up on axes $\rightarrow$ some coefficients become exactly zero

Ridge regression

- penalty term: $\lambda \sum_{j=1}^K w_j^2$
- uses L2 norm (squared coefficients)
- shrinks coefficients but **do not set them exactly to zero**
- keeps all predictors in the model
- constraint region is a circle (or hypersphere) which is smooth $\rightarrow$ solution only rarely ends up exactly on axes $\rightarrow$ coefficients rarely become exactly zero

Elastic net

- combines both penalties: $\lambda \sum_{j=1}^K |w_j| + \lambda \sum_{j=1}^K w_j^2$
- performs feature selection (like LASSO)
- handles correlated predictors better (like Ridge)

$K^+\Sigma^-$ channel within the isobar model

Least Absolute Shrinkage and Selection Operator (LASSO)

Fitting procedure with MINUIT library: **minimizing the χ^2**

$$\chi^2 = \sum_{i=1}^N \frac{[d_i - p_i(c_1, \dots, c_n)]^2}{\sigma_{d_i}^2},$$

$(c_1, \dots, c_n)$ – set of free parameters, $(d_1, \dots, d_N)$ – set of data points, p_i – theory, σ_{d_i} – error

Problem: χ^2 minimization cannot prevent **overfitting**

Remedy to the overfitting issue: regularization

- introduce a penalty term to the $\chi^2 \rightarrow$ penalization of large parameter values

$$\chi_P^2 = \chi^2 + P(\lambda)$$

- penalty term:** $P(\lambda) = \lambda^4 \sum_{i=1}^{N_{res}} |g_i|$

λ – regularization parameter, g_i – resonances' couplings

- Least Absolute Shrinkage Selection Operator (LASSO)
forces some of the parameters to zero $\rightarrow$ selection of a subset of the fit parameters

$K^+\Sigma^-$ channel within the isobar model

Information criteria:

- Akaike information criterion

$$AIC = 2n_i + \chi_P^2$$

- Corrected Akaike information criterion

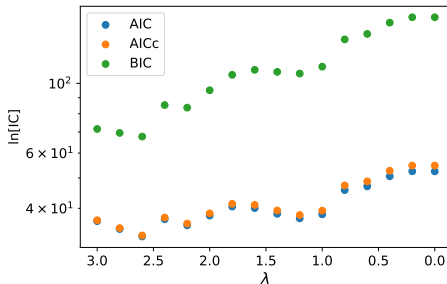
$$AICc = AIC + \frac{2n_i(n_i+1)}{N-n_i-1}$$

- Bayesian information criterion

$$BIC = n_i \ln(N) + \chi_P^2$$

n_i - no. of parameters corresponding to λ_i

N - number of data points



Applying the information criteria – forward selection

- 1 start with the full model: parameters initialized within $\langle -1; +1 \rangle$; use $\lambda_{\max}$
- 2 perform LASSO χ_P^2 minimization and compute IC
- 3 in each run reduce λ and run LASSO with the values of the previous run as starting values
- 4 repeat until $\lambda_{\min}$ is reached

Optimal λ occurs at the minimum of the IC.

$K^+\Sigma^-$ channel within the isobar model

PR C 104, 065202 (2021)

Fitting procedure

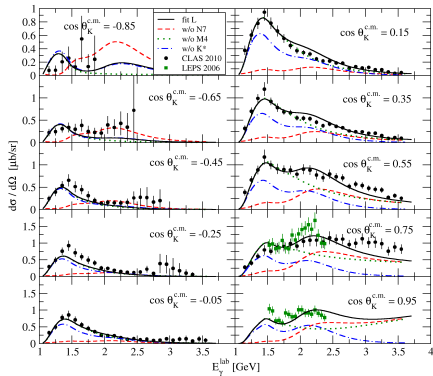
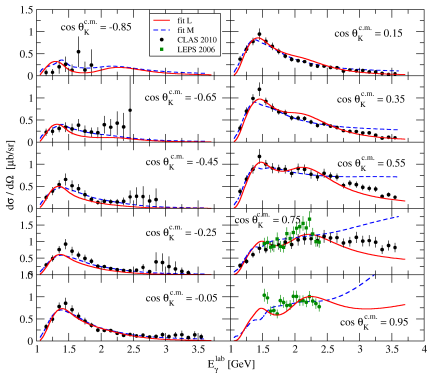
- resonance selection: motivation from previous analysis of $K^+\Lambda$ channel
- non resonant part: Born terms and exchanges of K^* and K_1 and Σ^* 's
- resonant part: exchanges of N^* 's and Δ^* 's in the s channel
- around 600 data utilized to fit ≤ 25 parameters
(new CLAS data on $\Sigma \rightarrow$ main motivation for this study)
- result with the smallest $\chi^2/\text{ndf} = 2.3 \rightarrow$ **fit M** (25 parameters, 14 resonances)
- **LASSO** applied at fit M: $\chi^2_P/\text{ndf} = 3.4 \rightarrow$ **fit L** (17 parameters, 9 resonances)

