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$\eta' N$ interaction: Where are we?

Aleš Cieplý

Nuclear Physics Institute, Řež/Prague, Czechia

Outline:

1. Introduction
2. $\eta N - \eta' N$ coupled channel model
3. Results and outlook
4. Summary

collaboration with P. C. Bruns[†], A. Gal
(+ E. Friedman, J. Mareš, J. Smejkal)

Introduction

- origin of the large η' mass: $U_A(1)$ anomaly, does not vanish when the chiral symmetry is restored, so η' cannot be treated as a Goldstone boson
- The η and η' effective masses are reduced in nuclear medium relating to self-energies corresponding to attractive optical potentials, $V^{\rm opt} = (V_0 + iW_0)\,\rho(r)/\rho(0)$, *CBELSA/TAPS (2013)*: $V_0 \approx -40$ MeV
- *Y. Matsumura et al. (LEPS2/BGOegg), PRL 137 (2026) 051901*: first direct measurement $\Delta m_{\eta'} \approx -60$ MeV, $\eta' \to \gamma\gamma$ in carbon target
- *S. Sakai, D. Jido, Phys. Rev. C 88 (2013) 064906*: linear sigma model used to study the η' mass in nuclear matter, $\Delta m_{\eta'} \approx -80$ MeV
- dressed in-medium meson propagator

$$D^*(\omega, \vec{k}, \rho) = 1/[\omega^2 - m^2 - k^2 - \Pi(\omega, \vec{k}, \rho) + i0]$$

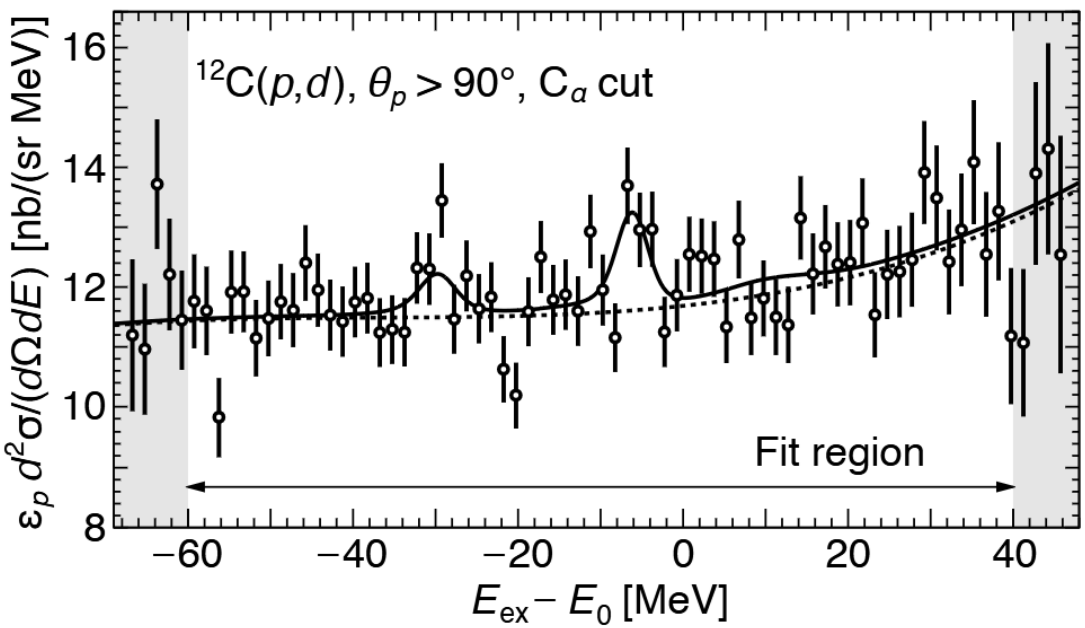
$$\Pi(\omega, \vec{k}, \rho) = 2\omega V^{\rm opt} = -4\pi \frac{\mathcal{M}}{\mu} f_{MN}(\omega, k, \rho)\,\rho \approx -4\pi(1 + \frac{m}{M})\, f_{MN}(\omega, k, \rho)\,\rho$$

the mass pole of the propagator is shifted: $m^{*2}(k) = m^2 - 4\pi \frac{\mathcal{M}}{\mu} f_{MN}(\omega, k, \rho)\,\rho$

attraction at threshold: $\Delta m = m^* - m < 0 \iff Re\, a_{MN} > 0$

Introduction

- *Haider, Liu (1986)*: concept of mesic nuclei, meson-nuclear systems bound by strong interaction, η and η' are promising candidates
- *J. J. Cobos-Martinez, K. Tsushima, Phys. Rev. C 109 (2024) 025202* local density approximation used to construct $V^{\rm opt}$ from the in-medium mass shifts derived from quark-meson couplig model to calculate the η-nuclear and η'-nuclear states
- $\eta' - {}^{11}C$ bound state observed at GSI in ${}^{12}C(p,d)$ reaction missing mass spectra *R. Sekiya et al., PRL 136 (2026) 142501*



