

TWO- AND THREE-BODY RESONANCES
IN THE $\bar{K}NN - \pi\Sigma N$ SYSTEM

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K⁻pp bound state

Prediction of the existence of deep and narrow K⁻pp bound state:

(T. Yamazaki and Y. Akaishi, Phys. Lett. B535 (2002) 70)

$$E_B = -48 \text{ MeV}, \Gamma = 61 \text{ MeV}$$

FINUDA collaboration: evidence for a deeply bound state:

(M. Agnello et. al., Phys. Rev. Lett. 94 (2005) 212303)

$$E_B = -115 \text{ MeV}, \Gamma = 67 \text{ MeV}$$

another interpretations of the experiment, different theoretical results...

Basic antikaon-nucleon interaction, existing models:

- Potentials used in few-body (many-body) calculations:
too simple, poor reproducing of the experimental data,
- “Alone” potentials: *cannot be used in few- or many-body calculations*

We need a potential:

1. reproducing all existing experimental data
2. suitable for using in few-body calculation.

Existing information about $\bar{K}N$ interaction :

- Strongly coupled with $\pi\Sigma$ channel through $\Lambda(1405)$ resonance

$$\text{PDG : } E_{\Lambda} = 1406.5 - i 25.0 \text{ MeV, } I = 0$$

Usual assumption :

a resonance in $I = 0 \pi\Sigma$ and a quasi - bound state in $I = 0 \bar{K}N$ channel

Alternative version : $\Lambda(1405)$ is an effect of two close poles

J. A. Oller, U. G. Meissner, Phys. Lett. B 500 (2001) 263,

D. Jido et. al, Nucl. Phys. A 725 (2003) 181

- Measured scattering data :

- Cross - sections of $K^- p \rightarrow K^- p$ and $K^- p \rightarrow MB$ reactions,

- Threshold branching ratios γ , R_c , and R_n

D.N. Tovee et al., Nucl. Phys. B33 (1971) 493,

R.J. Nowak et al., Nucl. Phys. B139 (1978) 61

- $K^- p$ scattering length (KEK) :

$$a_{K^- p}^{\text{KEK}} = -(0.78 \pm 0.15 \pm 0.03) + i (0.49 \pm 0.25 \pm 0.12) \text{ fm}$$

M. Iwasaki et al., Phys. Rev. Lett. 78 (1997) 3067,

T.M. Ito et al., Phys. Rev. C 58 (1998) 2366

- obtained from Deser-Trueman formula. **Experimentally measured** are:
strong interaction shift and width of the kaonic hydrogen atom $1s$ level state

$$\Delta E_{1s}^{\text{KEK}} = -323 \pm 63 \pm 11 \text{ eV}, \quad \Gamma_{1s}^{\text{KEK}} = 407 \pm 208 \pm 100 \text{ eV}$$

- $K^- p$ scattering length (DEAR) :

$$a_{K^- p}^{\text{DEAR}} = -(0.468 \pm 0.090 \pm 0.015) + i (0.302 \pm 0.135 \pm 0.036) \text{ fm}$$

G. Beer et al., Phys. Rev. Lett. 94 (2005) 212302

Experimentally measured

$$\Delta E_{1s}^{\text{DEAR}} = -193 \pm 37 \pm 6 \text{ eV}, \quad \Gamma_{1s}^{\text{DEAR}} = 249 \pm 111 \pm 30 \text{ eV}$$

Is it possible to construct a phenomenological $\bar{K}N - \pi\Sigma$ potential with one- and two-pole structure of $\Lambda(1405)$ resonance, equally properly reproducing:

- Measured $1s$ K^-p level shift and width (KEK or DEAR),
- Cross - sections of $K^-p \rightarrow K^-p$ and $K^-p \rightarrow MB$ reactions,
- Threshold branching ratios γ and $R_{\pi\Sigma} = \frac{R_c}{1 - R_n(1 - R_c)}$,

and suitable for using in few-body calculations?

J. Révai, N.V. Shevchenko, Phys. Rev. C 79 (2009) 035202

Isospin-breaking effects:

1. Kaonic hydrogen: direct inclusion of **Coulomb interaction**
2. Using of the **physical masses** during all calculation:

$$m_{K^-}, m_{\bar{K}^0}, m_p, m_n \text{ instead of } m_{\bar{K}}, m_N$$

Strong part of the total potential $V_s + V_C$:

$$V_I^{\alpha\beta}(\vec{k}^\alpha, \vec{k}'^\beta) = g_I^\alpha(\vec{k}^\alpha) \lambda_1^{\alpha\beta} g_I^\beta(\vec{k}'^\beta),$$