Characteristics of models

- 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
- fit L is very economical

$K^+\Sigma^-$ channel within the isobar model

Differential cross section in dependence on the photon lab energy



Notation: N7: $N(1720)3/2^+$, M4: $N(2060)5/2^-$

Ridge regression in the $K^+\Lambda$ channel

PR C 107, 045206 (2023)

Why?

- include recent measurements of polarization observables (PR C 93, (2016) 065201)
- need to investigate the role of hyperon resonances in KY photoproduction
- large values of hyperon couplings: ridge regression to suppress them during the fitting procedure

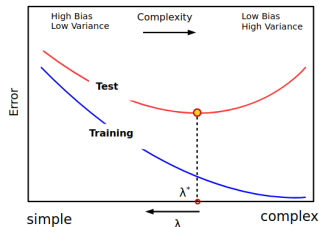
Ridge regularization

- $\chi_P^2 = \chi^2 + \lambda^4 \sum_{i=1}^{n_\Lambda} g_i^2$, (n_Λ = no. of Y couplings)
- parameter values reduced but they are *not* reduced to zero

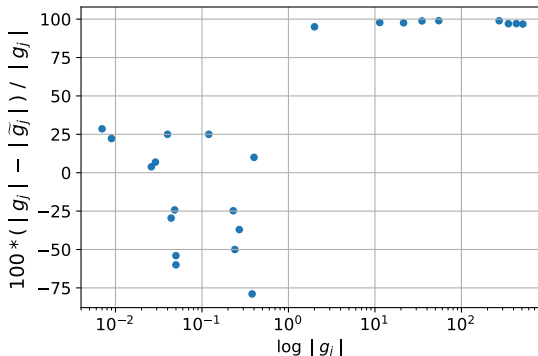
Cross validation (here 4-fold)



Bias-Variance trade-off



Relative percentage reduction of the resonance couplings



BS2

BS2r

Tag	Resonance	g_1	g_2
L1	$\Lambda(1405) \ 1/2^-$	9.67	—
S1	$\Sigma(1660) \ 1/2^+$	-8.09	—
L4	$\Lambda(1800) \ 1/2^-$	-11.55	—
S4	$\Sigma(1940) \ 3/2^-$	-0.86	0.18