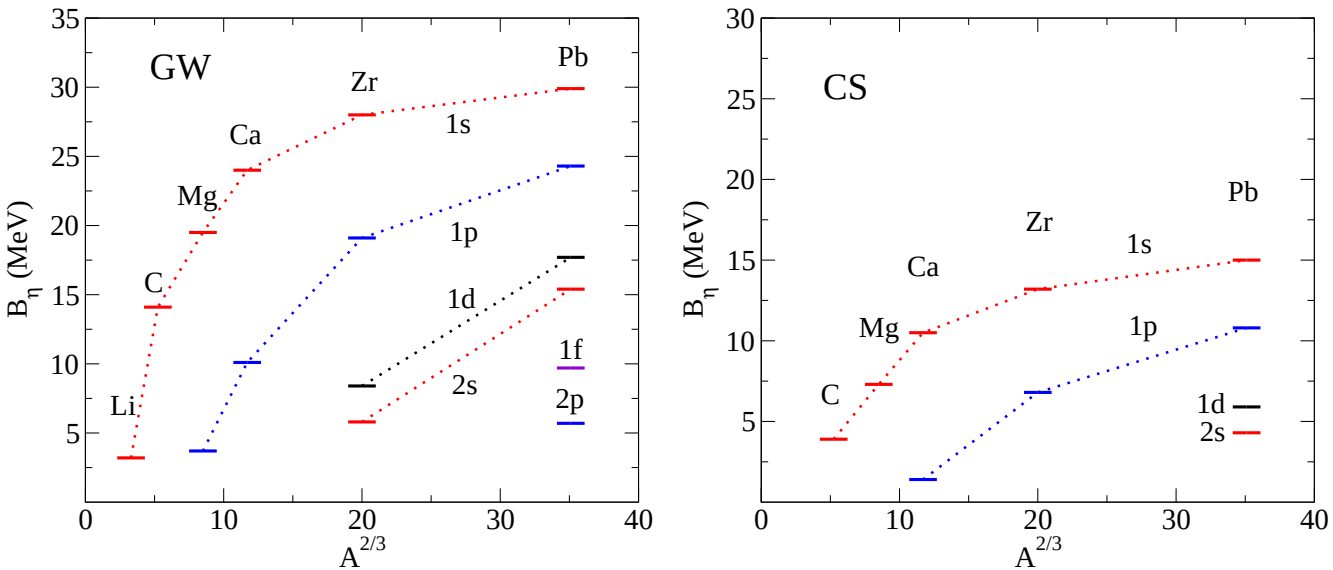
two peaks 6 and 30 MeV below η' emission threshold,
compatible with $V_0 \sim -61$ MeV, $|W_0| \lesssim 10$ MeV

η-nuclear bound states

chirally motivated coupled channels approaches: attraction with $Re\ a_{\eta N} \approx 0.3 - 1.0$ fm

two possible mechanisms of generating observable η-nuclear bound states found in self-consistent calculations of η-nuclear quasi-bound states:

- sufficiently large ηN attraction, $Re\ a_{\eta N} \approx 1$ fm (GW model, K-matrix approach)
- moderate attraction $Re\ a_{\eta N} \gtrsim 0.7$ fm combined with fast subthreshold decrease of $Im\ F_{\eta N}$ (CS model, chiral)



decay widths $\sim$ few MeV (only ηN contributions)
moderately larger widths expected due to $\pi\pi N$ and ηNN contributions

A. C., E. Friedman, A. Gal, J. Mareš - Nucl. Phys. A 925 (2014) 126

Chirally motivated $\eta N/\eta' N$ interactions

A. C., J. Smejkal - Nucl. Phys. A 919 (2013) 46 - no $\eta' N$ channel, $\eta = \eta_8$

P. C. Bruns, A. C. - Nucl. Phys. A 992 (2019) 121630 - including the $\eta_0 - \eta_8$ mixing

Involved channels: πN, ηN, $K\Lambda$, $K\Sigma$, $\eta' N$ ($I = 1/2$ sector)
πN, $K\Sigma$ ($I = 3/2$ sector)

Model features:

- only pseudoscalar meson - baryon channels considered, no $\pi\pi N$
- very large interval of energies $\sim 1.2 - 2.0$ GeV
- s-wave treatment sufficient for ηN and $\eta' N$ channels at energies close to the respective thresholds
- $N^*(1535)$ resonance about 40 MeV above the ηN threshold generated dynamically; the role of $N^*(1650)$ and $N^*(1895)$ discussed

Effective chiral Lagrangian

$$\begin{aligned}\mathcal{L}^{(1)}_{MB} &= i\langle\bar{B}\gamma_\mu[D^\mu, B]\rangle - M_0\langle\bar{B}B\rangle + i\frac{w_s}{F_0^2}\eta_0^2\left(\langle[D^\mu,\bar{B}]\gamma_\mu B\rangle - \langle\bar{B}\gamma_\mu[D^\mu,B]\rangle\right)\\ &+ \frac{1}{2}D\langle\bar{B}\gamma_\mu\gamma_5\{u^\mu,B\}\rangle + \frac{1}{2}F\langle\bar{B}\gamma_\mu\gamma_5[u^\mu,B]\rangle + \frac{1}{2}D_s\langle\bar{B}\gamma_\mu\gamma_5 B\rangle\langle u^\mu\rangle\end{aligned}$$

two extra terms due to inclusion of the η_0 field:

- η_0 - baryon contact term proportional to w_s
- η_0 - baryon axial coupling term proportional to D_s

$$\begin{aligned}\mathcal{L}^{(2)}_{MB} &= b_D\langle\bar{B}\{\chi_+,B\}\rangle + b_F\langle\bar{B}[\chi_+,B]\rangle + b_0\langle\bar{B}B\rangle\langle\chi_+\rangle\\ &+ d_1\langle\bar{B}\{u_\mu,[u^\mu,B]\}\rangle + d_2\langle\bar{B}[u_\mu,[u^\mu,B]]\rangle + d_3\langle\bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle\bar{B}B\rangle\langle u_\mu u^\mu\rangle\\ &+ (\text{some more } c_{D,F,0} \text{ and } d_{5,6,7} \text{ terms})\end{aligned}$$

$$c_{D,F,0} = d_{5,6,7} = 0$$

one-mixing-angle scheme ($\vartheta = -15.5^\circ$) to describe the singlet-octet mixing:

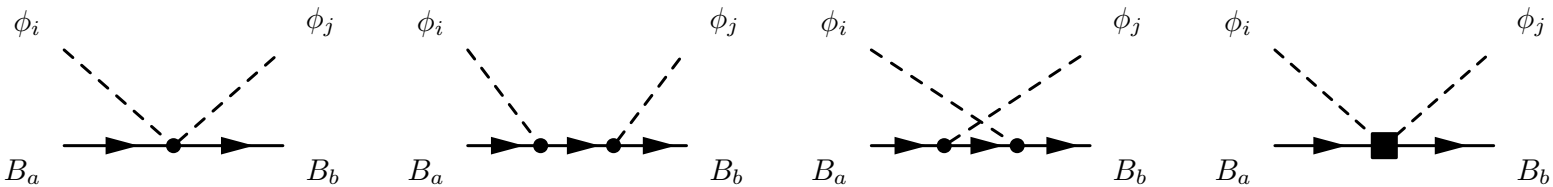
$$\eta_8 = \eta\cos\vartheta + \eta'\sin\vartheta\,, \quad \eta_0 = \eta'\cos\vartheta - \eta\sin\vartheta$$

Chirally motivated *MB* interactions

- effective potentials constructed to match the tree-level meson-baryon amplitudes derived from the chiral Lagrangian up to NLO order

$$v_{0+}(s) := f_{0+}^{\mathrm{tree}}(s) = \frac{\sqrt{E_B + M_B}}{F_\Phi} \left(\frac{C(s)}{8\pi\sqrt{s}} \right) \frac{\sqrt{E_B + M_B}}{F_\Phi}$$

- the matrix $C(s)$ comprises contributions from the Weinberg-Tomozawa, direct and crossed Born terms, and from NLO corrections to the WT term

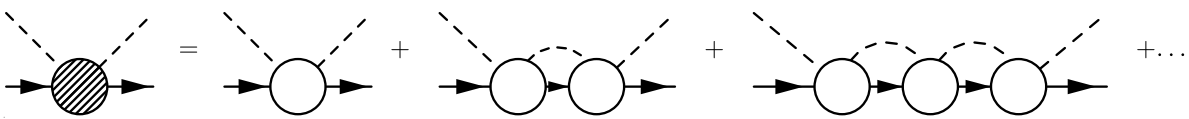


$\mathcal{O}(q^1)$ contact | direct s-term | crossed u-term | $\mathcal{O}(q^2)$ contact

- Lippmann-Schwinger equation used to sum the major part of the perturbation series

$$f = v + v\,G\,f = v + v\,G\,v + v\,G\,v\,G\,v\,\cdots = (1 - v\,G)^{-1}\,v$$

graphical representation:



Chirally motivated *MB* interactions

- the transition amplitudes f, effective potentials v and MB loop functions G are energy dependent and represented by matrices in the MB channel space
- we use separable form of the effective potentials

$$v_{c'c}(W=\sqrt{s}) = g_{c'}(k_{c'})\,[f_{0+}^{\rm tree}(W)]_{c'c}\,g_c(k_c)$$

with Yamaguchi form factors $g_c(k) = 1/[1+(k/\alpha_c)^2]$ that feature regulator scales (*soft cutoffs*) α_c

