Experimental challenges to confront $\bar{K}N$ *interaction* from UChPT

Albert Feijoo
Institut de Física Corpuscular (IFIC), València

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Aim: Experimental repercussions on the **meson-baryon interaction** in the **S=-1** sector at different energy regimes.10 channels involved in this sector: $K^- p, \bar{K}^0 n, \pi^0 \Lambda, \pi^0 \Sigma^0, \pi^+ \Sigma^-, \pi^- \Sigma^+, \eta \Lambda, \eta \Sigma^0, K^+ \Xi^-, K^0 \Xi^0$

Interaction: **QCD** is a gauge theory which **describes** the **strong interaction** governed by the effects of the color charge of its carriers: quarks and gluons.
Perturbative QCD is inappropriate to treat low energy hadron interactions.

Chiral Perturbation Theory (ChPT) is an effective theory with hadrons as degrees of freedom which respects the symmetries of QCD.

- limited to a moderate range of energies above threshold
- not applicable close to a resonance (singularity in the amplitude)

But it is not so straight forward …

$\bar{K}N$ interaction is dominated by the presence of the $\Lambda(1405)$ resonance, located only 27 MeV below the $\bar{K}N$ threshold.

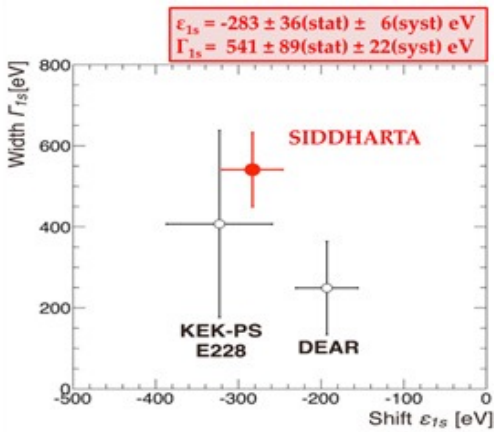
→ **A nonperturbative resummation is needed!!!**

In 1995, the problem was reformulated in terms of a Unitary extension of ChPT in coupled channels.
The pioneering work -- *Kaiser, Siegel, Weise,* Nuc. Phys. A 594 (1995) 325.

E. Oset, A. Ramos, Nucl. Phys. A 636, 99 (1998).
J. A. Oller, U. -G. Meissner, Phys. Lett. B 500, 263 (2001).
M. F. M. Lutz, E. Kolomeitsev, Nucl. Phys. A 700, 193 (2002).
B. Borasoy, E. Marco, S. Wetzel, Phys. Rev. C 66, 055208 (2002).
C. Garcia-Recio, J. Nieves, E. Ruiz Arriola and M. J. Vicente Vacas, Phys. Rev. D 67, 076009 (2003).
D. Jido, J. A. Oller, E. Oset, A. Ramos and U. G. Meissner, Nucl. Phys. A 725, 181 (2003).
B. Borasoy, R. Nissler, W. Wiese, Eur. Phys. J. A 25, 79 (2005).
V.K. Magas, E. Oset, A. Ramos, Phys. Rev. Lett. 95, 052301 (2005).
B. Borasoy, U. -G. Meissner and R. Nissler, Phys. Rev. C 74, 055201 (2006).

All of them obtaining in general similar features:
- **$\bar{K}N$ scattering data reproduced very satisfactorily**
- **Two-pole structure of $\Lambda(1405)$**

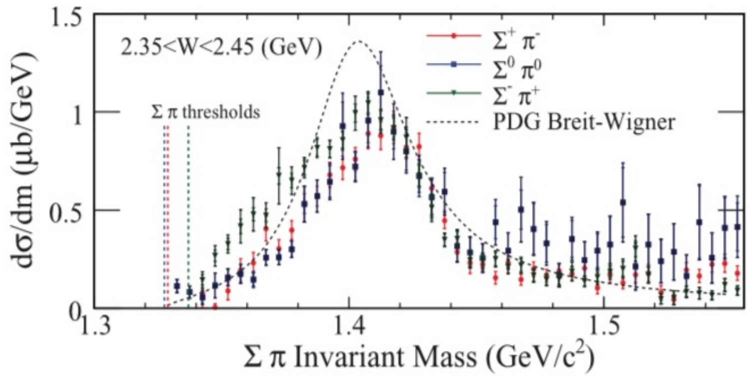
This topic has experienced a renewed interest after recent experimental advances:



M. Bazzi et al., Phys. Lett. B 704, 113 (2011).

Energy shift and width of the 1s state in kaonic hydrogen by SIDDHARTA@DAΦNE, 20% precision in the K^-p scattering length!!!

Photoproduction $\gamma p \longrightarrow K^+\pi\Sigma$ data by the CLAS@Jlab provided detailed line shape results of the $\Lambda(1405)$



K. Moriya *et al.*, Phys. Rev. C**87**, 035206(2013).

Y. Ikeda, T. Hyodo, W. Wiese, Nucl. Phys. A 881, 98 (2012).
A. Cieply and J. Smejkal, Nucl. Phys. A 881, 115 (2012).
Zhi-Hui Guo, J. A. Oller, Phys. Rev. C 87, 035202 (2013).
T. Mizutani, C. Fayard, B. Saghai and K. Tsushima, Phys. Rev. C 87, 035201 (2013).
L. Roca and E. Oset: Phys. Rev. C 87, 055201 (2013), Phys. Rev. C 88, 055206 (2013).
M. Mai and U. G. Meissner, Eur. Phys. J. A 51, 30 (2015).
A. F., V. Magas, A. Ramos, Phys. Rev. C 92, 015206 (2015); Nucl. Phys. A 954, 58 (2016); Phys. Rev. C 99 (2019) 035211.
P.C. Bruns, A. Cieply, Nucl. Phys. A 1019 (2022), 122378.

Lagrangian:

$$\mathcal{L}^{eff}(B,U) = \mathcal{L}^{(1)}_{MB}(B,U) + \mathcal{L}^{(2)}_{MB}(B,U)$$

→ derive an interaction kernel $\mathbf{V_{ij}}$

- **Leading order (LO)**

$$\mathcal{L}^{(1)}_{MB} = \langle \bar{B}(i\gamma_\mu D^\mu - M_0)B \rangle + \frac{1}{2} D \langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2} F \langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle$$

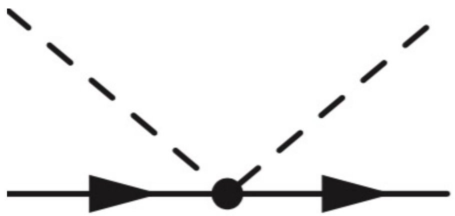
Lagrangian:

$$\mathcal{L}^{eff}(B,U) = \mathcal{L}^{(1)}_{MB}(B,U) + \mathcal{L}^{(2)}_{MB}(B,U)$$ → derive an interaction kernel **V_{ij}**

- **Leading order (LO)**

$$\mathcal{L}^{(1)}_{MB} = \langle \bar{B}(i\gamma_\mu D^\mu - M_0)B \rangle + \frac{1}{2} D \langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2} F \langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle$$

Weinberg-Tomozawa term (WT)



