SPHERE MEETING 2014
September 9-11, 2014, Prague, Czech Republic

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Cascade production in antikaon reactions on nuclei

In collaboration with **A. Ramos, A. Feijoo Aliau**

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Cascade production in antikaon reactions with protons $(K^{-}\mathrm{p} \longrightarrow K\Xi)$

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Perturbative QCD, with ***quark*** and ***gluon*** d.o.f.,
works well at **high energies** and high momentum transfers,
but **fails** to describe **dynamics of hadrons** at **low energies**

→ **Chiral Perturbation Theory:** (χPT)

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which respects the symmetries of QCD,
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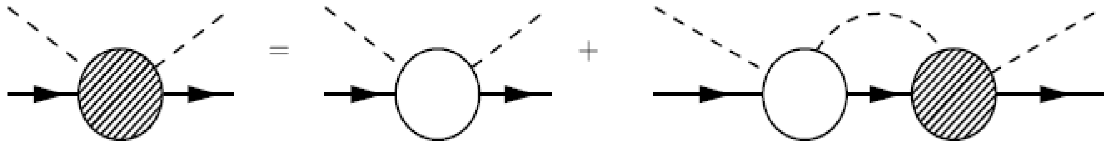
$S = -1$ sector: $\bar{K}N$ interaction

- $\bar{K}N$ scattering in the $I = 0$ channel is dominated by the presence of the $\Lambda(1405)$ resonance, located only 27 MeV below KN threshold ⇒
- χPT is not applicable ⇒
- **non-perturbative** techniques implementing unitarization in coupled channels are mandatory!

⇒ **Unitary extension of Chiral Perturbation Theory** $(U\chi PT)$

The pioneering work -- ***Kaiser, Siegel, Weise*** **, NP A594 (1995) 325**

Lippmann-Schwinger equation



$$T_{ij} = V_{ij} + V_{il} G_l T_{lj}$$

$$T_{ij}(E; k_i, k_j) = V_{ij}(k_i, k_j) + \sum_k \int d^3 q_k V_{ik}(k_i, q_k) \widetilde{G}_k(E; q_k) T_{kj}(E; q_k, k_j)$$

On shell factorization

System of the algebraic equations

$$T_{ij}(E) = V_{ij} + \sum_k V_{ik} G_k(E) T_{kj}(E) \,, \quad \rightarrow \quad T = (1 - VG)^{-1} V$$

$$G_k(E) = \int d^3 q_k \widetilde{G}_k(E; q_k)$$

V_{ij} - interaction kernel to be taken from the chiral Lagrangian

Loop function

G is a diagonal matrix given by the loop function of meson and baryon propagators:

$$G_l = i \int \frac{d^4q}{(2\pi)^4} \frac{M_l}{E_l(\vec{q})} \frac{1}{\sqrt{s} - q^0 - E_l(\vec{q}) + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

in which M_l and m_l are the masses of the baryons and mesons respectively.

In the dimensional regularization scheme this is given by

$$\begin{aligned} G_l &= i\,2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon} \\ &= \frac{2M_l}{16\pi^2} \Big\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln\frac{m_l^2}{M_l^2} - 2i\pi\frac{q_l}{\sqrt{s}} \\ &\quad + \frac{q_l}{\sqrt{s}} \big[\ln(s - (M_l^2 - m_l^2) + 2q_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2q_l\sqrt{s}) \\ &\quad - \ln(s - (M_l^2 - m_l^2) - 2q_l\sqrt{s}) - \ln(s + (M_l^2 - m_l^2) - 2q_l\sqrt{s}) \big] \Big\}, \end{aligned}$$

where μ is the scale of dimensional regularization, q_l denotes the three-momentum of the meson or baryon in the CM frame, and a_l are the subtraction constants.

Substraction contants

S=-1 channel there are 10 channels →
10 corresponding subtracting constants

$a_{K^-p}, a_{\bar{K}^0n}, a_{\pi^0\Lambda}, a_{\pi^0\Sigma^0}, a_{\pi^+\Sigma^-}, a_{\pi^-\Sigma^+}, a_{\eta\Lambda}, , a_{\eta\Sigma^0}, a_{K^+\Xi^-}, a_{K^0\Xi^0}$

Taking into account isospin symmetry:

$$a_{K^-p} = a_{\bar{K}^0n} = \boldsymbol{a_{\bar{K}N}}$$
$$a_{\pi^0\Lambda} = \boldsymbol{a_{\pi\Lambda}}$$
$$a_{\pi^0\Sigma^0} = a_{\pi^+\Sigma^-} = a_{\pi^-\Sigma^+} = \boldsymbol{a_{\pi\Sigma}}$$
$$\boldsymbol{a_{\eta\Lambda}}$$
$$a_{\eta\Sigma^0} = \boldsymbol{a_{\eta\Sigma}}$$
$$a_{K^+\Xi^-} = a_{K^0\Xi^0} = \boldsymbol{a_{K\Xi}}$$