- LSE solved algebraically

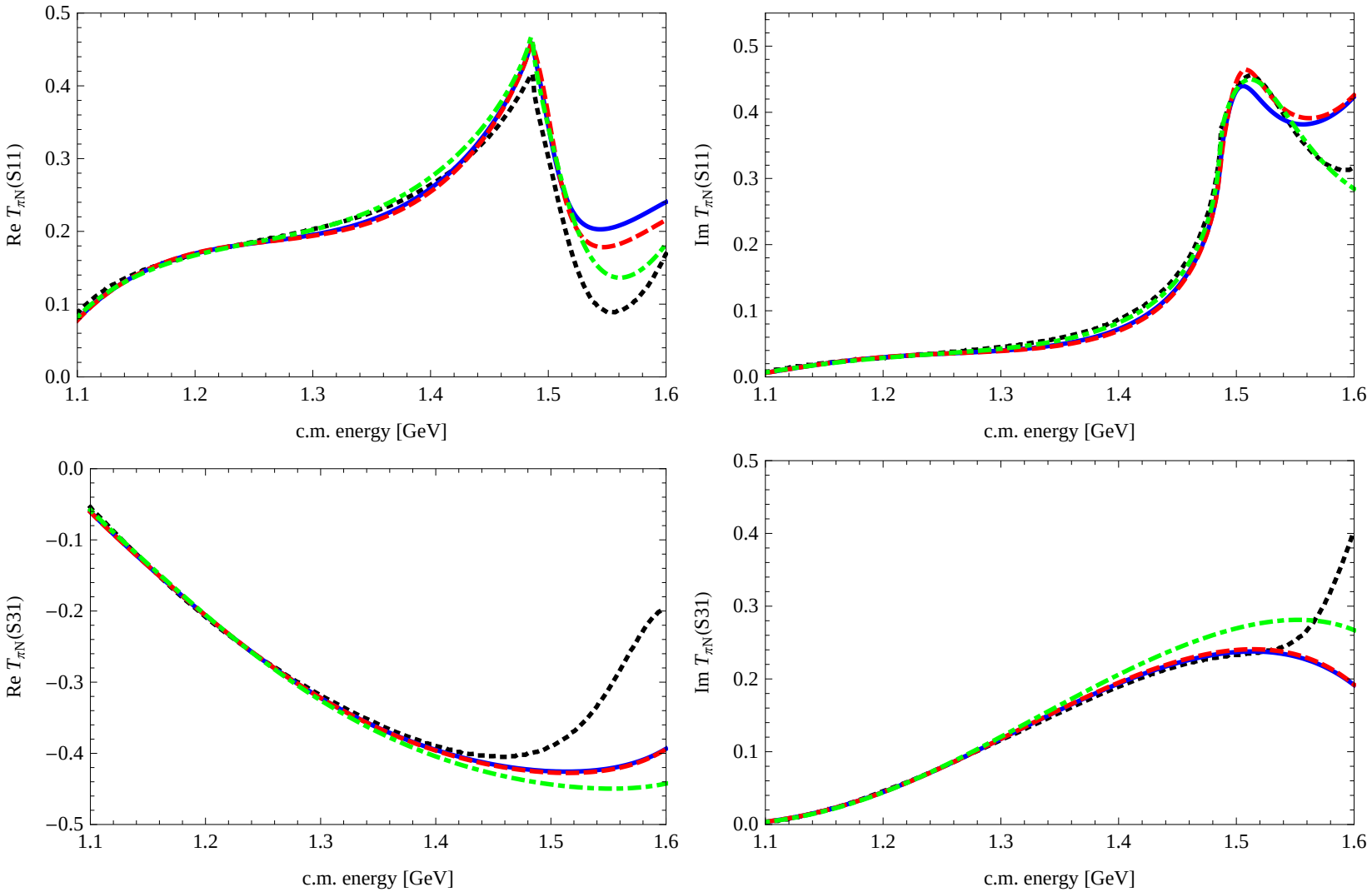
$$f_{c'c}(W) = g_{c'}(k_{c'})\left[(1-v(W)\cdot G(W))^{-1}\cdot v\right]_{c'c} g_c(k_c)$$

$$G_c(W) = -4\pi\int\frac{d^3p}{(2\pi)^3}\frac{g_c^2(p^2)}{k_c^2-p^2+{\rm i}0} = \frac{(\alpha_c+{\rm i}q_c)^2}{2\alpha_c}\,g_c^2(q_c)$$

- parameters: scales α_c, LECs (NLO couplings) from the chiral Lagrangian (α_c, b_0, b_F, 4 d's, 2 more due to η_0) fitted to reproduce πN partial wave amplitudes and $\pi^- p \longrightarrow \eta n$, $K^0\Lambda$ and $\eta' n$ cross sections
- several fitting strategies adopted represented by models A (most comprehensive), B (simplified $\pi\pi N$ inelasticity) and C (no $\eta_0-\eta_8$ mixing) etc.

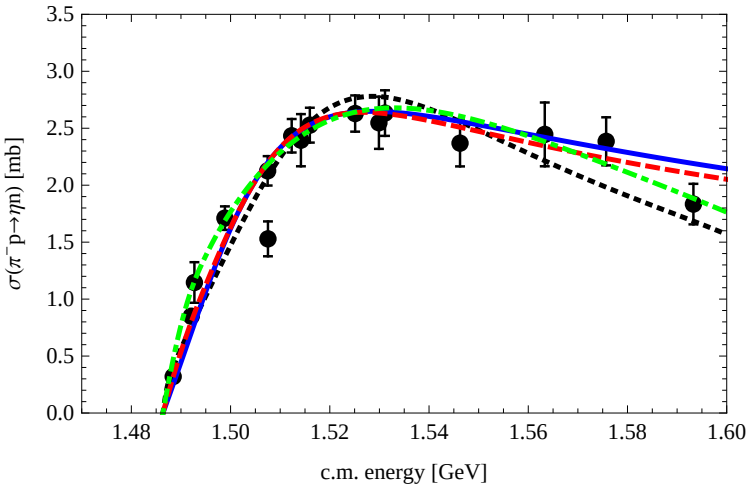
data reproduction - πN amplitudes

dimensionless $T^I_{0+}(s) = q_{\pi N}(s)[f^I_{0+}(s)]_{\pi N,\pi N}$ compared with the SAID solution