1. Dominant contribution.
2. Interaction mediated, basically, by the constant ***f*** of the leptonic decay of the pseudoscalar meson

Lagrangian:

$$\mathcal{L}^{eff}(B,U) = \mathcal{L}^{(1)}_{MB}(B,U) + \mathcal{L}^{(2)}_{MB}(B,U)$$ → derive an interaction kernel $\mathbf{V}_{ij}$

- **Leading order (LO)**

$$\mathcal{L}^{(1)}_{MB} = \langle \bar{B}(i\gamma_\mu D^\mu - M_0)B\rangle + \frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle$$

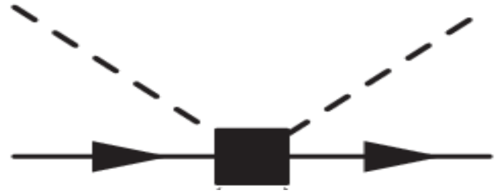
Born terms

1. Direct diagram (s-channel Born term)

$$V^D_{ij} = V^D_{ij}(D,F)$$

2. Cross diagram (u-channel Born term)

$$V^C_{ij} = V^C_{ij}(D,F)$$



- **Next to leading order (NLO),** just considering the **contact term**

$$
\begin{aligned}
\mathcal{L}_{\phi B}^{(2)} \quad = \quad & b_D \langle \bar{B}\{\chi_+, B\}\rangle + b_F \langle \bar{B}[\chi_+, B]\rangle + b_0 \langle \bar{B}B\rangle\langle\chi_+\rangle + d_1 \langle \bar{B}\{u_\mu, [u^\mu, B]\}\rangle \\
& + d_2 \langle \bar{B}[u_\mu, [u^\mu, B]]\rangle + d_3 \langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4 \langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle \\
& - \frac{g_1}{8M_N^2}\langle \bar{B}\{u_\mu, [u_\nu, \{D^\mu, D^\nu\}B]\}\rangle - \frac{g_2}{8M_N^2}\langle \bar{B}[u_\mu, [u_\nu, \{D^\mu, D^\nu\}B]]\rangle \\
& - \frac{g_3}{8M_N^2}\langle \bar{B}u_\mu\rangle\langle [u_\nu, \{D^\mu, D^\nu\}B]\rangle - \frac{g_4}{8M_N^2}\langle \bar{B}\{D^\mu, D^\nu\}B\rangle\langle u_\mu u_\nu\rangle \\
& - \frac{h_1}{4}\langle \bar{B}[\gamma^\mu, \gamma^\nu]Bu_\mu u_\nu\rangle - \frac{h_2}{4}\langle \bar{B}[\gamma^\mu, \gamma^\nu]u_\mu[u_\nu, B]\rangle - \frac{h_3}{4}\langle \bar{B}[\gamma^\mu, \gamma^\nu]u_\mu\{u_\nu, B\}\rangle \\
& - \frac{h_4}{4}\langle \bar{B}[\gamma^\mu, \gamma^\nu]u_\mu\rangle\langle u_\nu, B\rangle + h.c.
\end{aligned}
$$

New terms taken into account (the g_1–g_4 and h_1–h_4 terms)

- Contributions with g_3 get cancelled
- $b_0, b_D, b_F, d_1, d_2, d_3, d_4, g_1, g_2, g_4, h_1, h_2, h_3, h_4$ are not well established, so they should be treated as parameters of the model!

Finally, **unitarized amplitudes** can be obtained via the Bethe-Salpeter equation

$$f_{l\pm} = \left[1 - f_{l\pm}^{tree} G\right]^{-1} f_{l\pm}^{tree}$$

where *G* is the meson-baryon loop function (dimensional regularitzation)

$$G_l = \frac{2M_l}{(4\pi)^2}\left\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} + \frac{q_{\rm cm}}{\sqrt{s}}\ln\left[\frac{(s+2\sqrt{s}q_{\rm cm})^2-(M_l^2-m_l^2)^2}{(s-2\sqrt{s}q_{\rm cm})^2-(M_l^2-m_l^2)^2}\right]\right\}$$

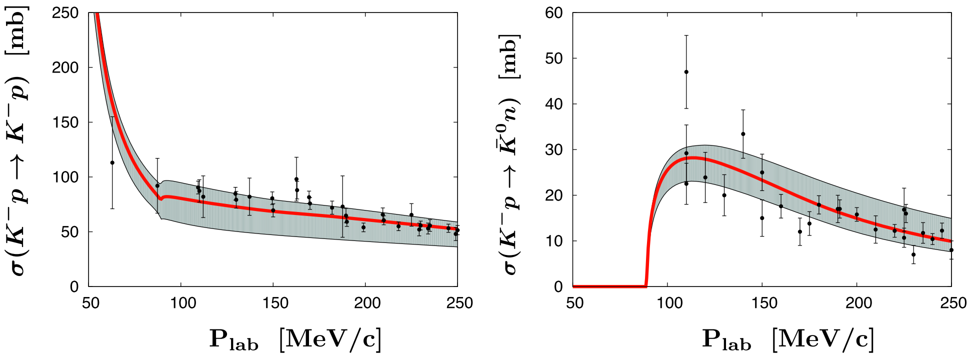
subtraction constants for the dimensional regularization scale $\mu = 1GeV$ in all k channels.

Total cross section:

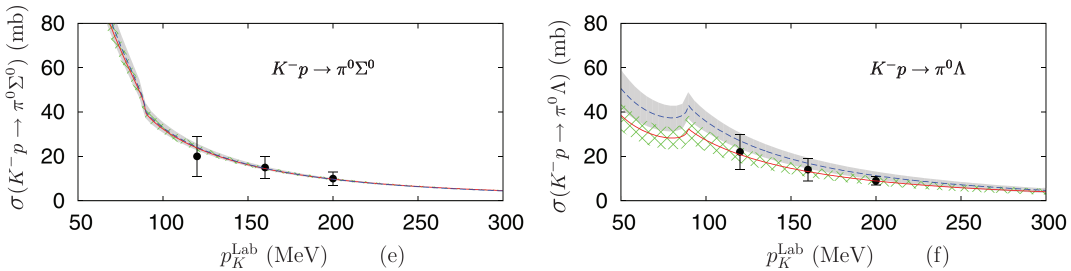
$$\sigma_{ij} = \frac{M_i\, M_j\, q_j}{4\,\pi\, s\, q_i}\left[|f_0|^2 + 2|f_{1+}|^2 + |f_{1-}|^2 + 3|f_{2+}|^2 + 2|f_{2-}|^2\right]$$

J^P=1/2- (S-wave: $|f_0|^2$); J^P=3/2+, J^P=1/2+ (P-wave: $2|f_{1+}|^2 + |f_{1-}|^2$); J^P=5/2-, J^P=3/2- (D-wave: $3|f_{2+}|^2 + 2|f_{2-}|^2$)