$\alpha, \beta = K(\bar{K}N \text{ channel})$ or $\pi(\pi\Sigma \text{ channel})$; $I = 0$ or 1 ;

• 1-pole $\Lambda(1405)$:

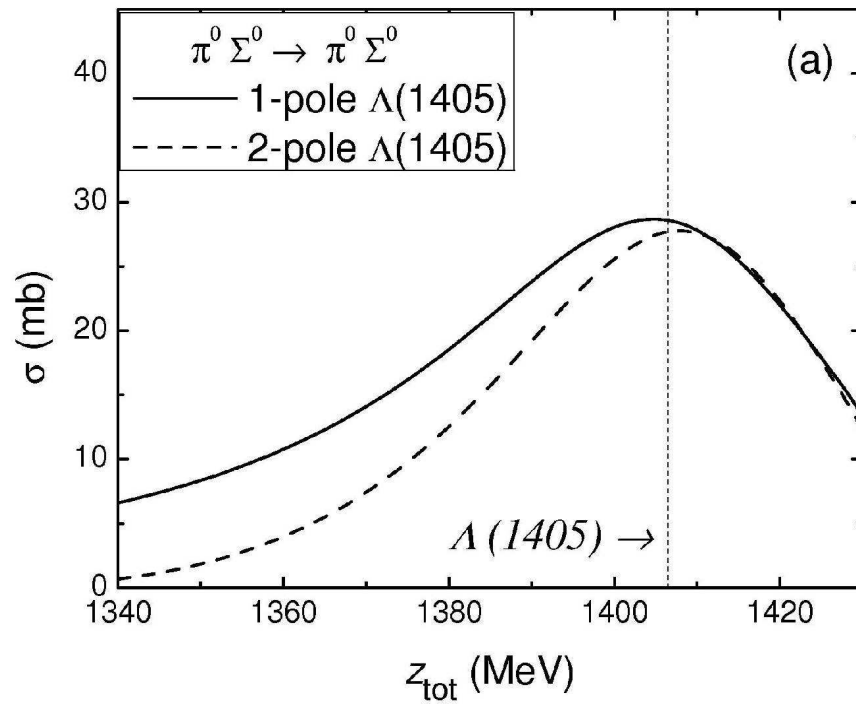
$$g_{I,1pole}^\alpha(k^\alpha) = \frac{1}{(k^\alpha)^2 + (\beta_1^\alpha)^2} \quad \text{for } \alpha = K \text{ or } \pi$$

• 2-pole $\Lambda(1405)$:

$$g_{I,1pole}^\alpha(k^\alpha) = \frac{1}{(k^\alpha)^2 + (\beta_1^\alpha)^2} \quad \text{for } \alpha = K$$

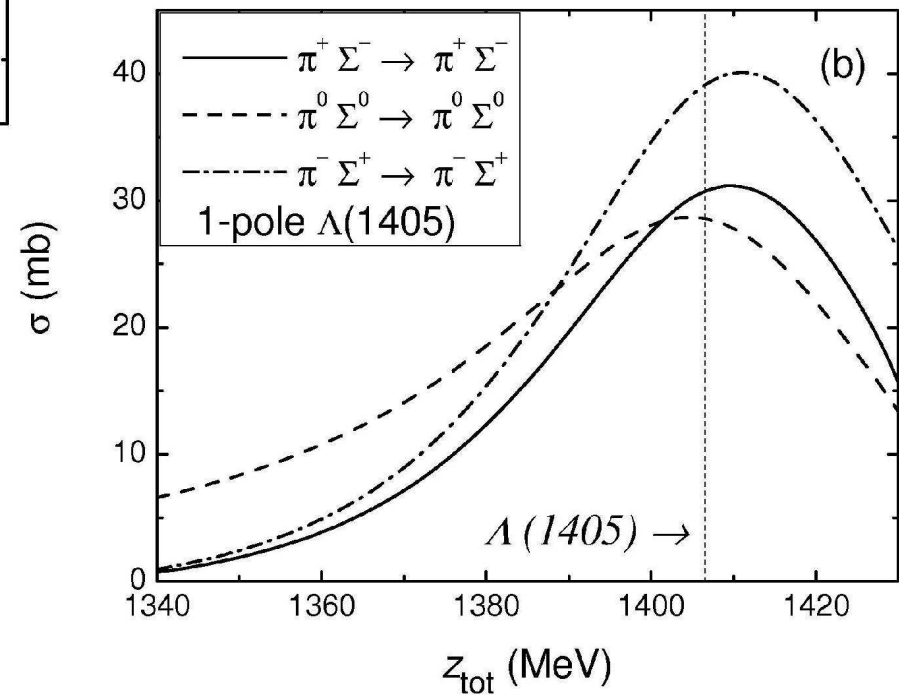
$$g_{I,2pole}^\alpha(k^\alpha) = \frac{1}{(k^\alpha)^2 + (\beta_1^\alpha)^2} + \frac{s(\beta_1^\alpha)^2}{[(k^\alpha)^2 + (\beta_1^\alpha)^2]^2} \quad \text{for } \alpha = \pi$$