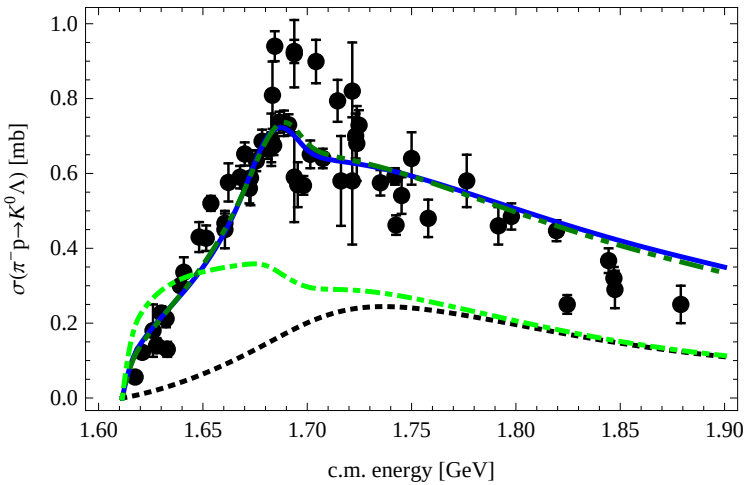


data reproduction - $\pi^- p$ cross sections

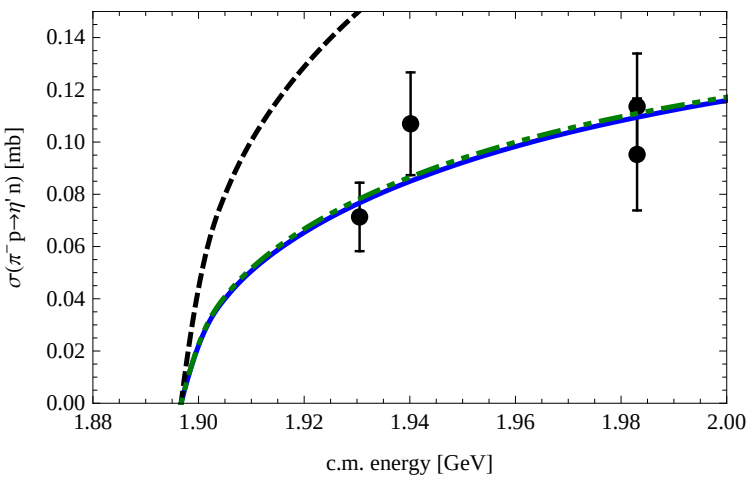
$\sigma_T(\pi^- p \to \eta n)$



$\sigma_T(\pi^- p \to K\Lambda)$



$\sigma_T(\pi^- p \to \eta' n)$

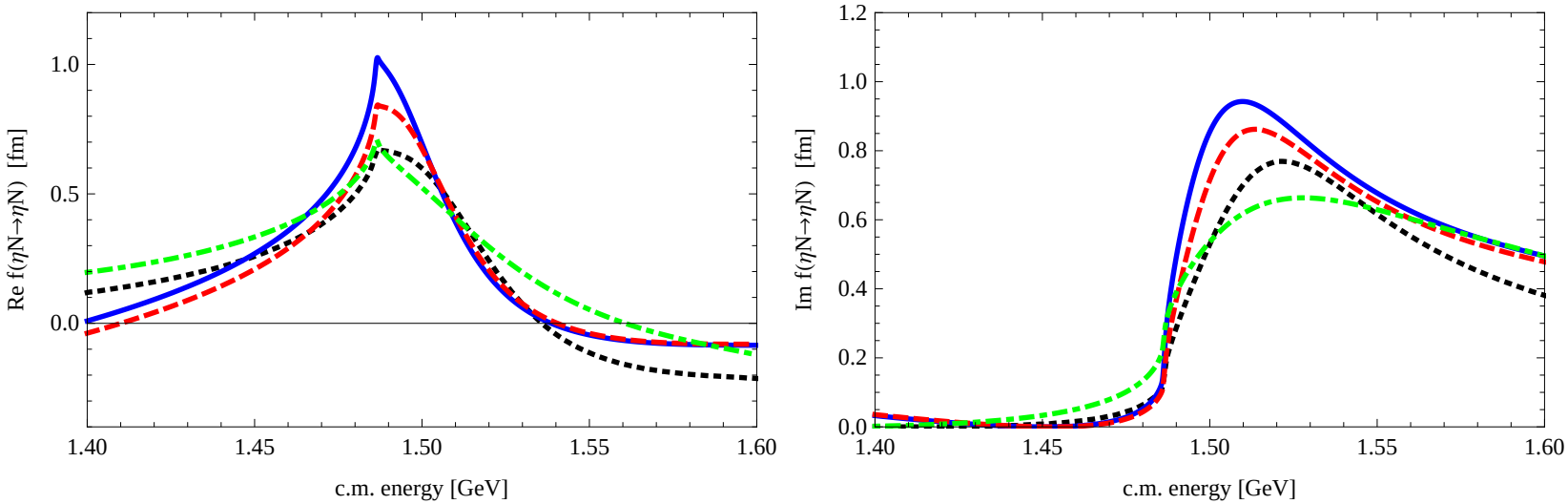


S_{11} scattering lengths (in fm):