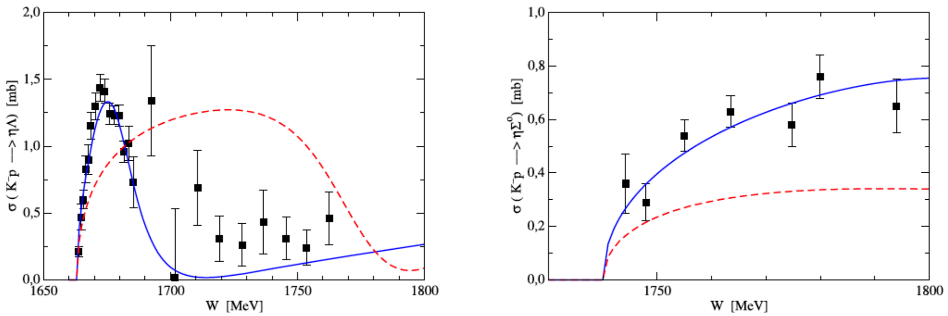
$K^- p \longrightarrow MB\ (S = -1)$ *total cross sections from different groups:*



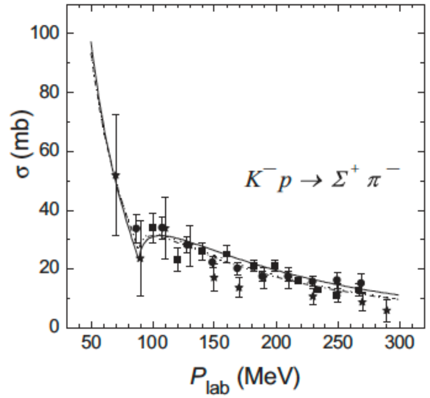
Y. Ikeda, T. Hyodo, W. Wiese, Nucl. Phys. A 881, 98 (2012).



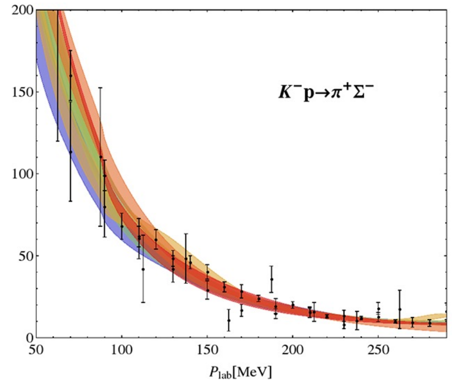
Zhi-Hui Guo, J. A. Oller, Phys. Rev. C 87, 035202 (2013).



P.C. Bruns, A. Cieply, Nucl. Phys. A 1019, (2022) 122378.

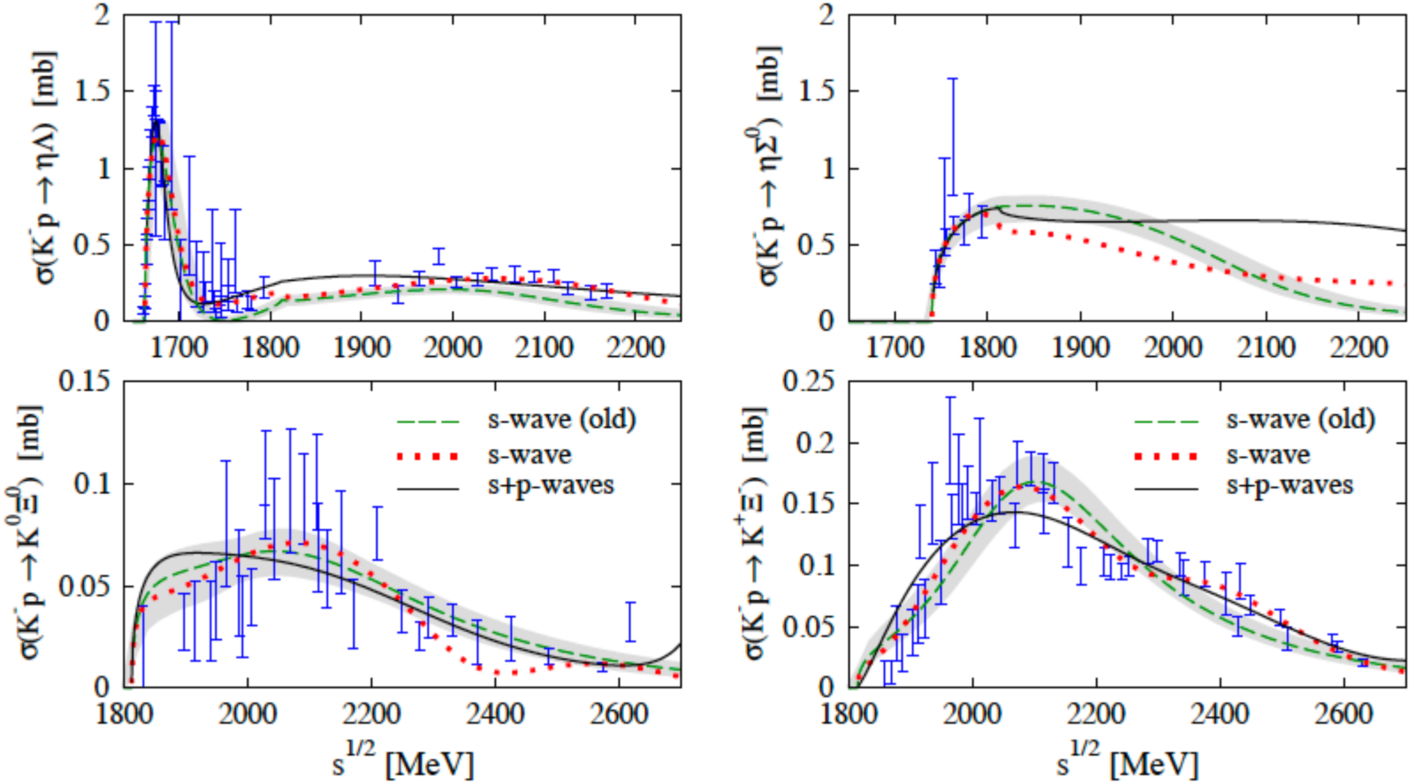


N.V. Shevchenko and Révai, Phys. Rev. C 90, 034003 (2014).