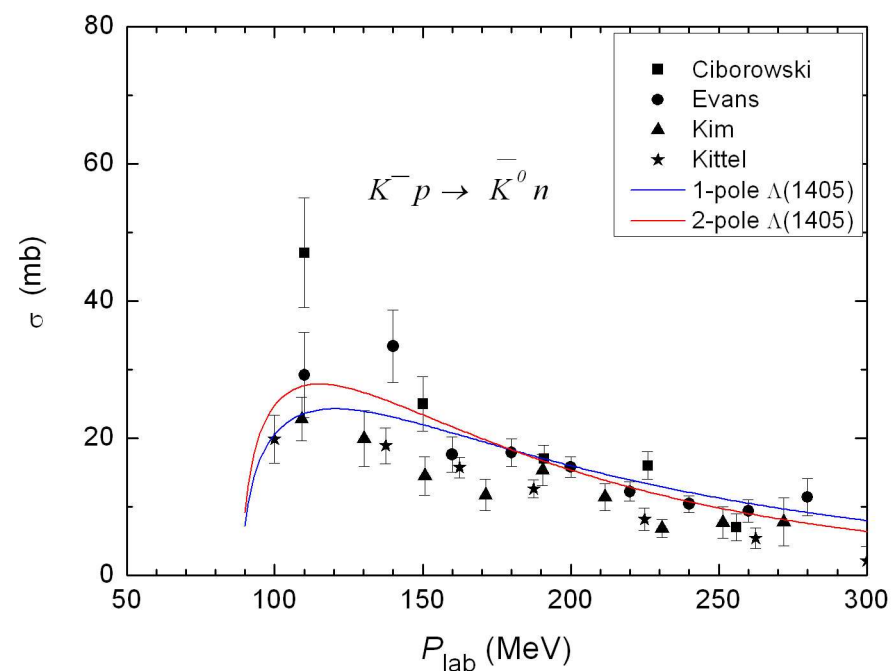
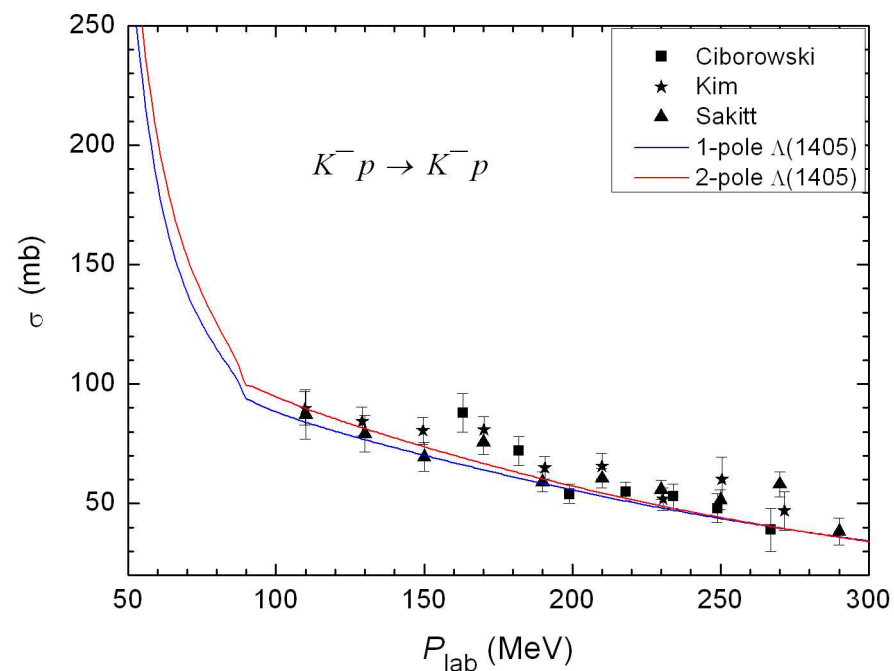
One- and two-pole (dynamically generated) $\Lambda(1405)$



