

SIDDHARTA impact on $\bar{K}N$ amplitudes used in in-medium applications

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Outline

- 1 Introduction
- 2 Separable meson-baryon potentials
- 3 Data reproduction
- 4 Free space and in-medium $\bar{K}N$ amplitudes
- 5 $\bar{K}$ -nuclear optical potential
- 6 Summary

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

A.C., E. Friedman, A. Gal, D. Gazda, J. Mareš - Phys. Lett. B 702 (2011) 402,

Phys. Rev. C 84 (2011) 045206

Introduction

A modern theoretical treatment of $\bar{K}N$ interaction is based on an **effective chiral Lagrangian** (a concept introduced by Weinberg for the πN interaction)

- CHPT implements the QCD symmetries in it's nonperturbative regime
- coupled channels techniques are used to deal with divergencies due to resonances in the strangeness $S = -1$ sector
- $\Lambda(1405)$ resonance generated dynamically; two $I = 0$ poles
- the leading order Tomozawa-Weinberg interaction does surprisingly well but NLO terms are necessary to achieve a good qualitative reproduction of the low energy $K^- p$ data
- new precise data on the 1s energy level characteristics in the kaonic hydrogen atom from SIDDHARTA experiment (plus the kaonic deuterium should follow soon)

OUR WORK: simultaneous description of the K -atomic and low energy $K^- p$ data to fix model parameters, then the model is used to study meson-baryon resonances and in-medium properties of the $\bar{K}N$ system

Separable meson-baryon potentials

the model describes interactions of the lightest meson and baryon octets:

$$\phi = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta \end{pmatrix} \quad B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

10 coupled $Q = 0$ channels:

$\pi^0\Lambda$	~ 1250 MeV
$\pi^0\Sigma^0, \pi^-\Sigma^+, \pi^+\Sigma^-$	~ 1330 MeV
$K^-p, \bar{K}^0n$	~ 1430 MeV
$\eta\Lambda, \eta\Sigma^0$	~ 1700 MeV
$K^0\Xi^0, K^+\Xi^-$	~ 1800 MeV

6 coupled $Q = -1$ channels:

$\pi^-\Lambda$	~ 1250 MeV
$\pi^-\Sigma^0, \pi^0\Sigma^-$	~ 1330 MeV
K^-n	~ 1430 MeV
$\eta\Sigma^-$	~ 1700 MeV
$K^0\Xi^-$	~ 1800 MeV

Separable meson-baryon potentials

We employ the effective chiral model of Kaiser, Siegel and Weise (1995) with the s-wave meson-baryon Lagrangian up to the second order, the heavy baryon formulation

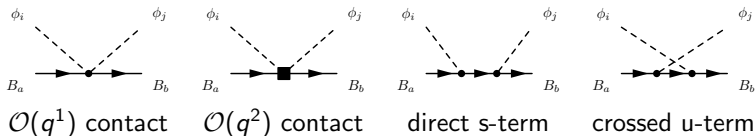
Parameters: f_π , f_K , f_η - meson decay constants

M_0 - baryon octet mass

$D \simeq 3/4$, $F \simeq 1/2$ - axial vector couplings, $g_A = F + D$

b_0 , b_D , b_F , four d 's - second order couplings

Schematic picture (taken from Borasoy, Nissler, Weise - 2005):



Separable meson-baryon potentials

Problem: χ PT is not applicable in the resonance region!

Solution: **effective separable potentials** constructed to match the chiral amplitudes up to $\mathcal{O}(q^2)$

$$V_{ij}(k, k'; \sqrt{s}) = \sqrt{\frac{1}{2\omega_i} \frac{M_i}{E_i}} g_i(k^2) \frac{C_{ij}(\sqrt{s})}{f_i f_j} g_j(k'^2) \sqrt{\frac{1}{2\omega_j} \frac{M_j}{E_j}}$$

