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 MeV, Γ = 61 MeV

FINUDA collaboration: evidence for a deeply bound state:

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

E_B = -115 MeV, Γ = 67 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 assuption:

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 $K^- p \to K^- p$ and $K^- p \to MB$ reactions,
- Threshold branching ratios γ, R_c, and R_n

*D.N. Tovee et al., Nucl. Phys. B*33 *(*1971*)* 493,

*R.J. Nowak et al., Nucl. Phys. B*139 *(*1978*)* 61

• $K^- p$ scattering length (KEK) :

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

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

T.M. Ito e t 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

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

• $K^- p$ scattering length (DEAR) :

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

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

Experimentally measured

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

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

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:

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

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

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

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

• 1-pole $\Lambda(1405)$:

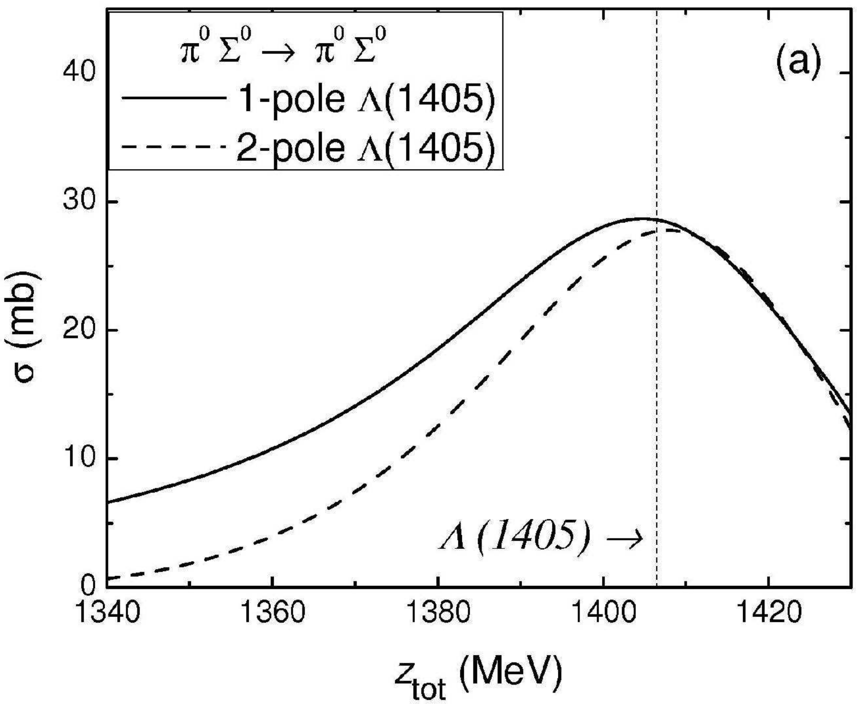
$$g_{I,1pole}^{\alpha}(k^{\alpha}) = \frac{1}{(k^{\alpha})^2 + (\beta_{\mathrm{I}}^{\alpha})^2} \qquad \text{for } \alpha = K \text{ or } \pi$$

• 2-pole $\Lambda(1405)$:

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

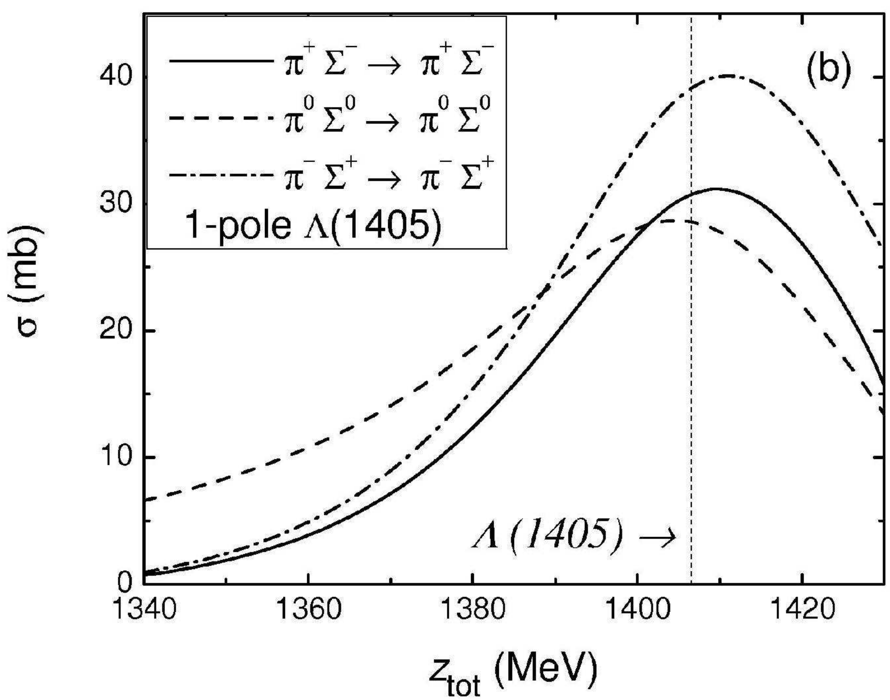
$$g_{I,2pole}^{\alpha}(k^{\alpha}) = \frac{1}{(k^{\alpha})^2 + (\beta_{\mathrm{I}}^{\alpha})^2} + \frac{s\,(\beta_{\mathrm{I}}^{\alpha})^2}{[\,(k^{\alpha})^2 + (\beta_{\mathrm{I}}^{\alpha})^2\,]^2} \qquad \text{for } \alpha = \pi$$