model	A	B	C
πN	(0.20, 0.00)	(0.20, 0.00)	(0.22, 0.00)
ηN	(1.05, 0.17)	(0.86, 0.13)	(0.73, 0.26)
$\eta' N$	(-0.41, 0.04)	(-0.41, 0.04)	—

model A - our best, model C (no η'),
model B (simple $\pi\pi N$),
E model, η mixing switched off

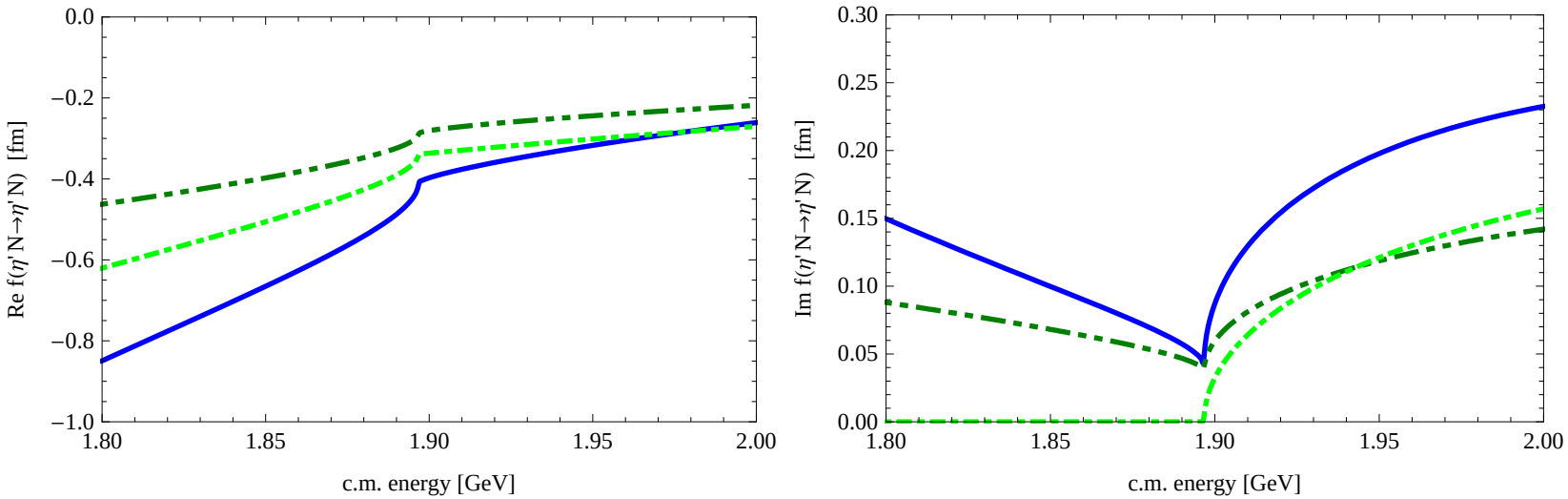
ηN elastic amplitude



model A (our best), model B (simple $\pi\pi N$), model C (no η'), CS model (dotted)

- Around threshold the ηN amplitude is clearly dominated by the $N^*(1535)$ resonance.
- the η_0 component increases the ηN attraction to Re $a_{\eta N} \approx 1$ fm in agreement with the phenomenological K-matrix analysis by *Green and Wycech, PRC 71 (2005) 014001*, and prediction made by *Bass and Thomas, PLB 634 (2006) 368*. Good news for the η-nuclear states!
- Different $\pi\pi N$ inelasticity settings adopted in our models lead to moderate variations of the ηN amplitude energy dependence.

$\eta' N$ elastic amplitude



model A (best), model E (η mixing switched off), model C ($\eta' N$ decoupled)

- analysis of the $pp \longrightarrow pp\eta'$ reaction measurement at COSY in Jülich provides

  $$\mathrm{Re}\, a_{\eta' N} = 0 \pm 0.43 \text{ fm and } \mathrm{Im}\, a_{\eta' N} = 0.37^{+0.40}_{-0.16} \text{ fm}$$

  Czerwinski et al. - PRL 113 (2014) 062004
- our $a_{\eta' N}$ predictions are remarkably stable, real part within the experimental limits, imaginary part too small due to model deficiencies
- our models predict repulsive $\eta' N$ interaction at the threshold
  maybe too early to conclude due to our model limitations

