HYP2022, Praha, June 27 - July 1, 2022

The study of $\pi\Sigma$ photoproduction in the $\Lambda(1405)$ region

P. C. Bruns, **A. Cieplý**

Nuclear Physics Institute, Řež, Czechia

M. Mai

Bonn University, Bonn, Germany

Outline:

1. Introduction
2. Formalism for the $\gamma p \rightarrow K^+\pi\Sigma$ reaction
3. $\pi\Sigma$ mass spectra predictions
4. Summary

Introduction

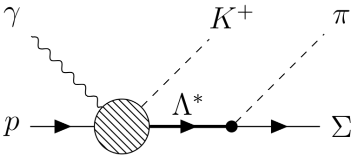
- $\Lambda(1405)$ is generated dynamically in chirally motivated $\pi\Sigma - \bar{K}N$ coupled channels approaches (state-of-the-art NLO models)
- two pole structure of the resonance - narrow $\bar{K}N$ molecular state submerged in $\pi\Sigma$ continuum
- model parameters fitted to experimental data available at energies from K^-p threshold up (kaonic hydrogen, threshold branching ratios, low energy cross sections)
- varied theoretical predictions for subthreshold energies and in the isovector sector
- analysis of $\pi\Sigma$ mass spectra in photoproduction reaction should help in both respects
- related topics include $\bar{K}$-nuclei and role of strangeness in dense nuclear matter (e.g. neutron stars)

Introduction

In the available $K^- p$ reactions data, the $\Lambda(1405)$ is hidden below the threshold.

The resonance can be seen in processes, where $\pi\Sigma$ re-scatter in the final state, e.g.

$$\gamma p \longrightarrow K^+ \pi\Sigma$$

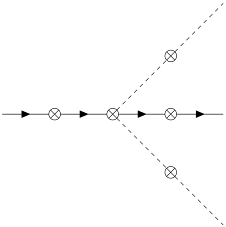


In this two meson protoproduction reaction the K^+ meson carries away momentum, enabling a scan in the invariant mass of the $\pi\Sigma$ system down to its production threshold.

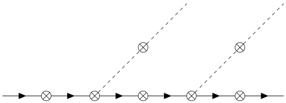
Formalism for the $\gamma p \to K^+\pi\Sigma$ reaction

formalism outlined in: P. C. Bruns - arXiv:2012.11298 [nucl-th] (2020)
application to $\pi\Sigma$ mass spectra predictions:
P. C. Bruns, A. C., M. Mai - arXiv:2206.08767 (2022), submitted to PRD

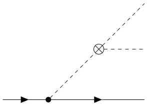
leading-order BChPT used to derive expressions for the photoproduction amplitude $\mathcal{M}$, constructed from tree level graphs:



Weinberg-Tomozawa (WT)



Born term (BT) - B1, B2



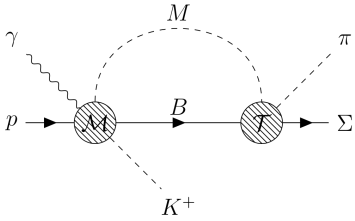
anomalous (AN)

lines: directed - baryons, dashed - pseudoscalar mesons; $\otimes$ symbols - photon insertions

$5 + (2 \times 7) + 1 = 20$ tree graphs, 16 independent $\mathcal{M}_j$ structure functions

Formalism for the $\gamma p \to K^+ \pi\Sigma$ reaction

Final state interaction of the MB pair needs to be accounted for:



$\pi\Sigma - \bar{K}N$ coupled channels models provide the $f^{c',c}_{\ell\pm}(M_{\pi\Sigma})$ amplitudes, that describe the scattering from channel c to channel c' ($c, c' = \pi\Lambda,\ \pi\Sigma,\ \bar{K}N,\ \eta\Lambda, \ldots$)

state-of-the-art approaches based on LO+NLO ChPT, complying with unitarity

$$\mathrm{Im}(f_{\ell\pm}) = (f_{\ell\pm})^{\dagger}(|\vec{p}^{\,*}|)(f_{\ell\pm}) \ ,$$

our aim: implement f_{0+} amplitudes to describe MB s-wave pairs produced in $\gamma p \to K^+ MB$ photoproduction

We need to project the $\mathcal{M}$ amplitude on the $MB_{\ell=0}$ state ...