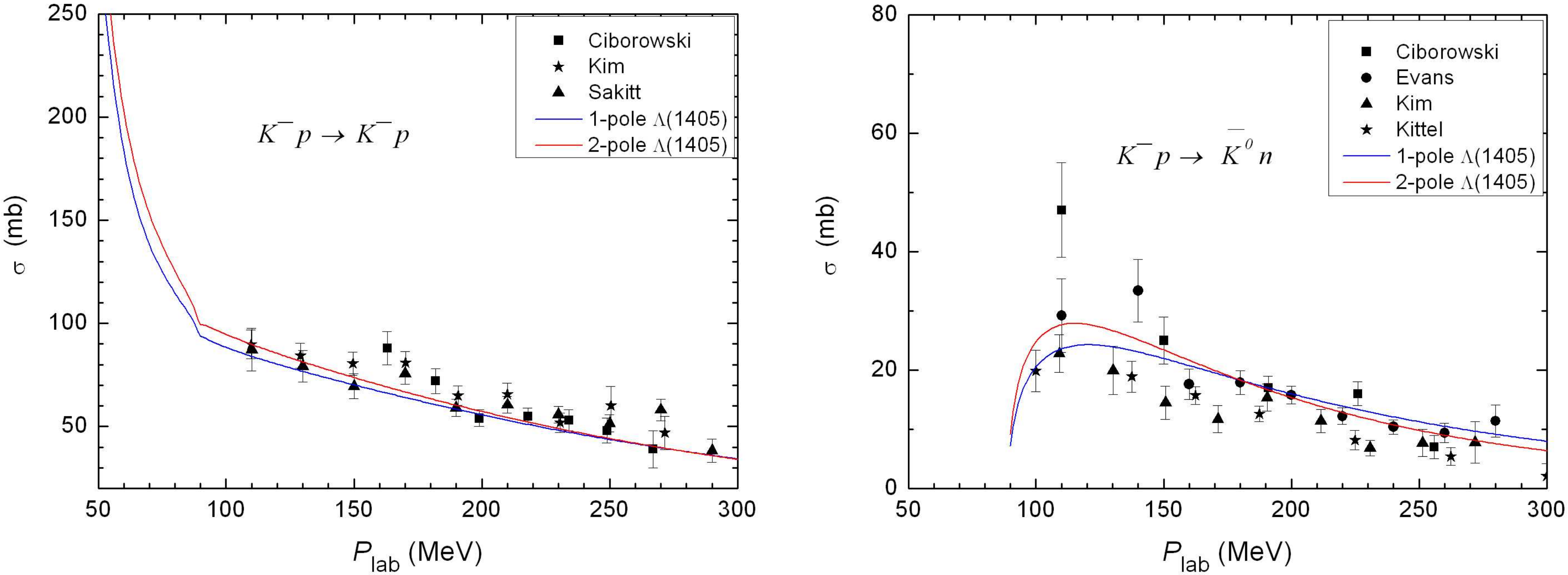
One- and two-pole (dynamically generated) Λ(1405)