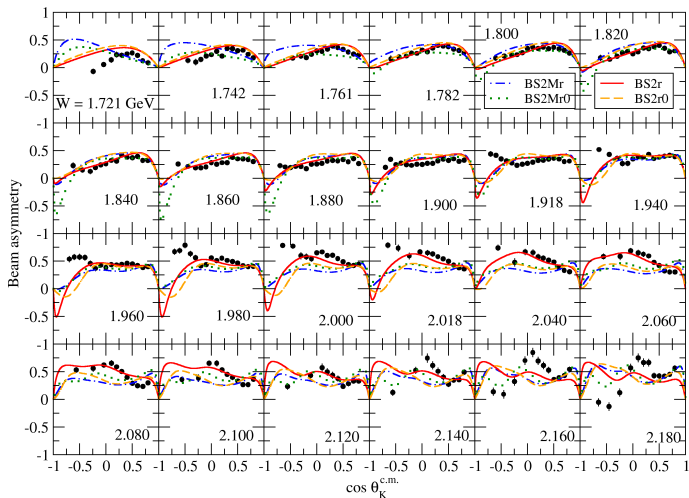
2.624
-5.925
-1.409
-0.685 0.079

g_j - values from the unregularized fitting

$\tilde{g}_j$ - values after performing Ridge regularization

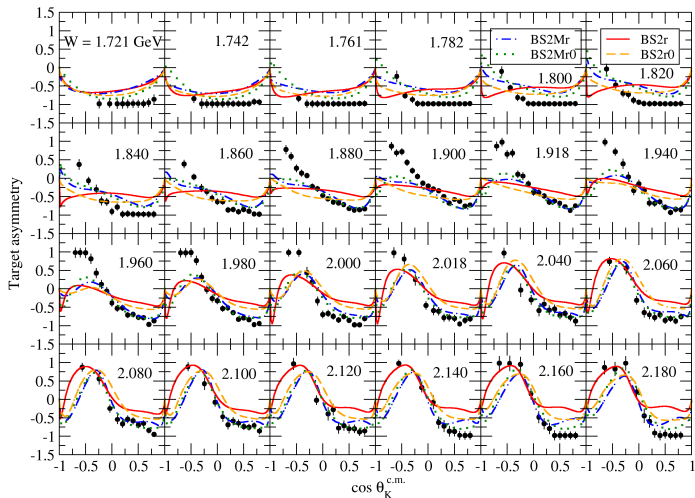
$K^+\Lambda$ channel

Beam asymmetry Σ



$K^+\Lambda$ channel

Target asymmetry T



$K^+\Sigma^0$ channel within the isobar model

Models A (w/o LASSO) and B (w/ LASSO) [PR C **110**, 065204 (2024)]

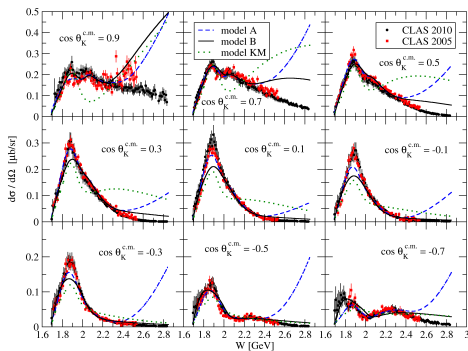
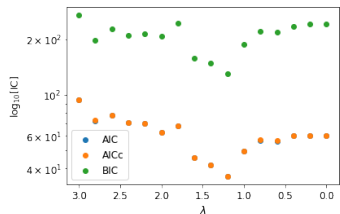
Resonances in models **A** and **B**:

- $N3(1535)1/2^-$, $N4(1650)1/2^-$, $N9(1680)5/2^+$,
 $N7(1720)3/2^+$, $P5(1820)5/2^+$, $M4(1860)1/2^-$,
 $P4(1875)3/2^-$, $P2(1900)3/2^+$, $\Delta(1900)3/2^+$,
 $P3(2000)5/2^+$, $M2(2300)1/2^+$;
- $K^*(892)$, $K_1(1272)$;
- $\Lambda(1890)$, $\Sigma(1660)$.

Model	no. of resonances	no. of parameters	$\chi^2(P)/\text{n.d.f.}$
A	15	29	2.02
B	7	14	4.67

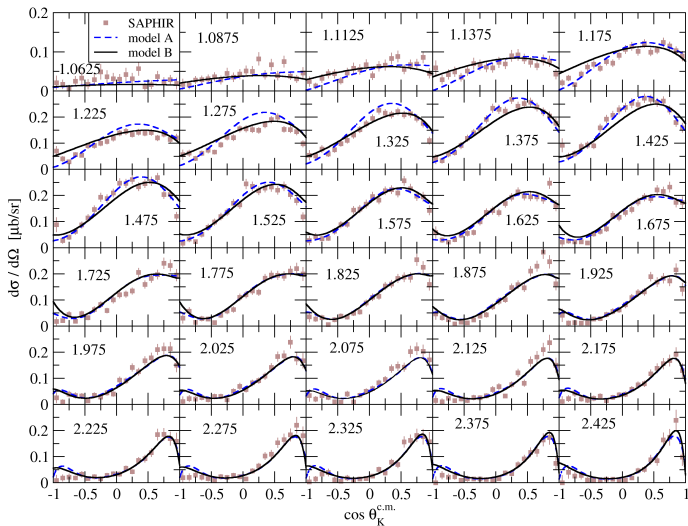
(initial motivation for selecting resonances:

PR C **66**, 035202 (2002))