M. Mai and U. G. Meissner, Eur. Phys. J. A 51, 30 (2015).

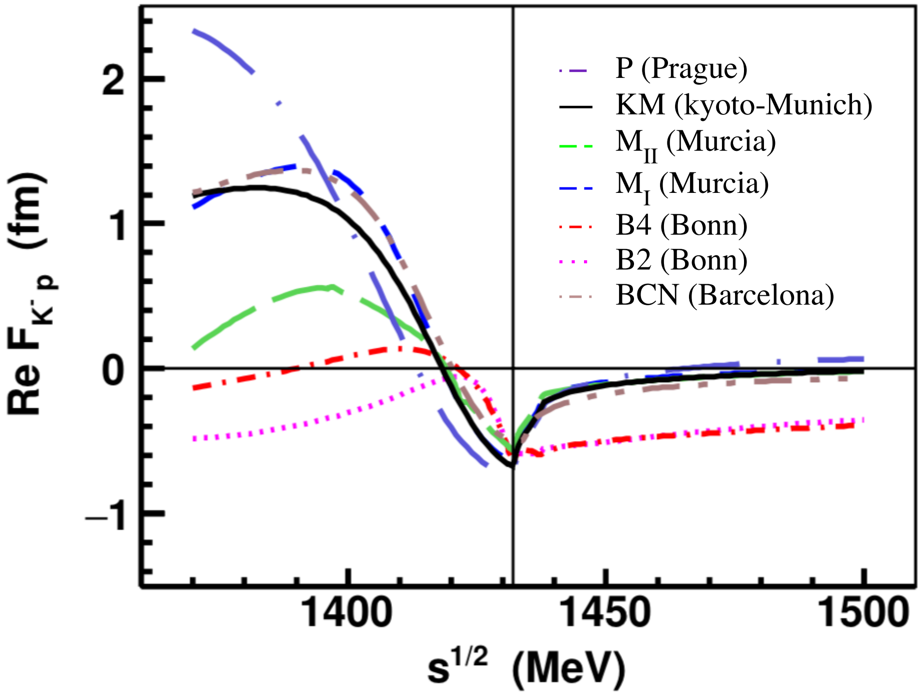
$K^- p \longrightarrow MB\ (S = -1)$ total cross sections: (even at higher energies and including higher partial waves)

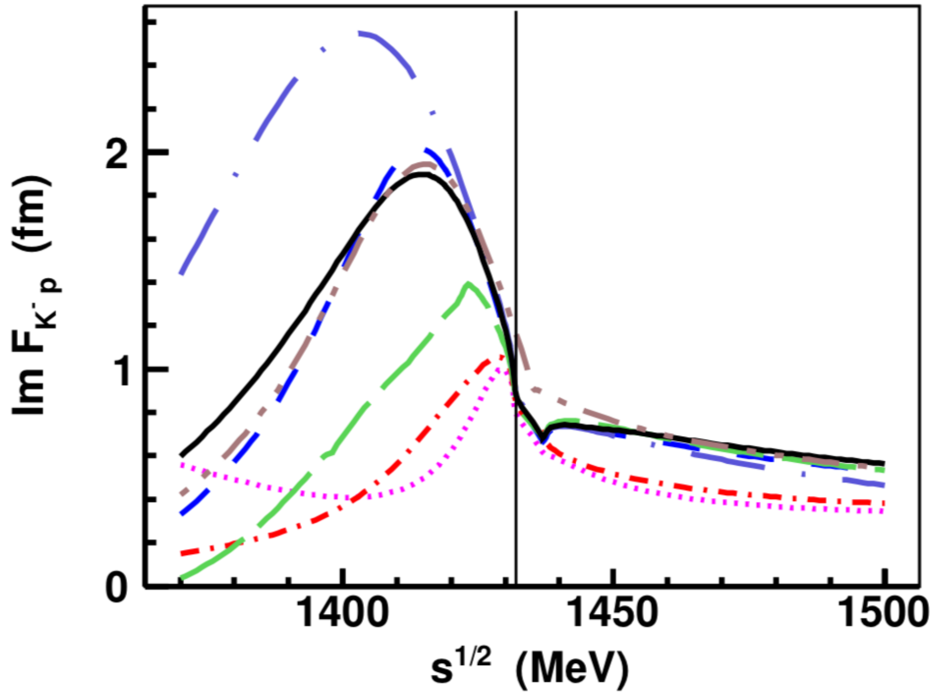


A. F., D. Gazda, V. Magas, A. Ramos, Symmetry 13 (2021) 8, 1434

Motivation: $\overline{K}N$ interaction background

$K^-p \longrightarrow K^-p$ scattering amplitudes generated by recent chirally motivated approaches:

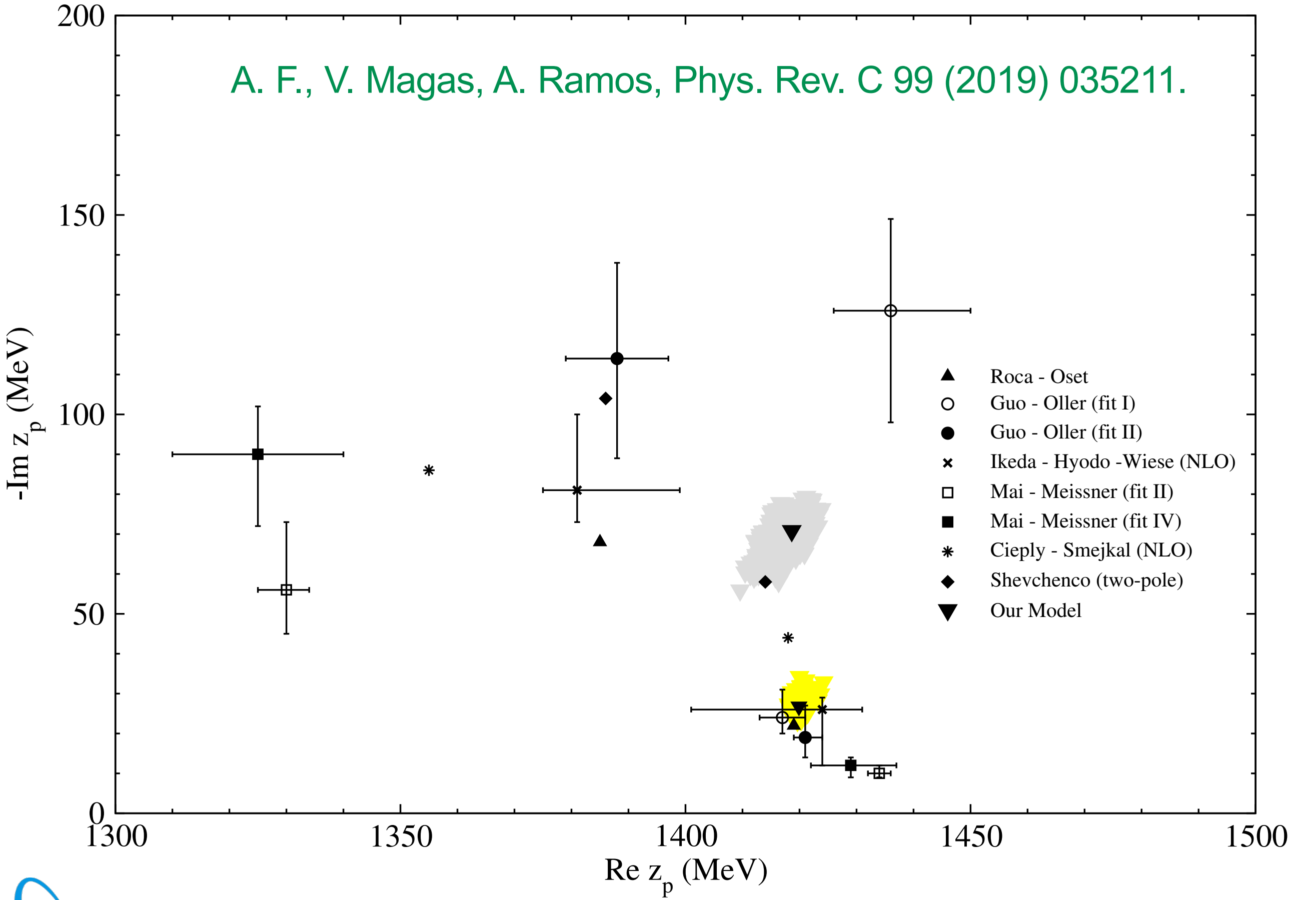




A. Cieply, J. Hrtánková, J. Mareš, E. Friedman, A. Gal and A. Ramos, AIP Conf. Proc. 2249, no.1, 030014 (2020).

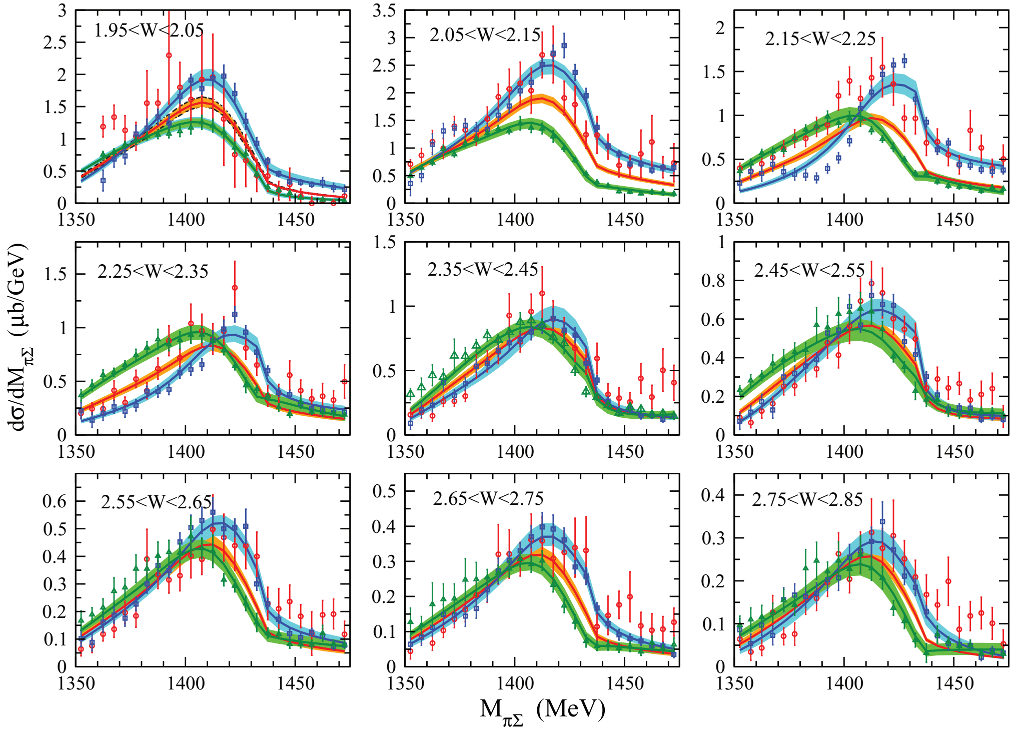
Motivation: $\overline{K}N$ interaction background

Pole positions of the $\Lambda(1405)$ for some state-of-the-art models:



Motivation: $\overline{K}N$ interaction background

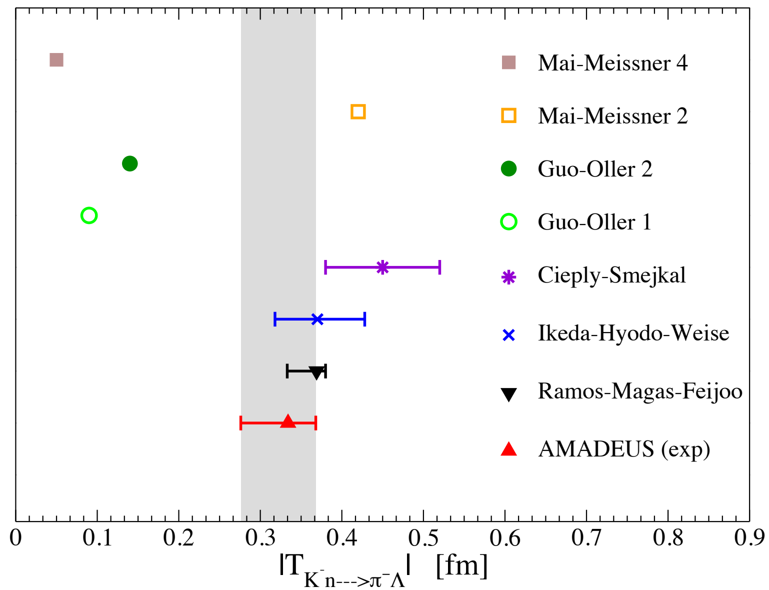
Many efforts have been made in order to extract information about subthreshold amplitudes…



L. Roca and E. Oset, Phys. Rev. C 88, 055206 (2013).

Fit to photoproduction data from CLAS

K. Moriya et al. (CLAS Collaboration), Phys. Rev. C 87, 035206 (2013).

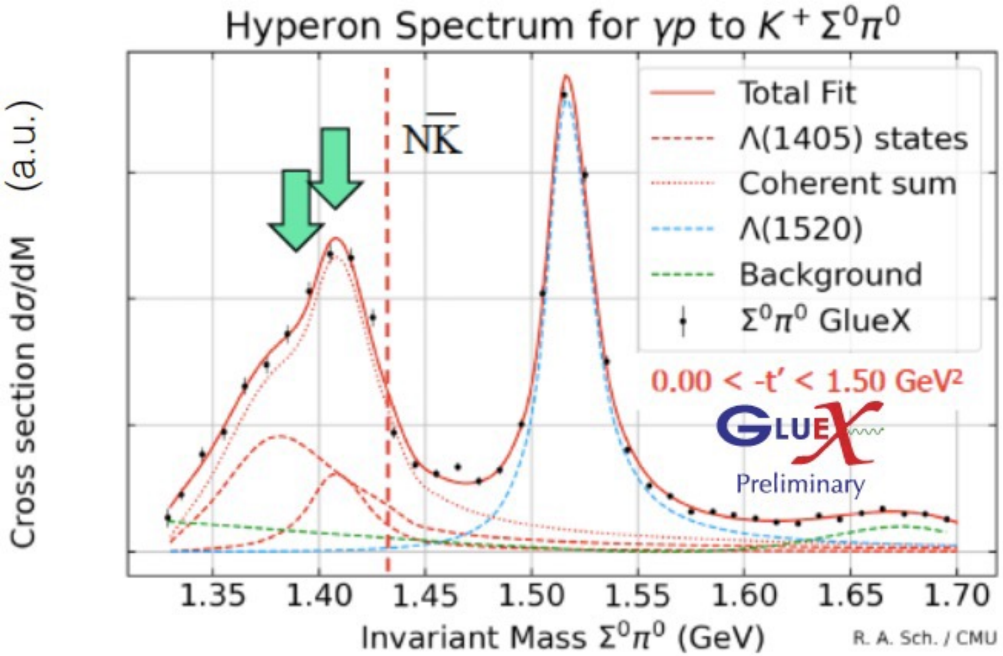


$K^-n \longrightarrow \pi^-\Lambda$ amplitude (pure $I=1$ process)

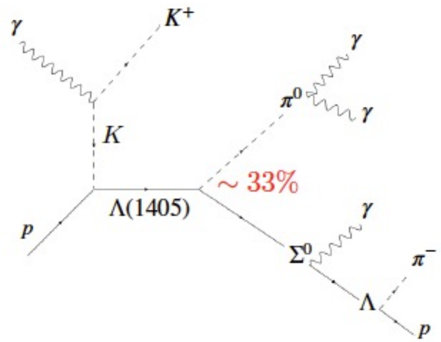
K. Piscicchia et al.., Phys.Lett. B782 (2018) 339-345.