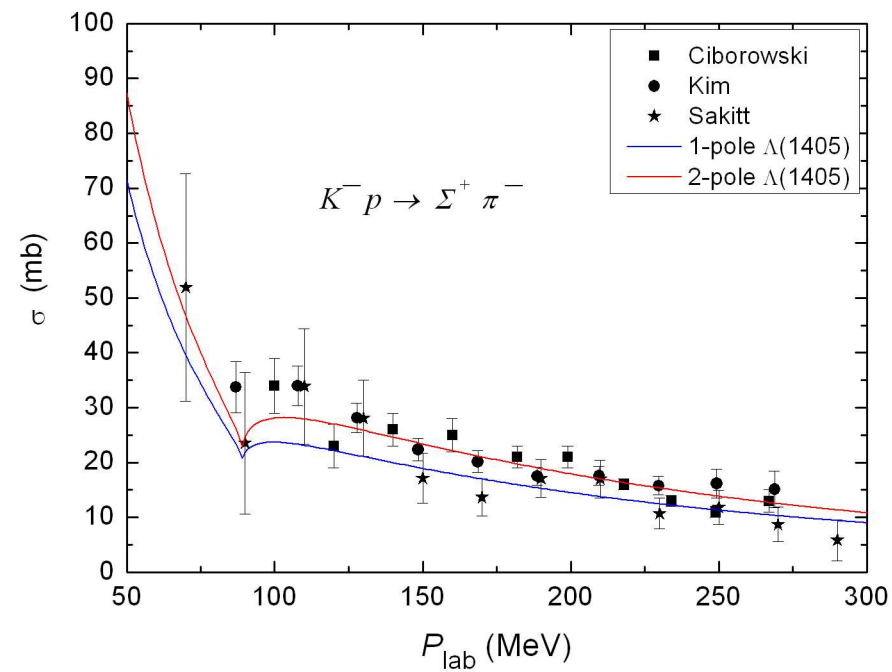
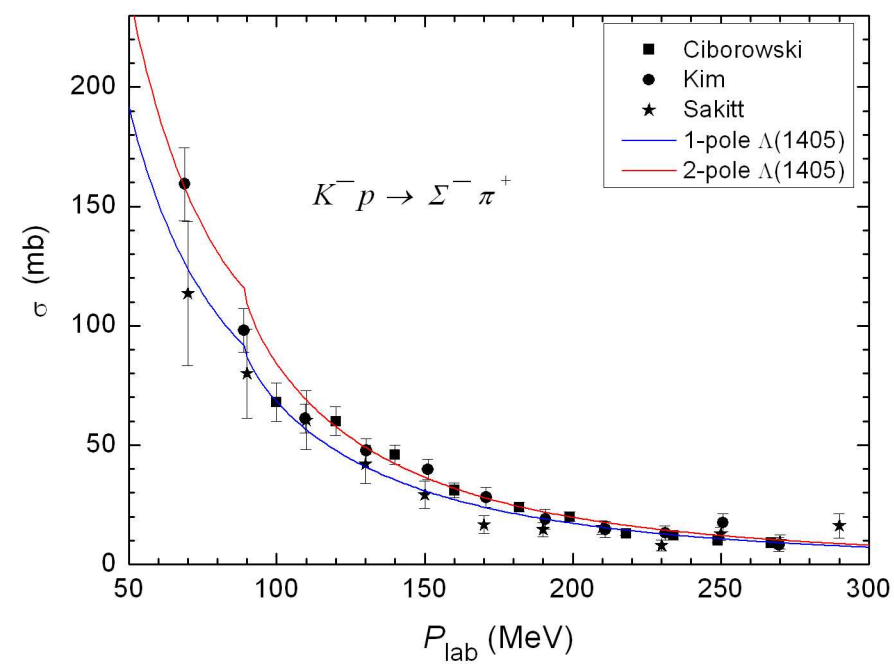
”1-pole” pole position:
1409 – i 32 MeV