$K^+\Sigma^0$ channel within the isobar model

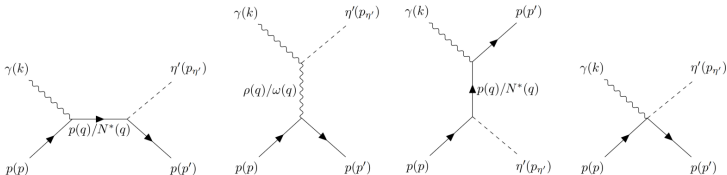
Models A (w/o LASSO) and B (w/ LASSO) – comparison with SAPHIR data (not fitted)



Photoproduction of η' mesons off protons

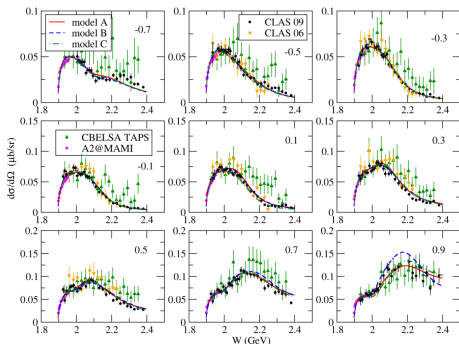
PR C 112, 025202 (2025)

Exchanges of p/N^* (s and u channels), and ρ/ω mesons in t channel + contact term



Resonance	Mass (MeV)	Width (MeV)	Status	BR
$N(1875)3/2^-$	1850–1920 (1875)	120–250 (250)	***	
$N(1895)1/2^-$	1870–1920 (1870)	80–200 (200)	****	10–40
$N(1900)3/2^+$	1890–1950 (1890)	100–320 (200)	****	4–8
$N(2100)1/2^+$	2050–2150 (2050)	200–320 (200)	***	5–11
$N(2120)3/2^-$	2060–2160 (2120)	260–360 (300)	***	2–6

- **model A:** $\chi^2/\text{n.d.f.} = 1.90$, PS, fit on $d\sigma$
- **model B:** $\chi^2/\text{n.d.f.} = 2.15$, PS, fit on $d\sigma + \Sigma$
- **model C:** $\chi^2/\text{n.d.f.} = 2.21$, PV, fit on $d\sigma + \Sigma$



From $K^+\Sigma^0$ channel to $K^0\Sigma^+$ channel

Strong vertices: isospin symmetry

- $K^+\Sigma^0 p \rightarrow K^0\Sigma^+ p$
- $g_{K^*\Sigma^+p} = \sqrt{2} g_{K^*\Sigma^0p}$

Electromagnetic vertices:

- s channel: γpp in both channels
- t channel: $K^* \rightarrow K\gamma$ decay width

$$\Gamma = \frac{1}{24} \frac{g_{K^*K\gamma}^2}{4\pi M^2} \left[m_{K^*} \left(1 - \frac{m_K^2}{m_{K^*}^2} \right) \right]^3$$

$$\Gamma_{K^* \rightarrow K^+\gamma} = 50 \pm 5 \text{ keV},$$

$$\Gamma_{K^* \rightarrow K^0\gamma} = 116 \pm 10 \text{ keV},$$

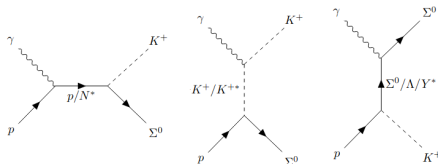
$$\Rightarrow g_{K^*K^0\gamma} = -1.52 g_{K^*K^+\gamma}$$

- u channel: not enough info on

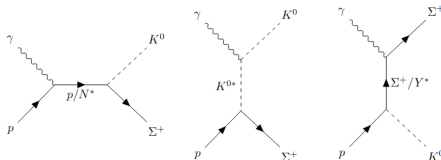
$$\gamma\Sigma^0\Sigma^0 \rightarrow \gamma\Sigma^+\Sigma^+$$

$$\gamma\Sigma^0 Y^* \rightarrow \gamma\Sigma^+ Y^*$$

Feynman diagrams for $\gamma p \rightarrow K^+\Sigma^0$



Feynman diagrams for $\gamma p \rightarrow K^0\Sigma^+$



$K^0 \Sigma^+$ channel (submitted to PR C)