Lippmann-Schwinger equation used to solve exactly the loop series

- kinematical factors guarantee a proper relativistic flux normalization with ω_i , M_i and E_i denoting the meson energy, the baryon mass and energy in the meson-baryon CMS
- coupling matrix C_{ij} determined by the chiral SU(3) symmetry, includes terms up to second order in the meson c.m. kinetic energies
- the formfactors $g_j(k) = 1/[1 + (k/\alpha_j)^2]$ account naturally for the off-shell effects with the inverse ranges α_j fitted to the low energy $\bar{K}N$ data
- our approach differs from the more popular on-shell scheme based on the Bethe-Salpeter equation and the unitarity relation for the inverse of the T -matrix

Separable meson-baryon potentials

The resulting meson-baryon amplitudes are of the separable form:

$$F_{ij}(p, p'; \sqrt{s}) = -\frac{g_i(p)g_j(p')}{4\pi f_i f_j} \sqrt{\frac{M_i M_j}{s}} [(1 - C(\sqrt{s}) \cdot G(\sqrt{s}))^{-1} \cdot C(\sqrt{s})]_{ij}$$

where the meson-baryon propagator $G(\sqrt{s})$ is diagonal in the channel indices i and j ,

$$G_i(\sqrt{s}; \rho) = \frac{1}{f_i^2} \frac{M_i}{\sqrt{s}} \int_{\Omega_i(\rho)} \frac{d^3 \vec{p}}{(2\pi)^3} \frac{g_i^2(p)}{p_i^2 - p^2 - \Pi_i(\omega_i, E_i, \vec{p}; \rho) + i0}$$

- integration domain $\Omega_i(\rho)$ is limited by the Pauli principle in the $\bar{K}N$ channels
- Π_i represents a sum of meson and baryon self-energies in channel i
- $\Pi_{\bar{K}} \sim F_{\bar{K}N} \rho \Rightarrow$ selfconsistent treatment required

Data reproduction

Threshold branching ratios:

$$\gamma = \frac{\sigma(K^- p \rightarrow \pi^+ \Sigma^-)}{\sigma(K^- p \rightarrow \pi^- \Sigma^+)} = 2.36 \pm 0.04 ,$$

$$R_c = \frac{\sigma(K^- p \rightarrow \text{charged particles})}{\sigma(K^- p \rightarrow \text{all})} = 0.664 \pm 0.011 ,$$

$$R_n = \frac{\sigma(K^- p \rightarrow \pi^0 \Lambda)}{\sigma(K^- p \rightarrow \text{all neutral states})} = 0.189 \pm 0.015.$$

$K^- p$ cross sections to six different meson-baryon final states:

at the $p_{LAB} = 110$ MeV for the $K^- p$, $\bar{K}^0 n$, $\pi^+ \Sigma^-$, $\pi^- \Sigma^+$

at the $p_{LAB} = 200$ MeV for the above channels plus $\pi^0 \Lambda$, $\pi^0 \Sigma^0$

Data reproduction

Kaonic hydrogen characteristics:

strong interaction energy shift	$\Delta E_N(1s)$
the decay width	$\Gamma(1s)$

two recent measurements at DAΦNE in Frascati:

DEAR (2005)	$\Delta E_N(1s) = 193 \pm 37(stat.) \pm 6(syst.) \text{ eV}$
	$\Gamma(1s) = 249 \pm 111(stat.) \pm 39(syst.) \text{ eV}$

SIDDHARTA (2011)	$\Delta E_N(1s) = 283 \pm 36(stat.) \pm 6(syst.) \text{ eV}$
	$\Gamma(1s) = 541 \pm 89(stat.) \pm 22(syst.) \text{ eV}$

our approach - **direct numerical solution of the K^-p bound state problem**, no Deser-like relation to the K^-p scattering length

Data reproduction

Fit to 15 experimental data:

3 branching ratios, 2 kaonic hydrogen characteristics, 10 cross sections

TW1 only the leading order (LO) Tomozawa-Weinberg interaction,
two parameters: $\alpha_i = \alpha_{TW} = 701$ MeV, $f_i = f_{TW} = 113$ MeV

NLO30 LO+NLO interactions, couplings f_i fixed at physical values
 $f_\pi = 92.4$ MeV, $f_K = 110.0$ MeV and $f_\eta = 118.8$ MeV,
inverse ranges of channels closed at the $\bar{K}N$ threshold set to
 $\alpha_{\eta\Lambda} = \alpha_{\eta\Sigma^0} = \alpha_{K\Xi} = 700$ MeV;
fitted 3 inverse ranges and 4 NLO d -couplings