”2-pole” poles positions:
1412 – i 32 MeV,
1380 – i 105 MeV

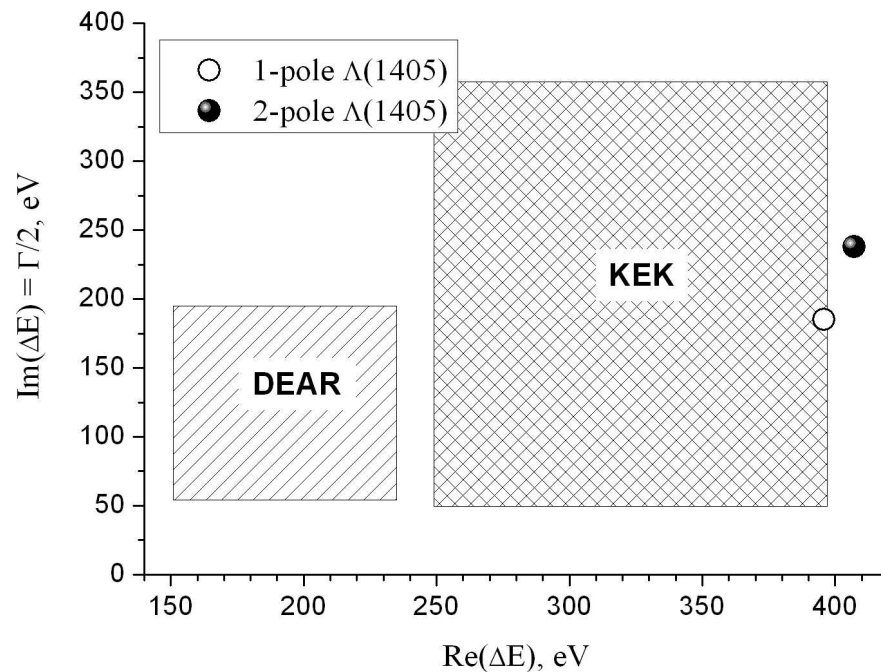




Comparison with experimental cross-sections



Experimental and theoretical $1s K^- p$ level shift and width:



– DEAR data are inconsistent with the scattering data

The two-body result:

both potentials describes the data equally well.

Three-body coupled-channels calculation

The same method as in

N.V. Shevchenko, A. Gal, J. Mareš; Phys. Rev. Lett. 98 (2007) 082301

N.V. Shevchenko, A. Gal, J. Mareš, J. Révai; Phys. Rev. C 76 (2007) 044004

Faddeev equations in Alt - Grassberger - Sandhas form :

$$U_{11} = T_2 G_0 U_{21} + T_3 G_0 U_{31}$$

$$U_{21} = G_0^{-1} + T_1 G_0 U_{11} + T_3 G_0 U_{31}$$

$$U_{31} = G_0^{-1} + T_1 G_0 U_{11} + T_2 G_0 U_{21}$$

define unknown operators U_{ij}

$$U_{11} : 1 + (23) \rightarrow 1 + (23)$$

$$U_{21} : 1 + (23) \rightarrow 2 + (31)$$

$$U_{31} : 1 + (23) \rightarrow 3 + (12)$$

$\pi\Sigma$ channel is included directly. Particle channels (α):

$$\alpha = 1 : |\bar{K}_1 N_2 N_3\rangle, \quad \alpha = 2 : |\pi_1 \Sigma_2 N_3\rangle, \quad \alpha = 3 : |\pi_1 N_2 \Sigma_3\rangle$$

i, j - usual Faddeev indexes
 α, β - channel indexes

Two - body T - matrices, $T_i^{\alpha\beta}$:

$$T_1 = \begin{pmatrix} T_1^{NN} & 0 & 0 \\ 0 & T_1^{\Sigma N} & 0 \\ 0 & 0 & T_1^{\Sigma N} \end{pmatrix}, T_2 = \begin{pmatrix} T_2^{KK} & 0 & T_2^{K\pi} \\ 0 & T_2^{\pi N} & 0 \\ T_2^{\pi K} & 0 & T_2^{\pi\pi} \end{pmatrix}, T_3 = \begin{pmatrix} T_3^{KK} & T_3^{K\pi} & 0 \\ T_3^{\pi K} & T_3^{\pi\pi} & 0 \\ 0 & 0 & T_3^{\pi N} \end{pmatrix}$$

T^{NN} , $T^{\Sigma N}$, and $T^{\pi N}$ are usual T - matrices;

elements of 2 - channel $T^{\bar{K}N-\pi\Sigma}$: $T^{KK} : \bar{K}N \rightarrow \bar{K}N$, $T^{K\pi} : \pi\Sigma \rightarrow \bar{K}N$

$T^{\pi K} : \bar{K}N \rightarrow \pi\Sigma$, $T^{\pi\pi} : \pi\Sigma \rightarrow \pi\Sigma$

Free Green functions $G_0^{\alpha\beta} = \delta_{\alpha\beta} G_0^\alpha$, transition operators are $U_{ij}^{\alpha\beta}$

Coulomb interaction is included in two-body $\bar{K}N - \pi\Sigma$,
but not in three-body $\bar{K}NN - \pi\Sigma N$ calculation.