Formalism for the $\gamma p \to K^+\pi\Sigma$ reaction

There are four independent structure functions $\mathcal{A}^i_{0+}(s, M^2_{\pi\Sigma}, t_K)$ constructed from $\mathcal{M}_j$, projected on s-wave and satisfying the partial-wave unitarity relation

$$\mathrm{Im}(\mathcal{A}^i_{0+}) = (f_{0+})^\dagger(|\vec{p}^{\,*}|)(\mathcal{A}^i_{0+})\,, \quad i = 1, \ldots, 4\,.$$

Neglecting $\ell > 0$ contributions, we get

$$\frac{d^2\sigma}{d\Omega_K dM_{\pi\Sigma}} = \frac{|\vec{q}_K||\vec{p}^{\,*}_\Sigma|}{(4\pi)^4 s|\vec{k}|}|\mathcal{A}|^2\,,$$

$$\begin{aligned} 4|\mathcal{A}|^2 &= (1-z_K)\left|\mathcal{A}^1_{0+} + \mathcal{A}^2_{0+}\right|^2 + (1+z_K)\left|\mathcal{A}^1_{0+} - \mathcal{A}^2_{0+}\right|^2 \\ &+ (1-z_K)\left|\mathcal{A}^1_{0+} + \mathcal{A}^2_{0+} + \frac{2|\vec{q}_K|(1+z_K)}{M_K^2 - t_K}\left((\sqrt{s}+m_N)\mathcal{A}^3_{0+} + (\sqrt{s}-m_N)\mathcal{A}^4_{0+}\right)\right|^2 \\ &+ (1+z_K)\left|\mathcal{A}^1_{0+} - \mathcal{A}^2_{0+} - \frac{2|\vec{q}_K|(1-z_K)}{M_K^2 - t_K}\left((\sqrt{s}+m_N)\mathcal{A}^3_{0+} - (\sqrt{s}-m_N)\mathcal{A}^4_{0+}\right)\right|^2, \end{aligned}$$

with $z_K \equiv \cos\theta_K$, θ_K being the angle between $\vec{q}_K$ and $\vec{k}$ in the overall c.m. frame.

Formalism for the $\gamma p \to K^+\pi\Sigma$ reaction

unitarized amplitudes for $\gamma p \to K^+ MB$ will be taken as the coupled-channel vector

$$(\mathcal{A}^{i}_{0+}) = (\mathcal{A}^{i(\mathrm{tree})}_{0+}) + (f_{0+})\,(8\pi M_{\pi\Sigma} G(M_{\pi\Sigma}))\,(\mathcal{A}^{i(\mathrm{tree})}_{0+})$$

The second term represents the final-state MB rescattering and $G(M_{\pi\Sigma})$ is a diagonal channel-space matrix with entries given by regularized loop integrals

$$\mathrm{i}\, G^{c=MB}(M_{\pi\Sigma}) = \int_{\mathrm{reg.}} \frac{d^4 l}{(2\pi)^4} \frac{1}{((p_\Sigma + q_\pi - l)^2 - m_B^2 + \mathrm{i}\epsilon)(l^2 - M_M^2 + \mathrm{i}\epsilon)}$$

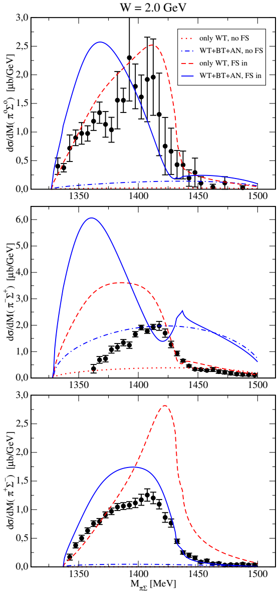
two coupled channels approaches for the f_{0+} amplitudes:

Bonn B2, B4 models - M.Mai, U.-G.Meißner, Eur. Phys. J. A 51 (2015) 30
BW model - D.Sadasivan, M.Mai, M.Döring, Phys. Lett. B 789 (2019) 329–335
dimensional regularization used in $G(M_{\pi\Sigma})$, mass scales μ_c

Prague P model - P.C.Bruns, A.C., Nucl. Phys. A 1019 (2022) 122378
Yamaguchi formfactors used in $G(M_{\pi\Sigma})$, inverse ranges α_c

matching at MB threshold: $\mu \approx 1\ \mathrm{GeV}$ relates to $\alpha_{\pi\Sigma} \approx 460$ MeV, $\alpha_{\bar{K}N} \approx 715$ MeV