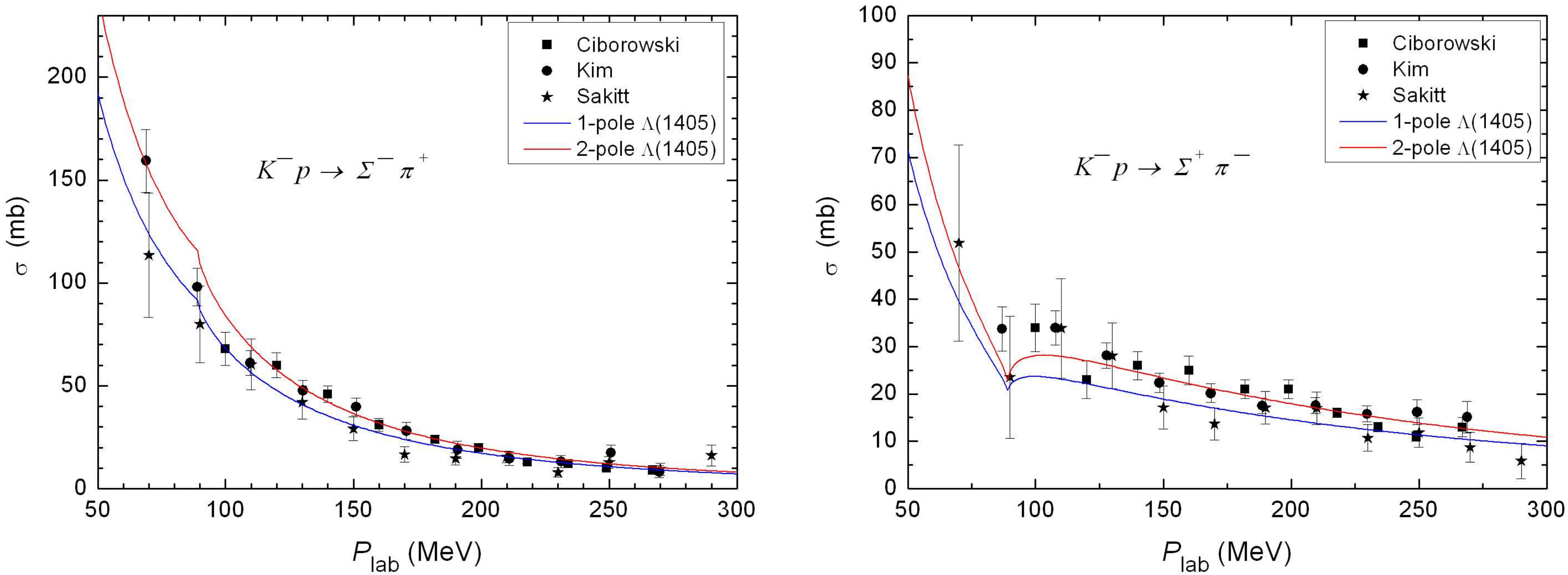
”1-pole” pole position:
1409 – *i* 32 MeV

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

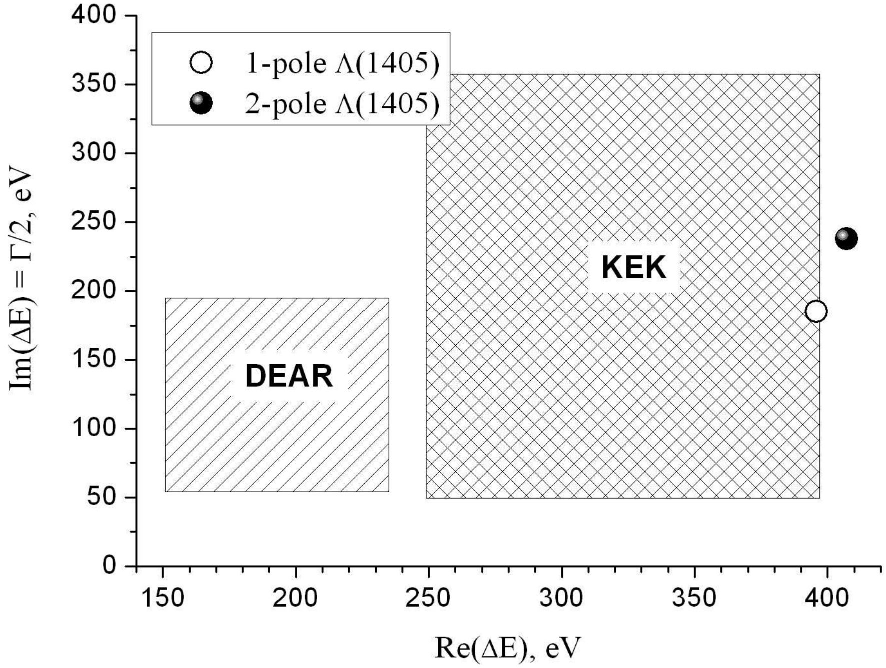




Comparison with experimental cross-sections



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



– DEAR data are inconsistent with the scattering data

<u>The two-body result</u>:

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}

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

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

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

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

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

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

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

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

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

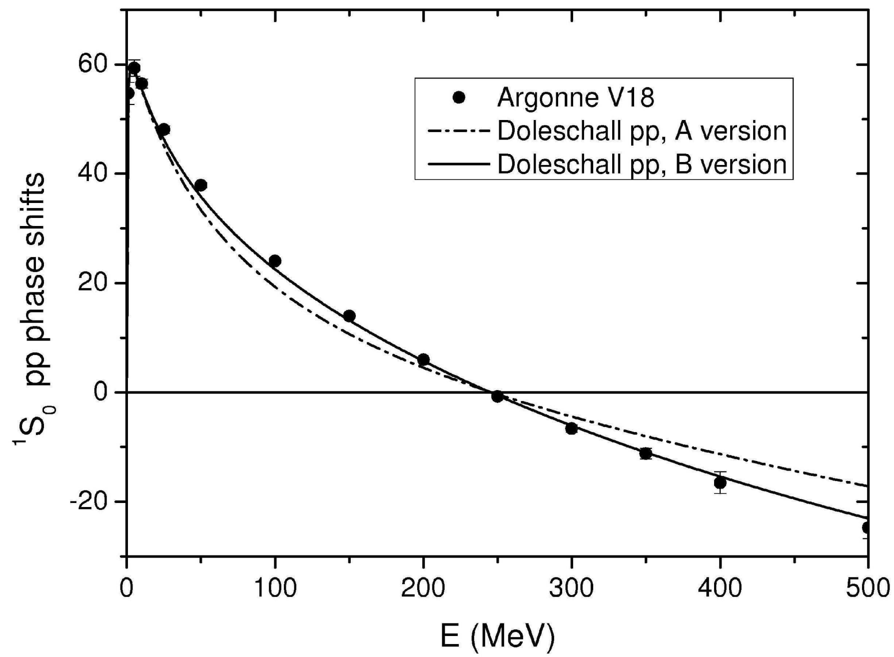
(for the three-body system Coulomb interaction plays a minor role and can be omitted, only the strong part of isospin-mixing interaction is used)

Two-term NN (pp) potential

P. Doleschall, private communication, 2009

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

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



Reproduces:

Argonne V18 NN phase shifts

(with sign change!),

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

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

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

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

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

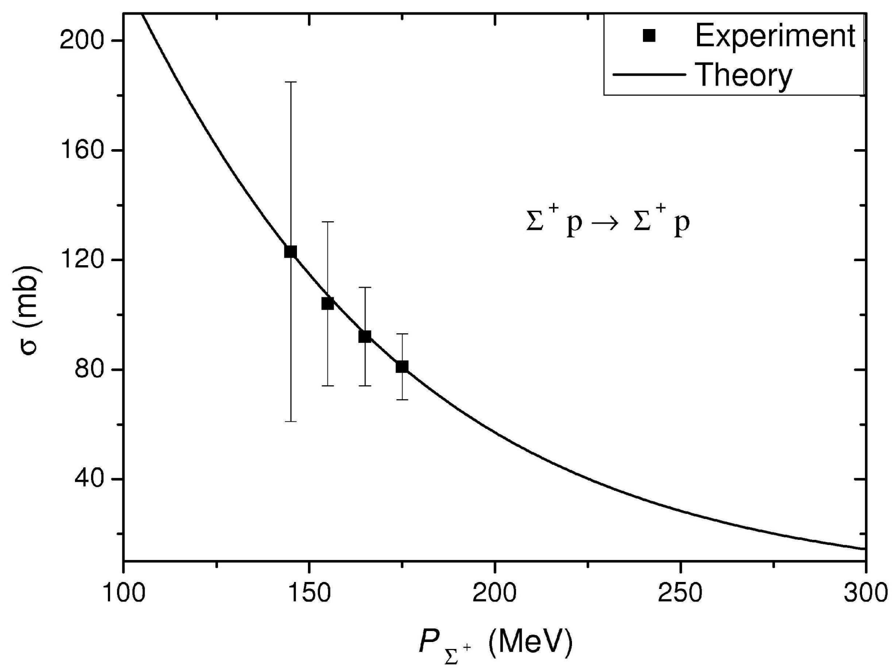
J. Révai, N.V. Shevchenko, 2009

$\mathrm{T}_I^{\Sigma N}(k,k';z)$ corresponds to

$$\mathrm{V}_I^{\Sigma N}(k,k') = \lambda_I^{\Sigma N}\; g_I^{\Sigma N}(k)\, g_I^{\Sigma N}(k')$$