Akaike differences and weights

- Akaike information criterion

$$AIC = 2n + \chi^2$$

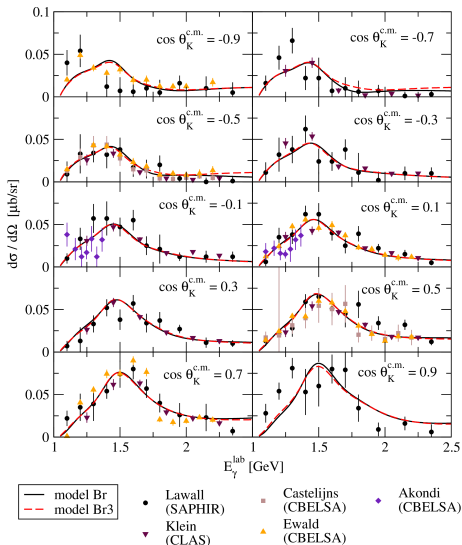
- Akaike difference

$$\Delta_i = AIC_i - AIC_{\min}$$

- Akaike weight

$$w_i = \frac{\exp(-\Delta_i/2)}{\sum_{r=1}^R \exp(-\Delta_r/2)}$$

Model	χ^2	AIC_i	Δ_i	w_i
Br	1586.38	1614.38	32.95	10^{-7}
Br3	1543.43	1581.43	0	0.999



$K^0\Sigma^+$ channel (submitted to PR C)

Bootstrap: correlation coefficients & parameter distributions

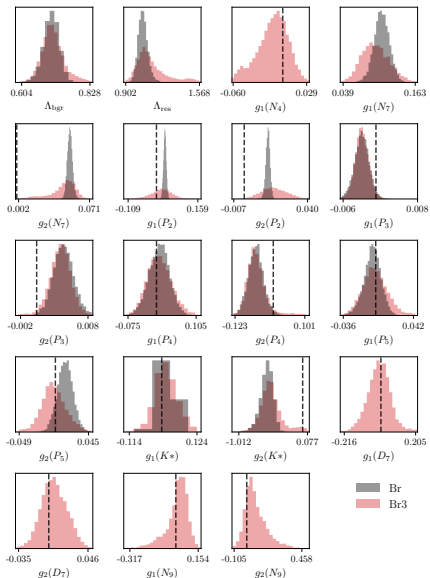
- Bootstrap belongs to the most powerful tools for exposing **parameter overfitting**
- here: 5000 bootstrap iterations
- Pearson correlation coefficients:

$$r_{xy} = \frac{\text{cov}(x,y)}{\sigma_x \sigma_y}$$

$$r_{xy} > 0.7 \Rightarrow \text{high interdependence}$$

$$r_{xy} \gtrsim 0.9 \Rightarrow \text{redundancy}$$

Parameter pair		r_{xy}	
x	y	Br	Br3
Λ_{bgr}	$g_2(K^*)$	0.95	0.91
Λ_{res}	$g_2(P_2)$	-0.78	0.71
Λ_{res}	$g_2(K^*)$	—	0.77
$g_1(N_4)$	$g_2(N_7)$	—	0.91
$g_1(P_2)$	$g_2(P_2)$	0.74	—
$g_1(P_2)$	$g_1(D_7)$	—	0.98
$g_1(P_2)$	$g_2(D_7)$	—	0.71
$g_2(P_2)$	$g_2(D_7)$	—	0.94
$g_1(P_3)$	$g_2(P_3)$	-0.90	-0.88
$g_1(P_4)$	$g_2(P_4)$	0.83	0.79
$g_1(P_5)$	$g_2(P_5)$	-0.85	-0.89
$g_1(D_7)$	$g_2(D_7)$	—	0.78
$g_1(N_9)$	$g_2(N_9)$	—	-0.91



Summary

Isobar model and Regge-plus-resonance model (not shown here) for

- $K^+\Lambda$ photoproduction and electroproduction
→ further use in hypernuclei electroproduction
[PR C **106**, 044609 (2022), PR C **108**, 024615 (2023), PR C **112**, 024609 (2025)]
- $K\Sigma$ photoproduction
→ $K^+\Sigma^0$, $K^+\Sigma^-$, and $K^0\Sigma^+$ channels
- charm photoproduction (not mentioned in this talk)

Regularization methods introduced as a remedy for overfitting and as model selection tools.

Outlook

- testing the models in the calculations of hypernuclei electroproduction
- extending the analysis of electroproduction of $K^+\Lambda$ beyond $Q^2 = 1 \text{ GeV}^2$
- describing electroproduction of η' mesons
- photoproduction of $K^0\Lambda$, $K\Lambda(1405)$, $K\Lambda(1520)$...

Thank you for your attention!