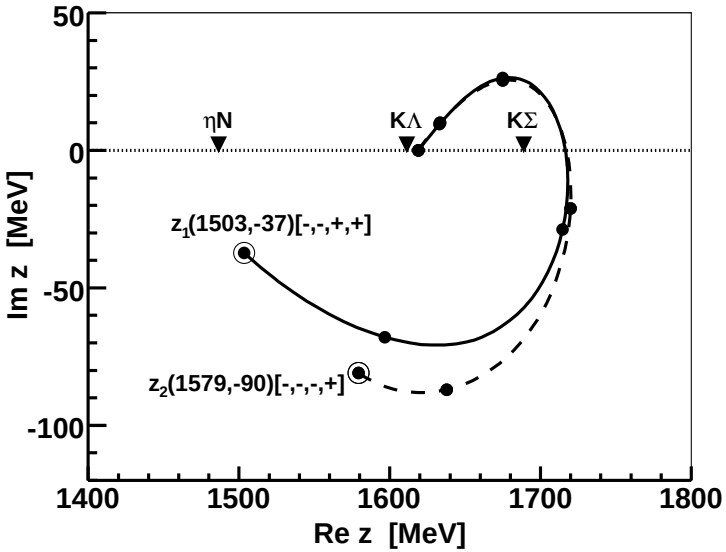
Dynamically generated N^* resonances

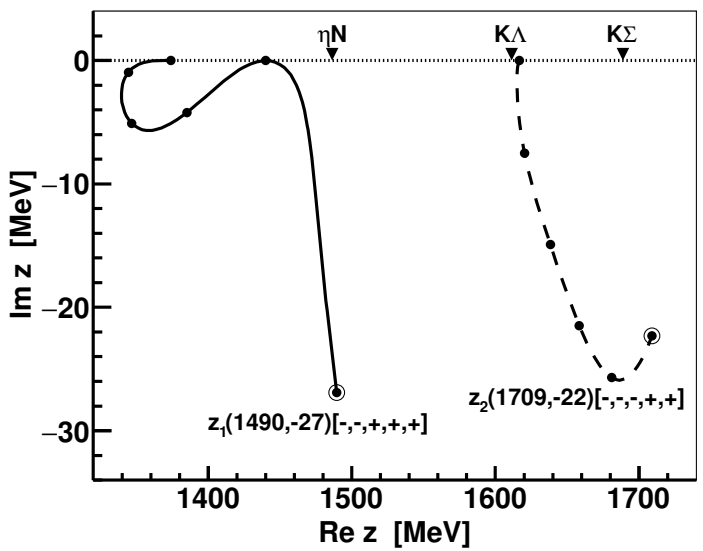
$N^*(1535)$ generated dynamically with a strong coupling to $K\Lambda$, satisfactory attributes when compared with PDG listings

$N^*(1650)$ generated dynamically with a strong coupling to $K\Sigma$, quite off the position listed in PDG as it is not restricted by the data used in our fits

$N^*(1895)$ missing in our approach; though, there is a pole coupling strongly to the $\eta' N$ channel ($\eta' N$ bound state with inter-channel couplings switched off) but drifting too far from being physically meaningful

poles oringins in ZCL (left - no η_0, right - with η_0):





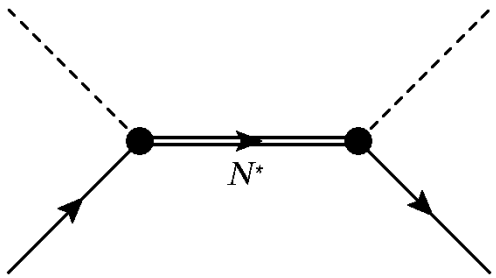
left - both resonances originate from the same $K\Sigma$ bound state
right - $N^*(1535)$ from $K\Lambda$, $N^*(1650)$ from $K\Sigma$ bound states

Outlook (some ideas)

A. Gal (private communication) - *Re* $a_{\eta' N} \gtrsim 0.5$ fm required for η'-nuclear states
see also *E. Friedman, A. Gal, Phys. Lett. B 870 (2025) 139916*

What can we do about the $\eta' N$ repulsion?

$N^*(1895)$ dominance around the $\eta' N$ threshold



$$f_{ji}(z) = f_{ji}^{\mathrm{BG}}(z) - \frac{g_j\, g_i}{z - z_R}$$

$$\Gamma_j = \lim_{z \to z_R} \mid 2q_j(z)\,(z - z_R)\, f_{jj}(z) \mid$$

$$= \mid 2q_j(z_R)\,(g_j)^2 \mid$$

similar model considered in *S. Sakai, D. Jido, PRC 107 (2023) 025207*

possible impact of ϕN quasibound state
E. Chizali et al., Phys. Lett. B 848 (2024) 138358
re-analysis of the experimental ϕp correlation function measured by ALICE, spin 3/2 channel constrained by LQCD results, supports an existence of ϕp bound state with $B_{\phi p} \approx 13 - 56$ MeV and scattering length $a_{\phi p}^{(1/2)} = [\,-1.5(7) + i\,0.0(5)\,]$ fm
it is difficult to understand where so large ϕp attraction comes from but if it is confirmed, it may affect the $\eta' N$ channel with a threshold not too far below it

Outlook (some ideas)