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

All parameters were fitted to reproduce experimental cross-sections

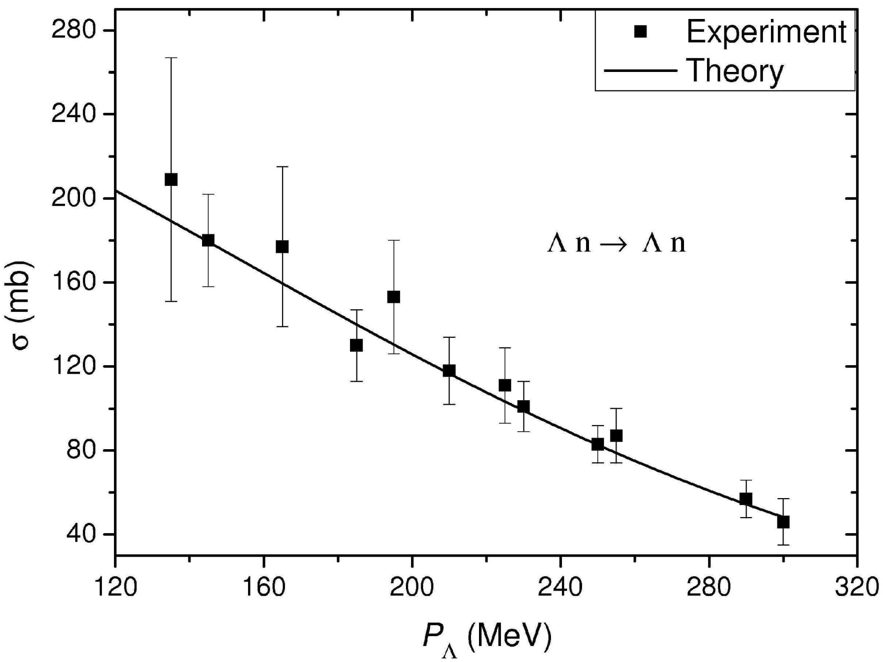


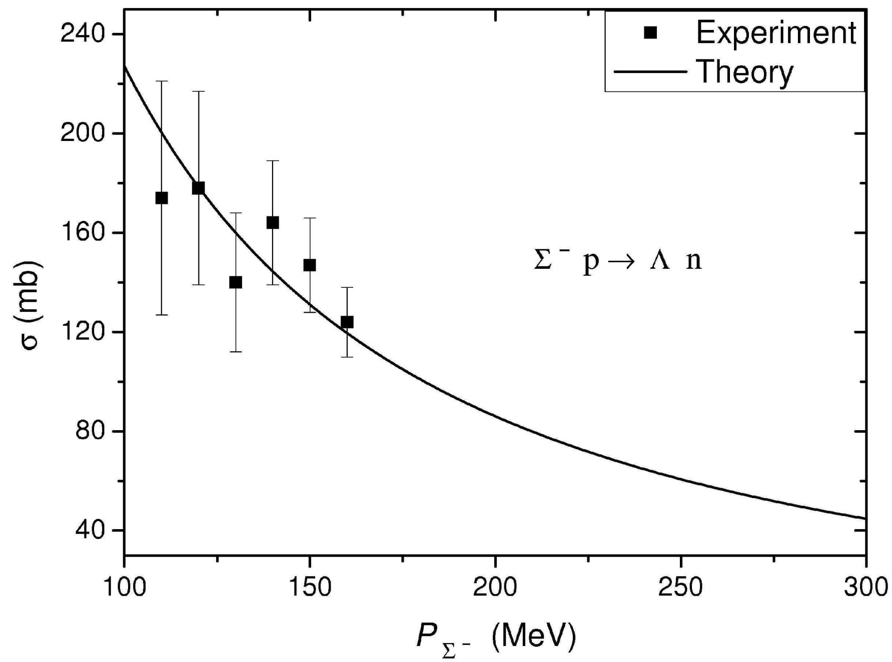
Pure *I=3/2* part

I=3/2
Real parameters, one-channel case

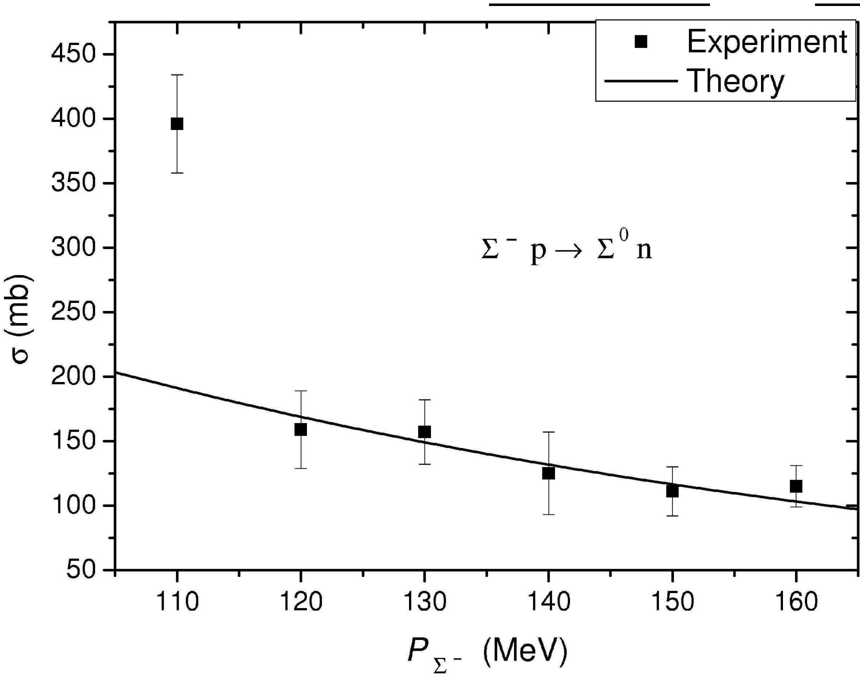