$\pi\Sigma$ mass spectra predictions



CLAS data (2013) by Moriya et al.

c.m. energy $W = \sqrt{s} = 2.0$ GeV

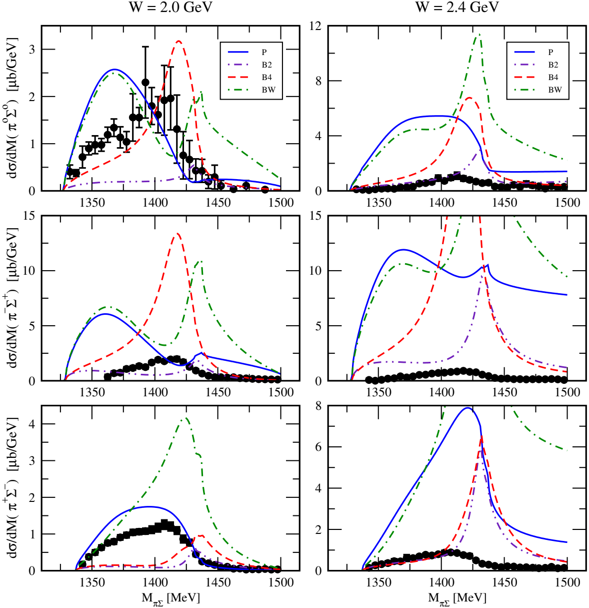
P model used for the *MB* amplitudes

- only WT, no FSI:
  small (or zero for $\pi^+\Sigma^-$) cross sections
- WT+BT+AN, no FSI:
  the cross sections remain flat, the $\pi^-\Sigma^+$ one reaches magnitude comparable with the data
- addition of FSI:
  MB rescattering is responsible for the peak structure
  $\pi^0\Sigma^0$ and $\pi^+\Sigma^-$ reproduced rather well
  Born terms move the peak to lower energies

parameter-free predictions!

no adjustment to the f_{0+} amplitudes

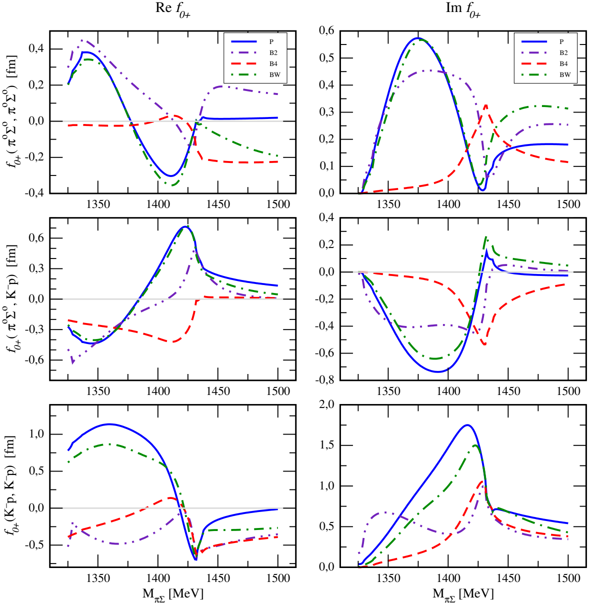
$\pi\Sigma$ mass spectra predictions



W = 2.0 GeV

W = 2.4 GeV

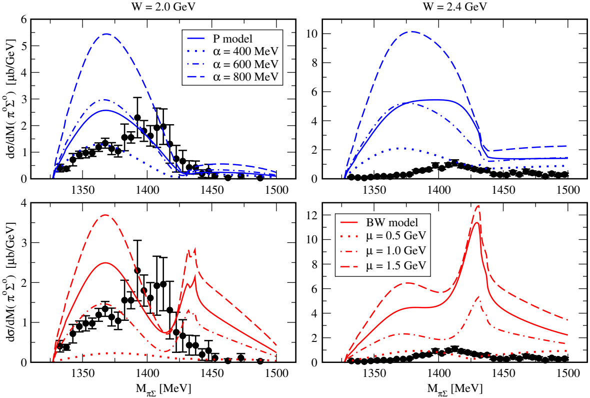
f_{0+} amplitudes



$\pi\Sigma$ mass spectra predictions

Can one tune the magnitude of the generated cross sections?