(for the three-body system Coulomb interaction plays a minor role and can be omitted, only the strong part of isospin-mixing interaction is used)

Two-term NN (pp) potential

P. Doleschall, private communication, 2009

$$V_{pp} = \sum_{i=1}^2 |g_i\rangle \lambda_i \langle g_i| \rightarrow$$

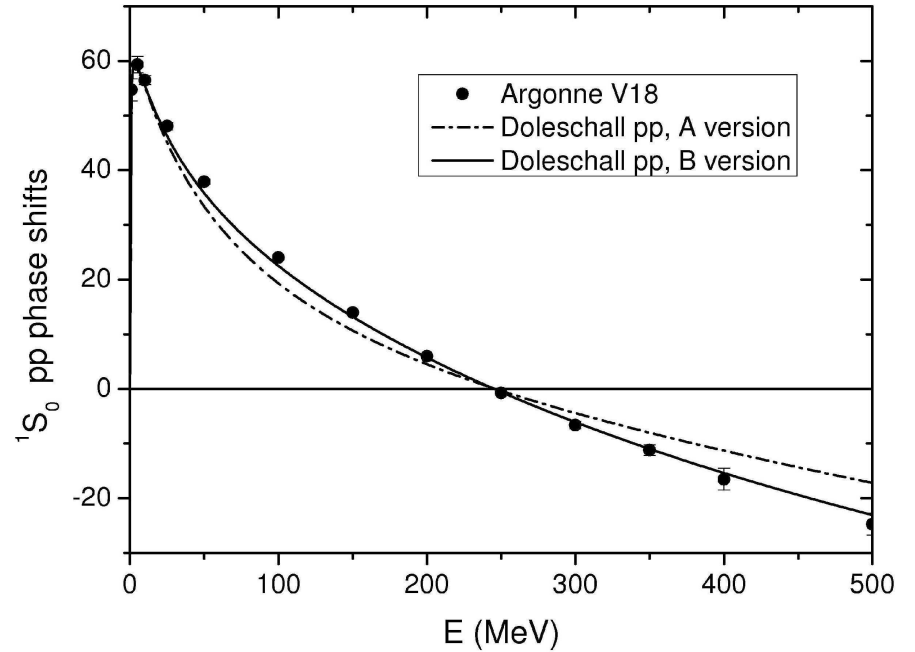
$$T_{pp} = \sum_{i,j=1}^2 |g_i\rangle \tau_{ij} \langle g_j|$$

Reproduces:

Argonne V18 NN phase shifts
(with sign change!),

$$a^A(pp) = 16.553 \text{ fm}, \quad r_{eff}^A(pp) = 2.845 \text{ fm}$$

$$a^B(pp) = 16.558 \text{ fm}, \quad r_{eff}^B(pp) = 2.880 \text{ fm}$$



$$\text{Version A: } g_i^A(k) = \sum_{m=1}^2 \frac{\gamma_{im}^A}{(\beta_{im}^A)^2 + k^2}, \quad i = 1, 2$$

$$\text{Version B: } g_1^B(k) = \sum_{m=1}^3 \frac{\gamma_{1m}^B}{(\beta_{1m}^B)^2 + k^2}, \quad g_2^B(k) = \sum_{m=1}^2 \frac{\gamma_{2m}^B}{(\beta_{2m}^B)^2 + k^2}$$

New $\Sigma N(-\Lambda N)$ interaction

J. Révai, N.V. Shevchenko, 2009

$T_I^{\Sigma N}(k, k'; z)$ corresponds to

$$V_I^{\Sigma N}(k, k') = \lambda_I^{\Sigma N} g_I^{\Sigma N}(k) g_I^{\Sigma N}(k')$$

$$\text{with } g_I^{\Sigma N}(k) = \frac{1}{k^2 + (\beta_I^{\Sigma N})^2}$$

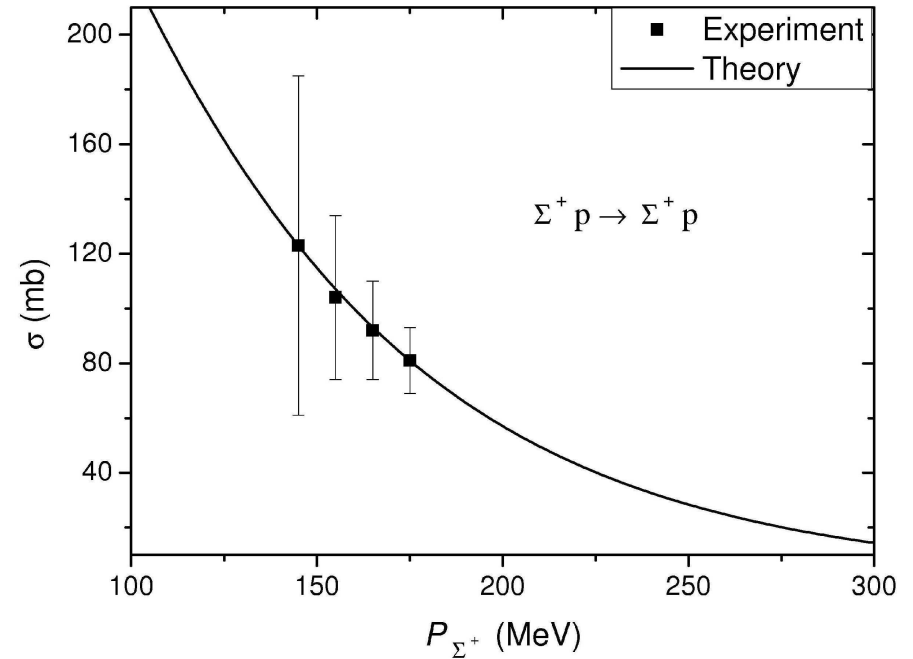
All parameters were fitted to reproduce
experimental cross-sections