CS30 LO+NLO model taken from our previous work, included DEAR data instead of SIDDHARTA

inverse ranges (in MeV) and d -couplings (in GeV^{-1}):

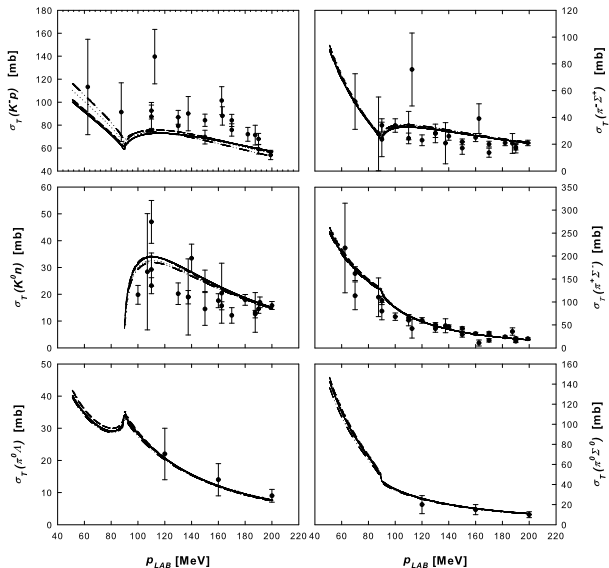
model	$\alpha_{\pi\Lambda}$	$\alpha_{\pi\Sigma}$	$\alpha_{\bar{K}N}$	d_0	d_D	d_F	d_1
CS30	291	601	639	-0.450	0.026	-0.601	0.235
NLO30	297	491	700	-0.812	0.288	-0.737	-0.016

Data reproduction

K^-p threshold data calculated in several LO and LO+NLO coupled-channel chiral models.

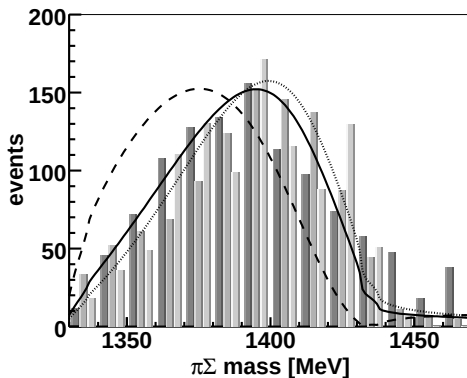
model	ΔE_{1s}	Γ_{1s}	γ	R_c	R_n	$z_1(l=0)$	$z_2(l=0)$
TW1	323	659	2.36	0.636	0.183	(1371, -54)	(1433, -25)
JOORM	275*	586*	2.30	0.618	0.257	(1389, -64)	(1427, -17)
IHW	373*	495*	2.36	0.66	0.20	(1384, -90)	(1422, -16)
NLO30	310	607	2.37	0.660	0.191	(1355, -86)	(1418, -44)
CS30	260	692	2.37	0.655	0.188	(1398, -51)	(1441, -76)
BNW	236*	580*	2.35	0.653	0.194	(1408, -37)	(1449, -106)
IHW	306*	591*	2.37	0.66	0.19	(1381, -81)	(1424, -26)
exp.	283	541	2.36	0.664	0.189	—	—
error ($\pm$)	42	111	0.04	0.011	0.015	—	—

Data reproduction



Data reproduction

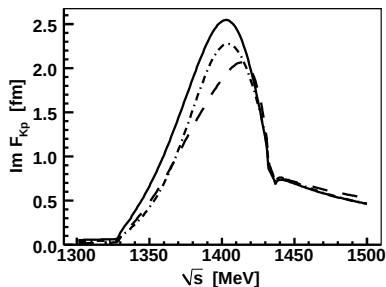
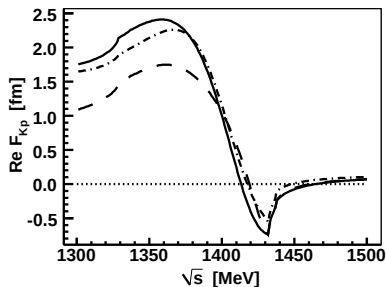
$\pi\Sigma$ mass distribution: comparison with results taken from three "compatible" experiments:



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

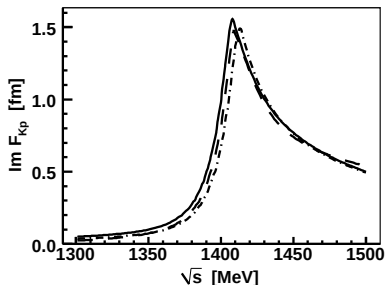
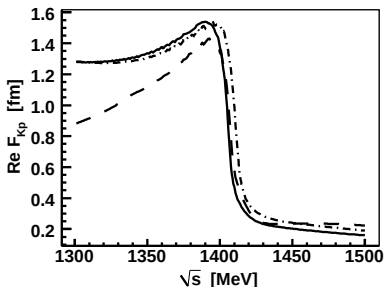
Free space and in-medium $\bar{K}N$ amplitudes

Energy dependence of the real (left panel) and imaginary (right panel) parts of the elastic K^-p amplitude in the free space. Dashed curves: TW1 model, dot-dashed: CS30 model, solid curves: NLO30 model.

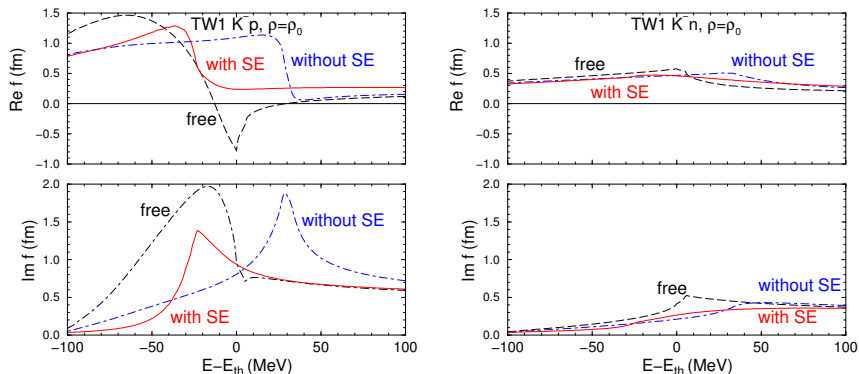


Free space and in-medium $\bar{K}N$ amplitudes

Energy dependence of the real (left panel) and imaginary (right panel) parts of the elastic K^-p amplitude in nuclear medium at the nuclear density $\rho = \rho_0$. Dashed curves: TW1 model, dot-dashed: CS30 model, solid curves: NLO30 model.



Free space and in-medium $\bar{K}N$ amplitudes



Energy dependence of the c.m. reduced amplitudes f_{K-p} (left panels) and f_{K-n} (right panels) in our TW1 model. The upper and lower panels refer to the real and imaginary parts of the $\bar{K}N$ amplitudes, respectively. Dashed curves: free space, dot-dashed: Pauli blocked amplitude (without SE) at $\rho = \rho_0$, solid curves: including meson and baryon self energies (with SE) at $\rho = \rho_0$.

$\bar{K}$ -nuclear optical potential

single nucleon approximation, a coherent sum of $\bar{K}N$ interactions:

$$V_{K^-} = - \frac{2\pi}{\omega_K} \left(1 + \frac{\omega_K}{m_N}\right) F_{K^-N}(\vec{p}, \sqrt{s}; \rho) \rho$$

The kaons interacting with nuclei probe the subthreshold energy region!

two-body c.m. system: $\vec{p}_K + \vec{p}_N = \vec{0}$

K^- -nucleus c.m. system: $\vec{p}_K + \vec{p}_N \neq \vec{0}$

bound hadrons, averaging over angles, local density approximation, Fermi gas model:

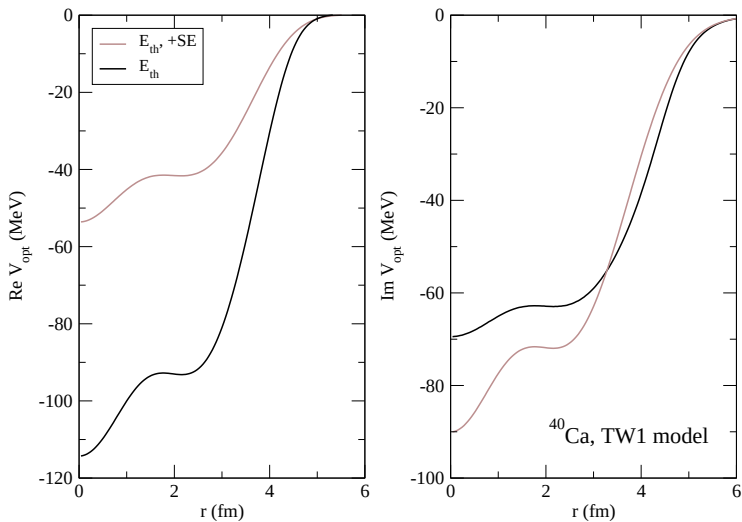
$$\sqrt{s} \approx E_{\text{th}} - B_N - \frac{m_N}{m_N + m_K} B_K - 15.1 (\rho/\rho_0)^{2/3} + \frac{m_K}{m_N + m_K} \text{Re } \mathcal{V}_{K^-}(\rho) \quad (\text{in MeV})$$

in nuclear medium, one has to use realistic momenta in the form factors $g_i(p)$

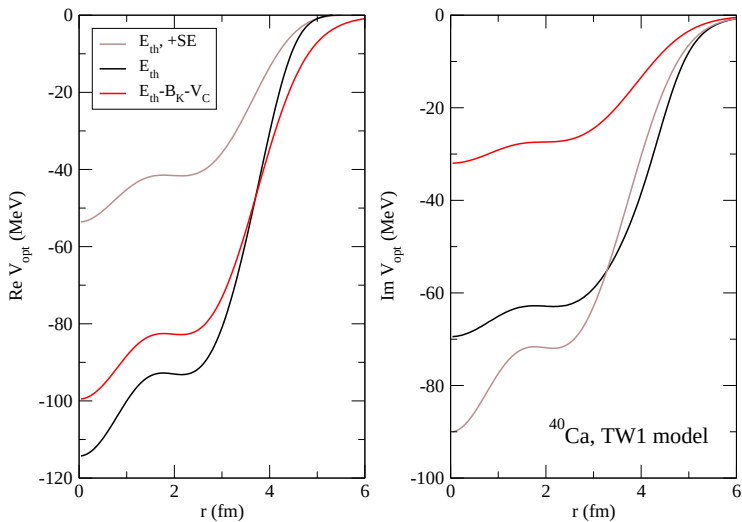
$$p^2 \approx \frac{m_K m_N}{(m_N + m_K)^2} [2m_K T_N(\rho/\rho_0)^{2/3} - 2m_N (B_K + \text{Re } \mathcal{V}_{K^-}(\rho))],$$