AMADEUS collaboration, KLOE detector at DAFNE

Exciting results reported by **GlueX Collaboration** in the $\pi^0\Sigma^0$ invariant mass distribution from the $\gamma p \longrightarrow K^+\pi^0\Sigma^0$ process!!!



Wickramaarachchi's talks: HYP2022 (Prague) and QNP2022 (Floria)



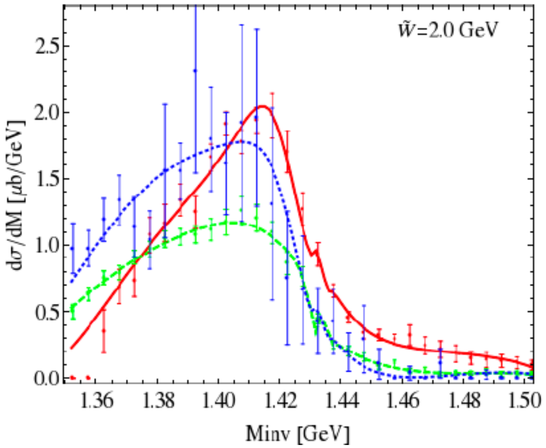
- The fitting procedure supports the composite state nature of the $\Lambda(1405)$
- Very valuable information can be extracted from further experimental and theoretical analysis of these data.

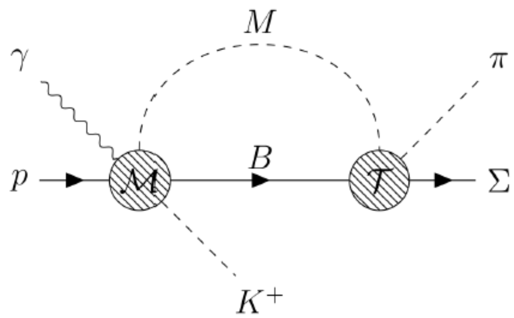
Experimental challenges: $\pi^0\Sigma^0$ invariant mass from photoproduction

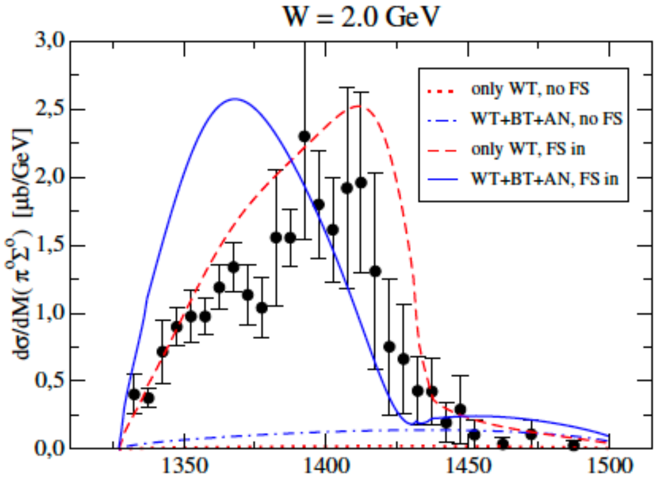
Reproduction of the photoproduction data from CLAS: (K. Moriya et al. (CLAS Collaboration), Phys. Rev. C 87, 035206) (2013)

L. Roca and E. Oset, Phys. Rev. C 88, 055206 (2013);
Phys. Rev. C 88, 055206 (2013)
M. Mai, U.-G. Meissner, Eur. Phys. J. A 51, 30 (2015)

P. Bruns, Cieply and M. Mai, arXiv:2206.08767 [nucl-th]







$$\mathcal{M}^j(\tilde{W}, M_{\rm inv}) = \sum_{i=1}^{10} C^i(\tilde{W})\, G^i(M_{\rm inv})\, f_{0+}^{i,j}(M_{\rm inv})$$

$$[\mathcal{A}^i_{0+}(s, M_{\pi\Sigma})] = [\mathcal{A}^{i(\text{tree})}_{0+}(s, M_{\pi\Sigma})] + [f_{0+}(M_{\pi\Sigma})]\,[8\pi M_{\pi\Sigma} G(M_{\pi\Sigma})]\,[\mathcal{A}^{i(\text{tree})}_{0+}(s, M_{\pi\Sigma})]$$

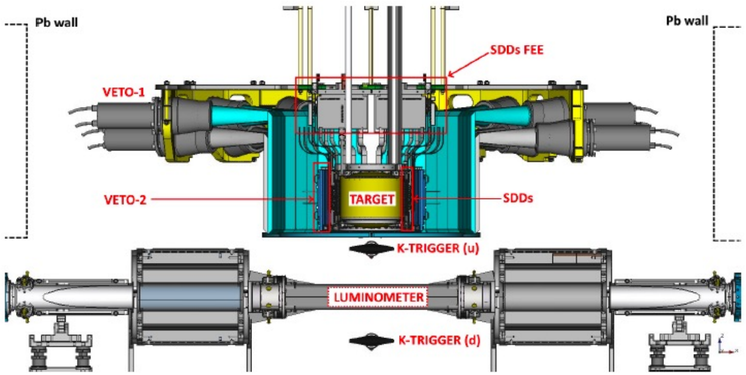
Experimental challenges: Measurement of the Γ_{1s} and E_{1s} in kaonic deuterium

The SIDDHARTA 2 (at DAFNE) high precision X-ray measurement of the $K^{-}d\ 2p \longrightarrow 1s$ transition:

- Deviations from the expected electromagnetic energy level will provide information about the strong interaction

FIGURE 1. Cross-section layout of the SIDDHARTA-2 setup installed above the DAΦNE collider's Interaction Region. The red boxes highlight the SDDs arrays (around the target cell), the Front End Electronic and the veto-2 system behind the solid state detectors. On the side of the setup, Pb walls (black dotted lines) act as passive shielding for the machine electromagnetic background.