$I=3/2$

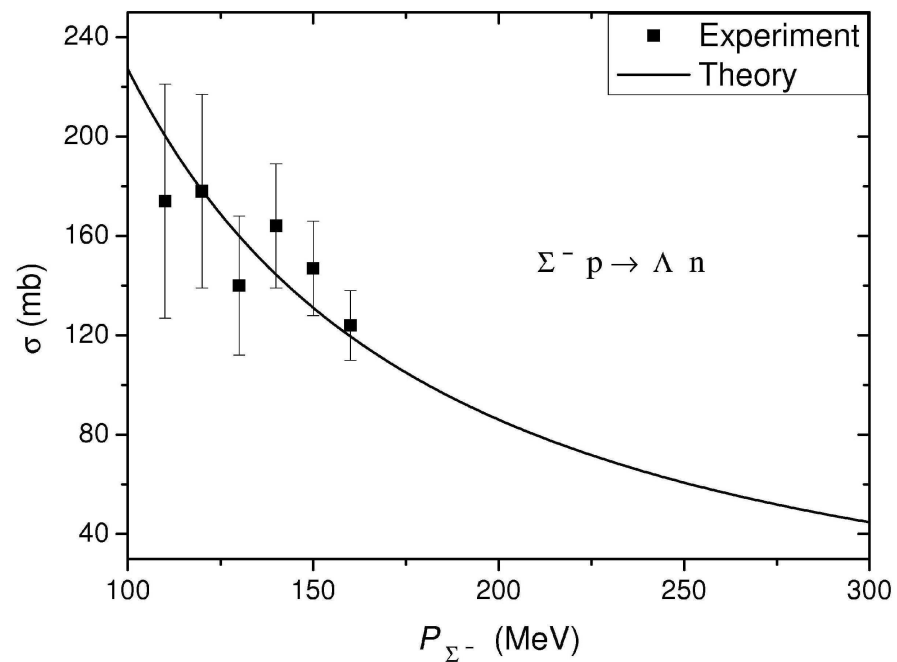
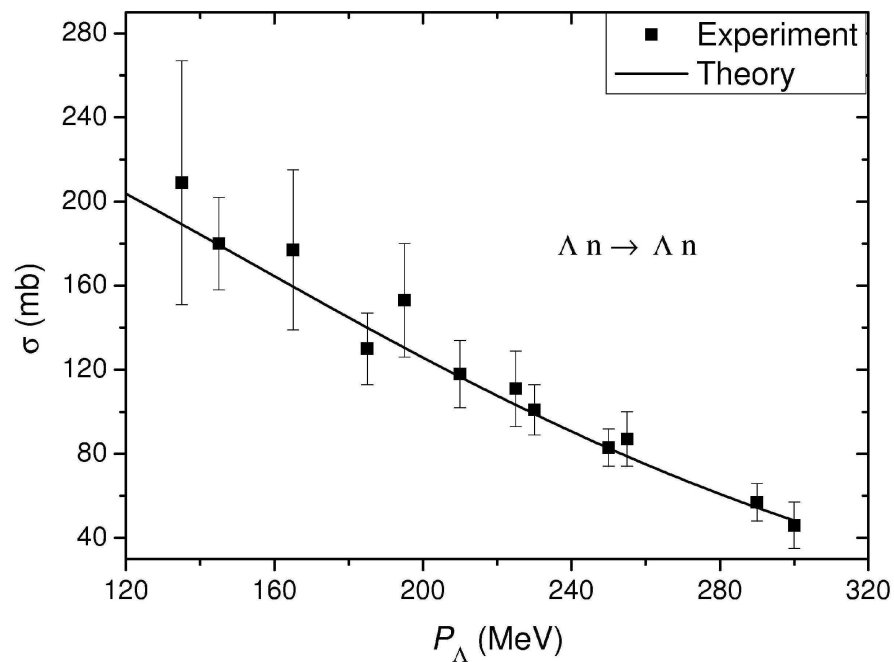
Real parameters, one-channel case