modifying the first loop-function that connects the $\mathcal{A}^{\mathrm{tree}}$ amplitude with the f_{0+} one



top - P model, uniform inverse range $\alpha = 400 \ldots 800$ MeV

bottom - BW model, uniform mass scale $\mu = 0.5 \ldots 1.5$ GeV

Comparison with other approaches

L. Roca, E. Oset - Phys. Rev. C 87 (2013) 055201
M. Mai, U.-G. Meißner - Eur. Phys. J. A 51 (2015) 30
makeshift photoproduction amplitude $\mathcal{A} = C(\sqrt{s})\, G(M_{\pi\Sigma})\, f_{0+}(M_{\pi\Sigma})$

S.X. Nakamura, D. Jido - PTEP 2014 (2014) 023D01
similar to our approach with some non-relativistic simplifications, additional contributions from K^* exchange, phenomenological energy dependent contact terms, and adjustments to the first loop function and to the photoproduction vertex

E. Wang et al. - Phys. Rev. C 95 (2017) 015205
focus on triangle singularity contribution $\gamma p \to N^*(2030) \to K^*\Sigma \to K^+\Lambda(1405)$ combined with K, K^* meson exchanges and a contact term

All these fit a good number of model parameters to reproduce the CLAS data.

In contrast, we just demonstrate what can be achieved with a parameter-free approach based on (unitarized) ChPT.

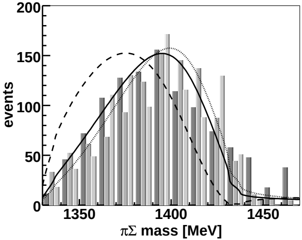
Summary

- The up-to-date (NLO) chirally motivated $\pi\Sigma - \bar{K}N$ models provide very different predictions for the *MB* amplitudes at energies below $\bar{K}N$ threshold. The Λ(1405) energy region can be accessed by studying processes involving $\pi\Sigma$ rescattering in the final state.
- The $\pi\Sigma$ photoproduction on protons represents such a process where the *MB* rescattering plays a crucial role as our results demonstrate.
- Our approach to the two-meson photoproduction implements coupled-channel unitarity, low-energy theorems from ChPT and gauge invariance.
- The approach was used to make predictions that are completely parameter-free. Adopting different models for the *MB* amplitudes leads to varied structure of the computed $\pi\Sigma$ mass distributions that can accommodate spectra with either one or two peaks.
- The agreement with the CLAS experimental data is not satisfactory but can be improved by a combination of including the photoproduction data in fits of the $\pi\Sigma - \bar{K}N$ model, modifying the *MB* loop function, or by considering additional contributions to the photoproduction amplitude.

Extras

$\Lambda(1405)$ in experimental data on $\pi\Sigma$ mass distributions

relatively old *compatible* experiments:
Thomas (1973), Hemingway (1984), ANKE (2008).

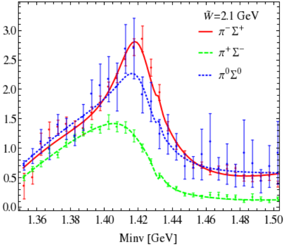


A.C., J. Smejkal - Nucl. Phys. A 881 (2012) 115

$$\frac{dN_{\pi\Sigma}}{dM} \sim \left| T_{\pi\Sigma,\pi\Sigma}(I=0) + r_{KN/\pi\Sigma}\, T_{\pi\Sigma,\bar{K}N}(I=0) \right|^2 p_{\pi\Sigma}$$

HADES (2013) would fit in nicely too.

new experiments:
ANKE/HADES (2008/2013) - $pp \longrightarrow pK^+\,\pi\Sigma$
CLAS/GlueX (2013/2022) - $\gamma p \longrightarrow K^+\,\pi\Sigma$
J-PARC (2016) - $K^- d \longrightarrow n\,\pi\Sigma$
future - weak decays of heavy hadrons,
e.g. $\Lambda_c \longrightarrow \pi^+ MB$, $MB = \pi\Sigma$ or $\bar{K}N$



CLAS data reproduction
K. Moriya et al. - Phys. Rev. C 87 (2013) 035206
M. Mai, U.-G. Meißner - Eur. Phys. J. A 51 (2015) 30