A.C., E. Friedman, A. Gal, D. Gazda, J. Mareš - PRC84 (2011) 045206

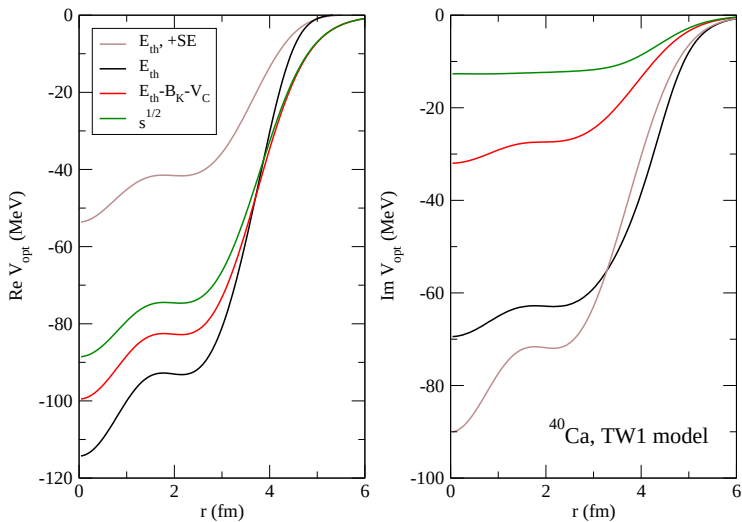
$\bar{K}$ -nuclear optical potential



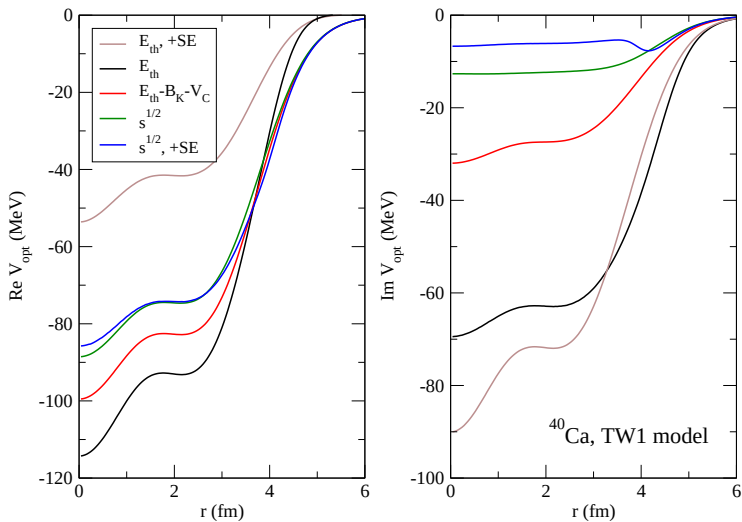
$\bar{K}$ -nuclear optical potential



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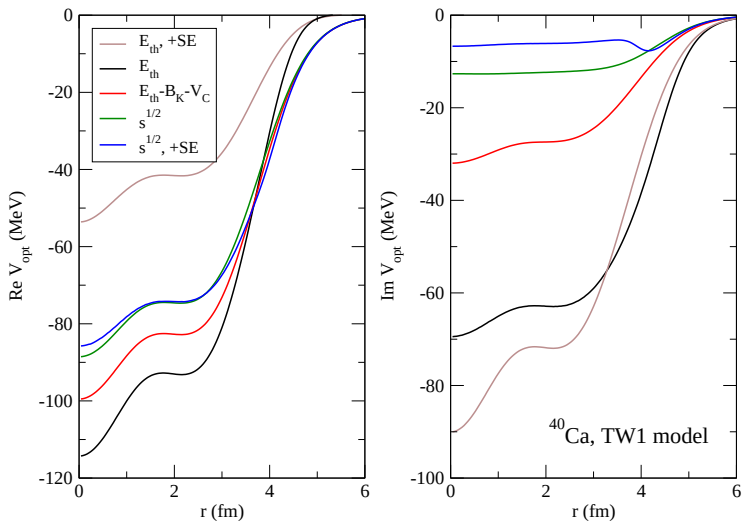


$\bar{K}$ -nuclear optical potential



calculations by D. Gazda, J. Mareš, to appear in Nucl. Phys. A 881 (2012) 159

$\bar{K}$ -nuclear optical potential



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Summary

- The in-medium dynamics of the $\Lambda(1405)$ resonance is responsible for the rapid increase of the real part of our K^-p amplitude at energies about 30 MeV below the $\bar{K}N$ threshold.
- The Pauli blocking pushes the resonance structure above the threshold and the kaon self-energy is responsible for moving it back to energies where it is located in the free space.
- The construction of the optical potential from subthreshold $\bar{K}N$ energies allows to link the shallow $\bar{K}$ -nuclear potentials based on the chiral $\bar{K}N$ amplitude evaluated at threshold and the deep phenomenological optical potentials obtained in fits to kaonic atoms.
- Our LO+NLO model fitted to the SIDDHARTA data generates $\bar{K}N$ amplitudes (in vacuum and in the nuclear medium) that are very close to those obtained with our older model that used the DEAR data.
Reason: kaonic hydrogen characteristics computed with the old model were already more compatible with SIDDHARTA than with DEAR.
- New measurements of $K^-p \rightarrow \pi^0\Lambda$ and $K^-p \rightarrow \pi^0\Sigma^0$ reactions at low kaon energies would be highly appreciated.