I=1/2

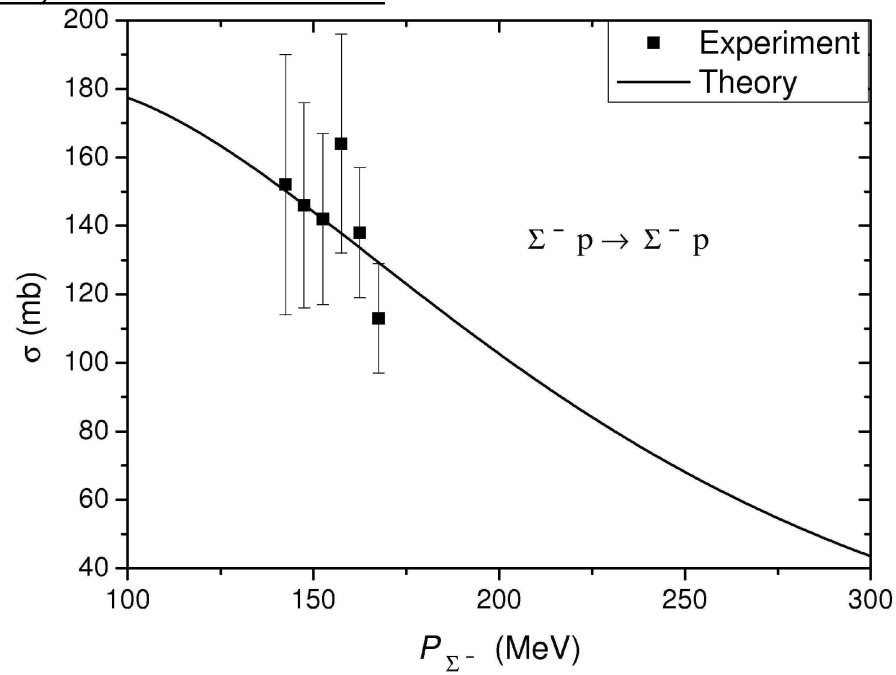
1. Two-channel $\Sigma N - \Lambda N$ potential, real parameters
2. One-channel ΣN potential, complex strength parameter





Pure *I=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	$-30.90 - i\ 47.38$	$-59.66 - i\ 41.31$