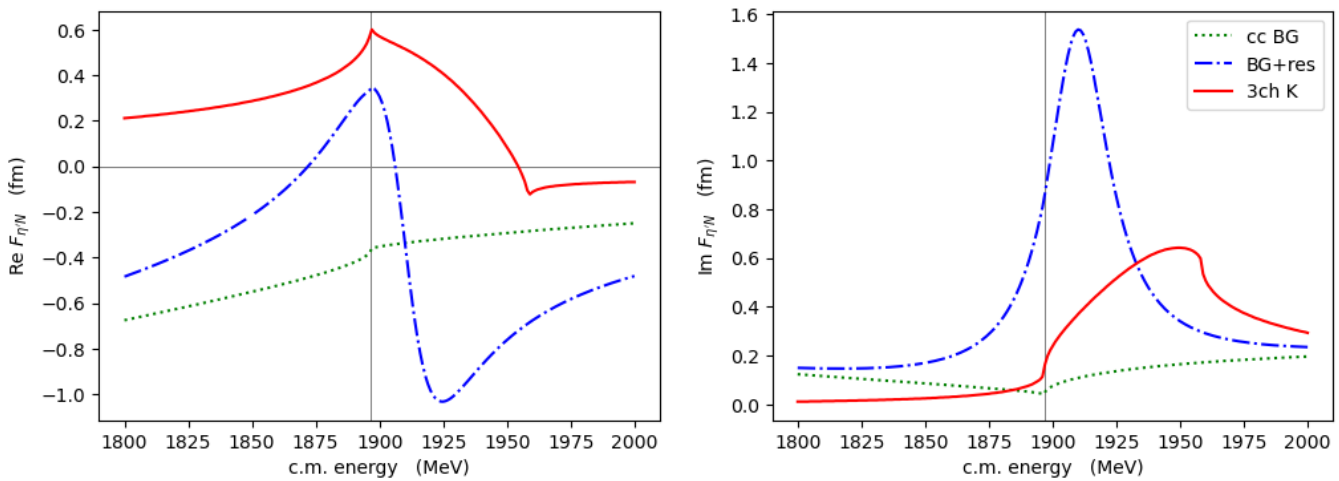
a toy model: K-matrix approach inspired by what Wycech, Green did for $\pi N - \eta N$

$$K_{ij} = B_{ij} + \frac{\gamma_i \gamma_j}{E_R - E}$$

we need at least one channel below the $\eta' N$ threshold! sample setting:

channel	$K\Sigma$	$\eta' N$	ϕN
threshold [MeV]	1680	1897	1958
$(\gamma_i)^2$	0.1	0.6	0.7

one resonance at $E_R = 1910.5$ MeV, no background $B_{ij} = 0$



Outlook (some ideas)

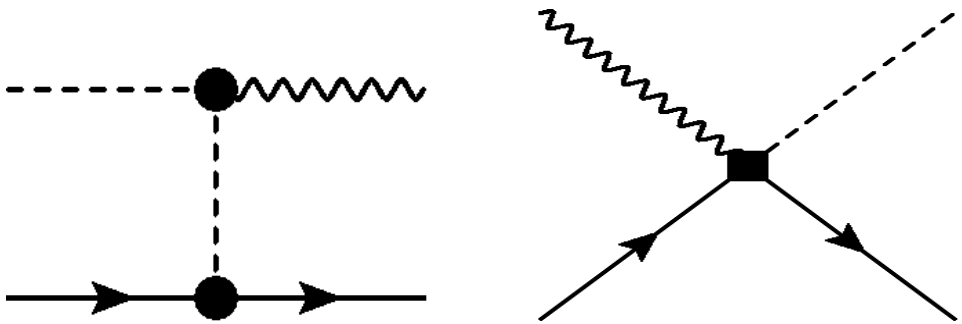
a more comprehensive approach:

MB coupled channels involving both, pseudoscalar and vector mesons

channel space: πN, ηN, $K\Lambda$, $K\Sigma$, $\eta' N$ + ρN, ωN, ϕN, $K^*\Lambda$, $K^*\Sigma$

dynamically generated resonance formed from the $K^*\Sigma$ channel may play a role
$E_{\rm th} \approx 2.1$ GeV too high? could be brought down by CC dynamics

contributions from:



vertices defined by VMD and hidden local symmetry Lagrangian
there are already some models on the market, though without the $\eta' N$ channel:

Garzon, Oset (2013, 2015)
Khemchandani, Martinez Torres, Nagahiro, Hosaka (2012, 2013, ...)

Summary

- ηN and $\eta' N$ in-medium mass shifts indicate attractive η/η'-nuclear optical potentials and positive real parts of the scattering lengths.
- η'-nuclear quasi-bound states have been reported quite recently. Some predictions for the η-nuclear states are available.
- Our chirally motivated coupled channel model predicts sufficiently strong ηN attraction but a repulsive $\eta' N$ interaction.
- It is not clear where the reported strong ϕN attraction found in the femtoscopic analysis of the correlation function measured by ALICE comes from. It opens a question whether this may be related somehow to the $\eta' N$ interaction too.
- The $N^*(1895)$ resonance or $\eta' N$ couplings to VB channels are good candidates to play a role in future studies of the discussed topic.

Thank you for your attention !!!