M. MILIUCCI *et al.*,



M. Miliucci Measur.Sci.Tech. 33 (2022) 9, 095502

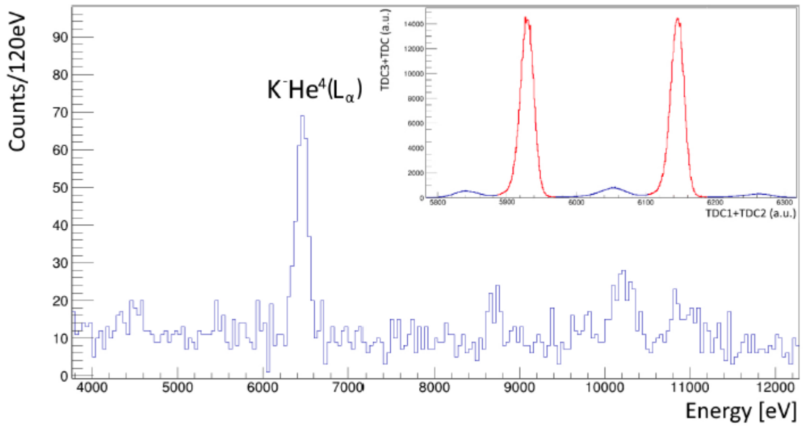


FIGURE 2. Preliminary calibrated spectrum for a sample of 5 pb^{-1} integrated luminosity acquired during the SIDDHARTINO run. The $K^{-}He^{4}$ $L\alpha$ transition signal is clearly visible, after the Kaon trigger selection. On the top right inset, the MIPs and Kaons (red) distributions on the K-trigger system.

K^- scattering on the deuteron at low energies:

- **The pioneering work –** G. Toker, A. Gal, J. M. Eisenberg, Nucl. Phys. A 362, 405 (1981)

The $K^-d \rightarrow \pi^-\Lambda p$ reaction (+ other three-body K⁻ reactions), with s-wave kaons, within Faddeev formalism for charge-independent separable two-body coupled-channel interactions

- S.S. Kamalov, E. Oset, A. Ramos, Nucl. Phys. A 690, 494-508 (2001)

Considering charge exchange process (+ fixed center approximation of Faddeev Equations)

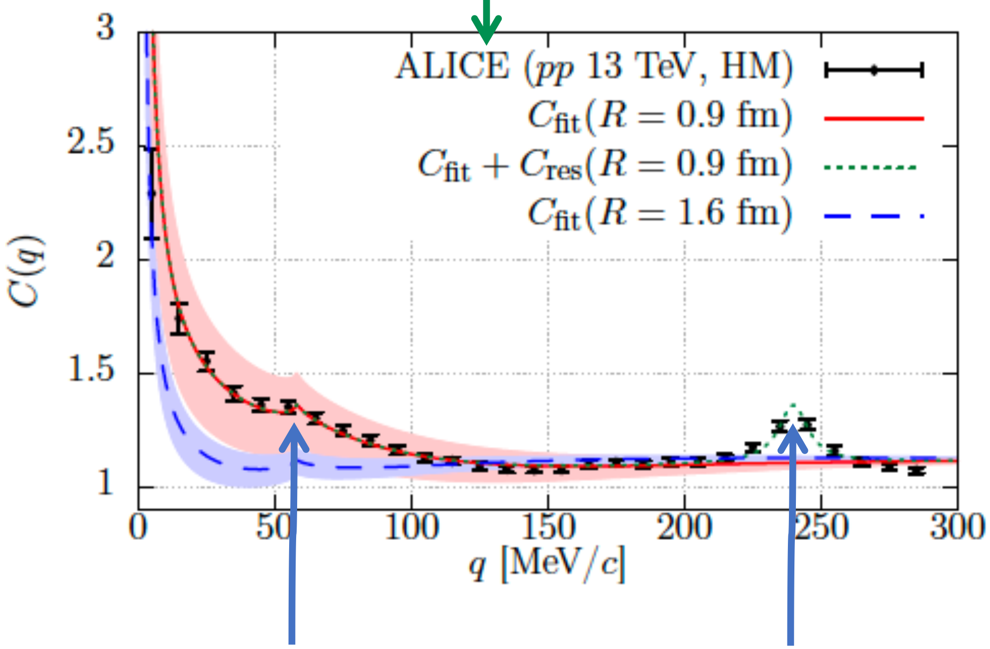
TABLE VII. K^-d scattering length (in fm).

Authors [Ref.]	A_{K^-d}
Present work (*c*)	$-1.58 + i1.37$
Borasoy *et al.* [37] [BNW (*c*)]	$-1.59 + i1.59$
Present work (*s*)	$-1.57 + i1.37$
Borasoy *et al.* [37] [BNW (*s*)]	$-1.67 + i1.52$
Doring-Meissner [48]	$-1.46 + i1.08$
Shevchenko [50] (one-pole)	$-1.48 + i1.22$
Shevchenko [50] (two-pole)	$-1.51 + i1.23$
Revai [120] (one-pole)	$-1.52 + i0.98$
Revai [120] (two-pole)	$-1.60 + i1.12$
Oset *et al.* [121]	$-1.54 + i1.82$
Bahaoui *et al.* [4]	$-1.80 + i1.55$

Mizutani et al., Phys. Rev. C 87, 035201 (2013).

Relevant studies on this topic following the Fadeev scheme with different approximations, different two-body amplitudes…

S.Acharyaetal.(ALICE),Phys.Rev.Lett.124,092301(2020)



Correlation function in momentum space: two-particle production probability normalized by the product of single-particle production probabilities.

$$C(q) = \int d^3r \sum_j \omega_j S_j(r) |\Psi_j^{(-)}(q;r)|^2$$

Tuning parameters:

- R (size of the source)
- $\omega_{\pi\Sigma}$ source weight in the $\pi\Sigma$ chanels

Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi and W. Weise, *Phys.Rev.Lett.* 124, 132501 (2020)

These kind of antineutrino production processes were theoretically studied in:

X.L. Ren, E. Oset, L. Alvarez-Ruso, M.J. Vicente Vacas, Phys. Rev. C 91(4), 045201 (2015)

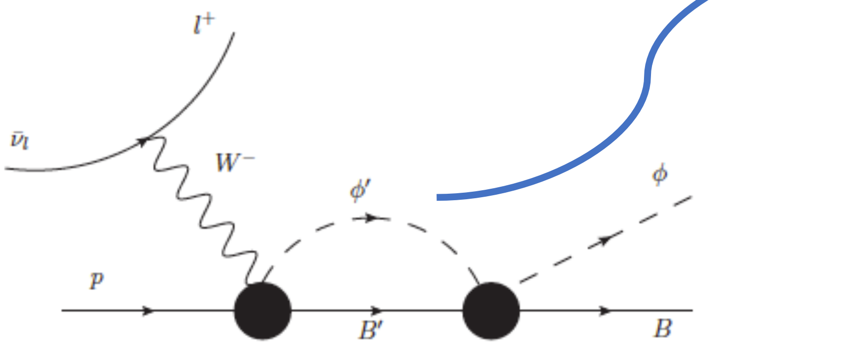


Fig. 17 Feynman diagram for the process $\bar{\nu}_l p \to l^+ \phi B$.