$I=1/2$

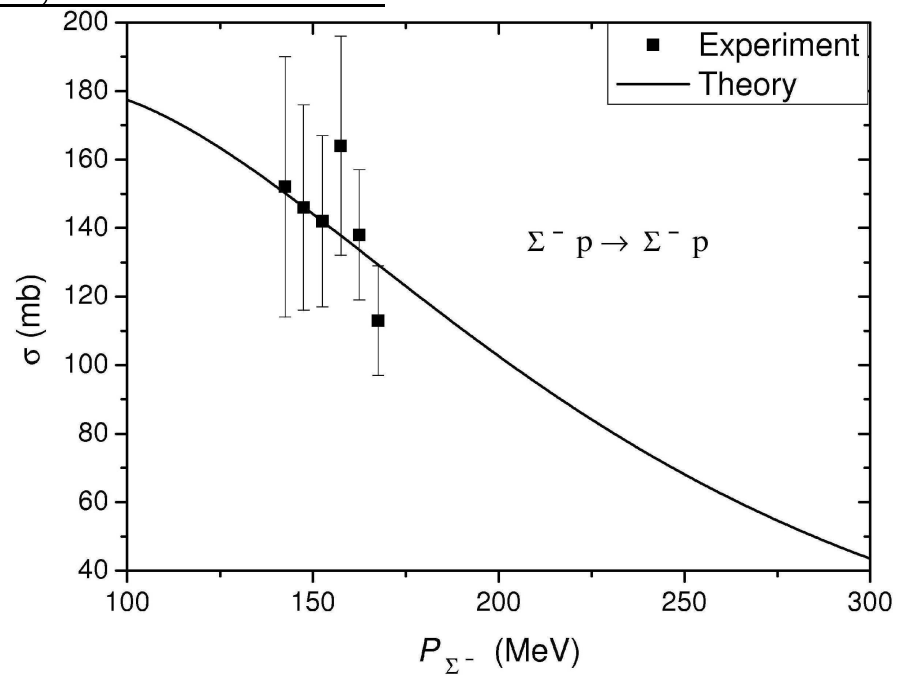
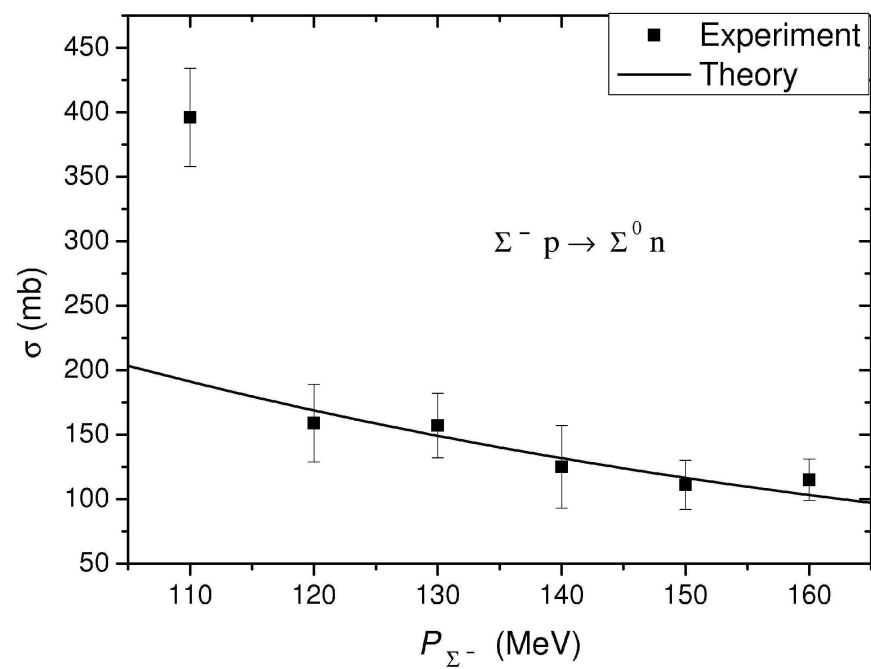
1. Two-channel $\Sigma N - \Lambda N$ potential, real parameters
2. One-channel ΣN potential, complex strength parameter



Pure $I=3/2$ part



Pure $I=1/2$ and $I=1/2, I=3/2$ mixtures



New three-body calculations results (preliminary):

- Isospin-breaking $\bar{K}N - \pi\Sigma$ interaction:
one- and two-pole structure of $\Lambda(1405)$ resonance
- Two-term NN (pp) potential
- New $I = 1/2$ $\Sigma N(-\Lambda N)$ and $I = 3/2$ ΣN interaction

	1-pole $\Lambda(1405)$ resonance	2-pole $\Lambda(1405)$ resonance
NN A-version	$-29.63 - i 47.31$	$-59.50 - i 41.13$
NN B-version	$-30.90 - i 47.38$	$-59.66 - i 41.31$