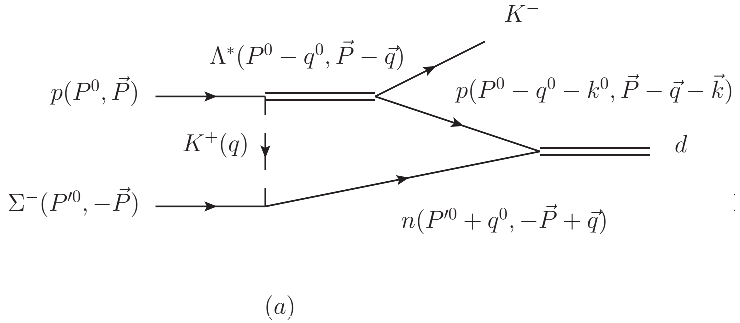
- **One of the possible output of the MicroBooNE Coll. (Σ, Λ and related hyperons production under analysis)**

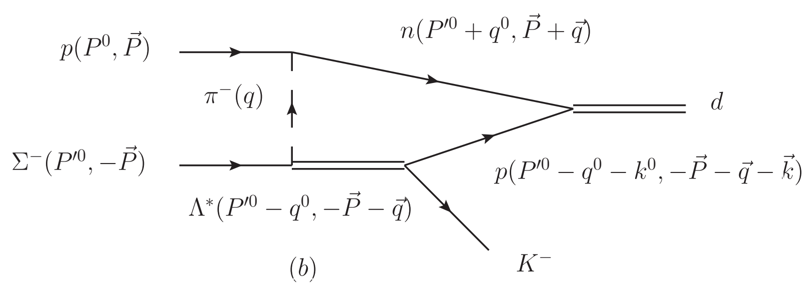
- **It is expected that SBND will be able measure such processes with huge statistics**

Suggestion for a measurement: $\Lambda(1405)$ mediated triangle singularity in the $K^- d \longrightarrow p\Sigma^-$

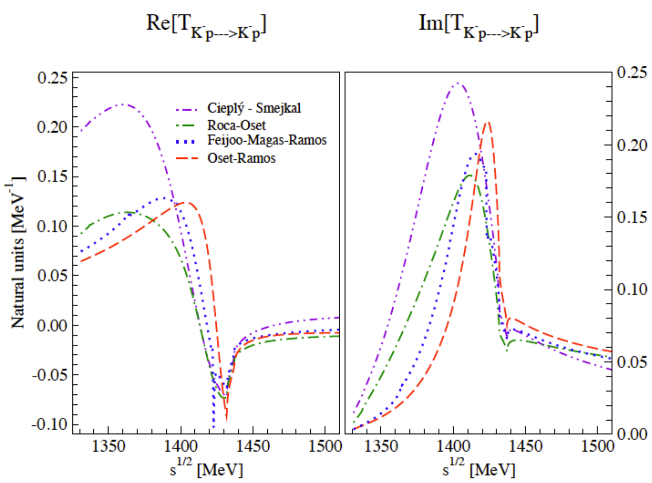
This reaction proceeds via these 2 mechanisms:

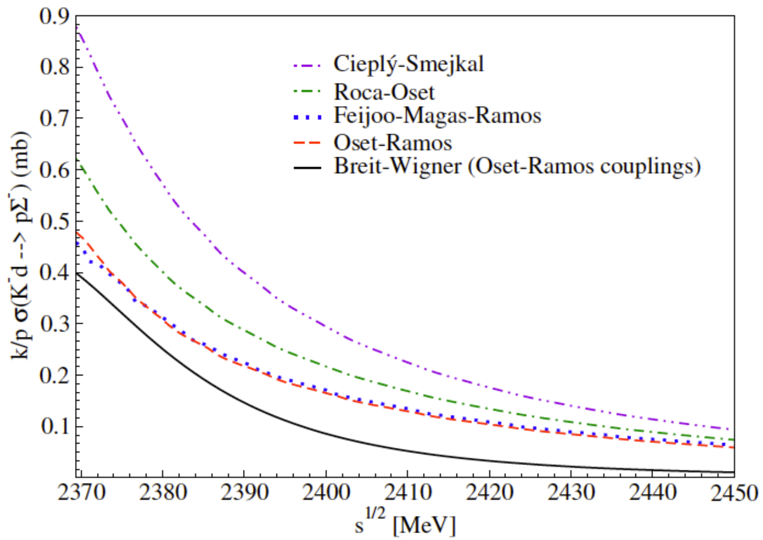
A. F., Molina, L.R. Dai, and E. Oset, arXiv:2105.09654 [nucl-th]





$K^- d \longrightarrow p\Sigma^-$ x-sections for different models:



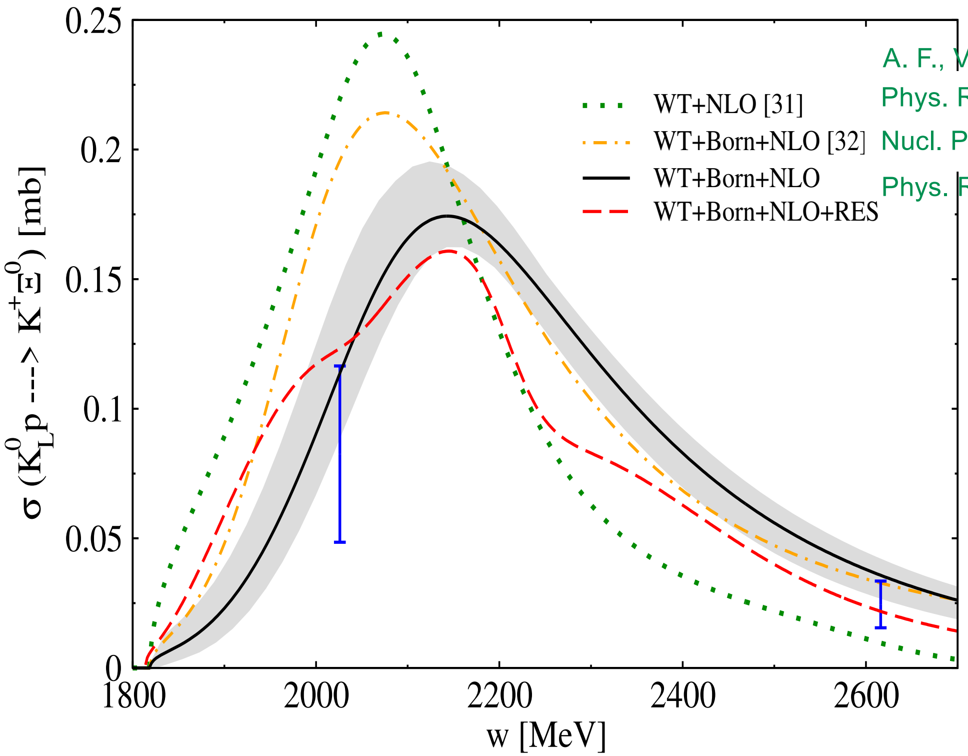


Motivation: Evolution of our chiral model

Prediction for Isospin filtering processes at higher energy:

$K_L^0 p \longrightarrow K^+ \Xi^0$ reaction (pure $I = 1$ process)

J-Lab proposal for the secondary K_L beam



A. F., V. Magas, A. Ramos,
Phys. Rev. C 92, 015206 (2015)
Nucl. Phys. A 954, 58 (2016)
Phys. Rev. C 99, 3, 035211 (2019)

”**We are just at the beginning of the data taking in a higher precision era** and it is most probable that exciting outputs were obtained in the near future. The interpretation of the experiments and studies to learn about the nature $\overline{K}N$ interaction is a task **that will require the combined efforts of both experimentalists and theoreticians**.”

Review, Nucl.Phys. A954 (2016) 371-392

Thank you for your attention