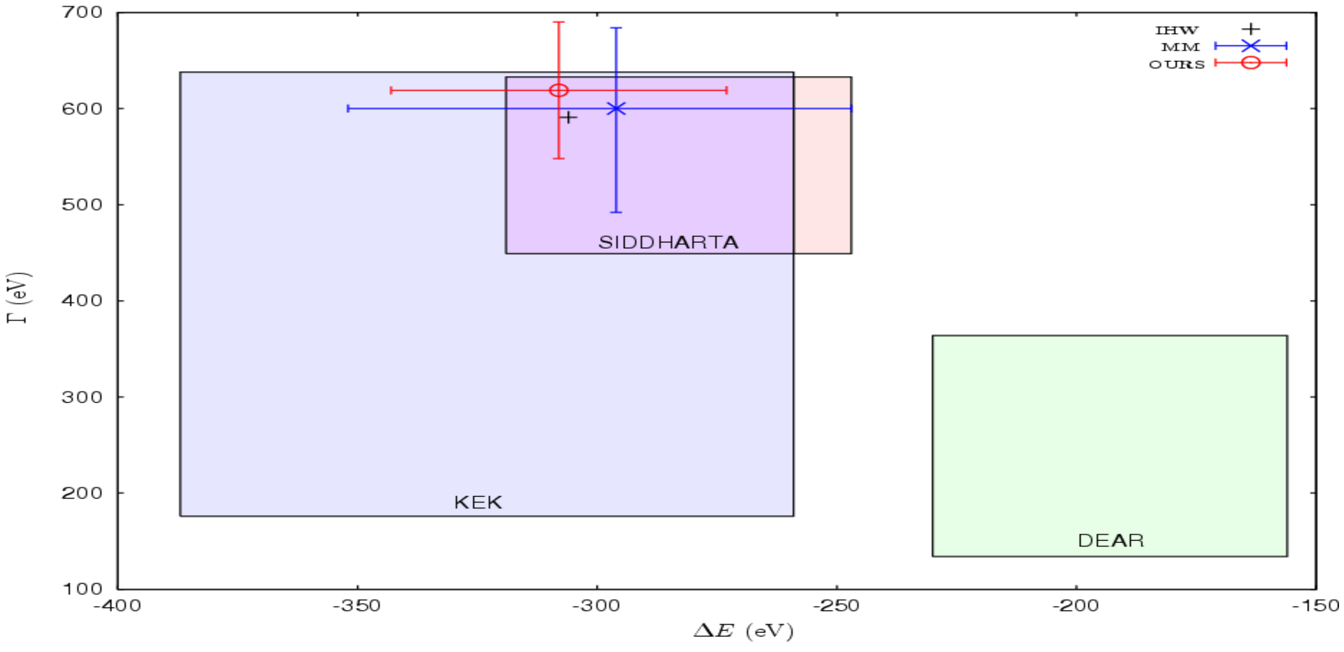
6 PARAMETERS!

Recent experimental advances

- The **SIDDHARTA** collaboration at DAΦNE collider has determined the most precise values of shift and width of the 1s state of the kaonic hydrogen induced by the strong interaction.

[M. Bazzi et al, Phys. Lett. B704 (2011) 113]

These measurements allowed us to clarify the discrepancies between KEK and DEAR results for the kaonic hydrogen shift and width of the ground state.



Chiral meson-baryon effective Lagrangian at NLO

Recent Publications:

- B. Borasoy, R. Nißler, W. Wiese, **Eur. Phys. J. A25 (2005) 79**
- Y. Ikeda, T. Hyodo, W. Wiese, **Phys. Lett. B706 (2011) 63; Nucl. Phys. A881 (2012) 98**
- Z.-H. Guo, J.A. Oller, **Phys. Rev. C87 (2013) 035202**
- M. Mai, U.G. Meissner, **Nucl. Phys. A900 (2013) 51**
- A. Feijoo, **Master Thesis**, U. of Barcelona (**Nov 2012**)
- A. Feijoo, V. Magas, A. Ramos, **arXiv:1311.5025; arXiv:1402.3971**

FORMALISM

Effective Chiral Lagrangian up to LO

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

$$\mathcal{L}_{MB}^{(1)}(B,U) = \langle \bar{B} i\gamma^\mu \nabla_\mu B\rangle - M_B\langle \bar{B}B\rangle + \frac{1}{2}D\langle \bar{B}\gamma^\mu\gamma_5\{u_\mu, B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma^\mu\gamma_5[u_\mu, B]\rangle$$

$$\nabla_\mu B = \partial_\mu B + [\Gamma_\mu, B]$$

$$\Gamma_\mu = \frac{1}{2}(u^\dagger\partial_\mu u + u\partial_\mu u^\dagger)$$

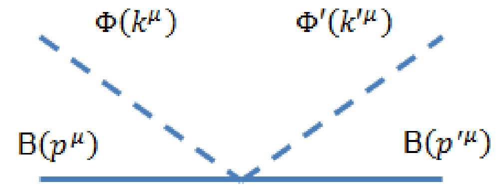
$$U = u^2 = exp\left(\frac{i\sqrt{2}\Phi}{f}\right)$$

$$u_\mu = iu^\dagger\partial_\mu U u^\dagger$$

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

- ***WT, lowest order term***

$$\mathcal{L}_{MB}^{(1)}(B,U) = \langle \bar{\boldsymbol{B}} i\gamma^\mu \frac{1}{4f^2}[(\boldsymbol{\Phi}\partial_\mu\boldsymbol{\Phi} - \partial_\mu\boldsymbol{\Phi}\boldsymbol{\Phi})\boldsymbol{B} - \boldsymbol{B}(\boldsymbol{\Phi}\partial_\mu\boldsymbol{\Phi} - \partial_\mu\boldsymbol{\Phi}\boldsymbol{\Phi})]\rangle$$



$$V_{ij}^{WT} = -C_{ij}\frac{1}{4f^2}\bar{u}(p)\gamma^\mu u(p)(k_\mu + k'_\mu) \quad \xrightarrow{\text{At low energies}} \quad \boldsymbol{V_{ij}^{WT}} = -\boldsymbol{C_{ij}}\frac{\boldsymbol{1}}{\boldsymbol{4f^2}}(\boldsymbol{k^0} + \boldsymbol{k'^0})$$

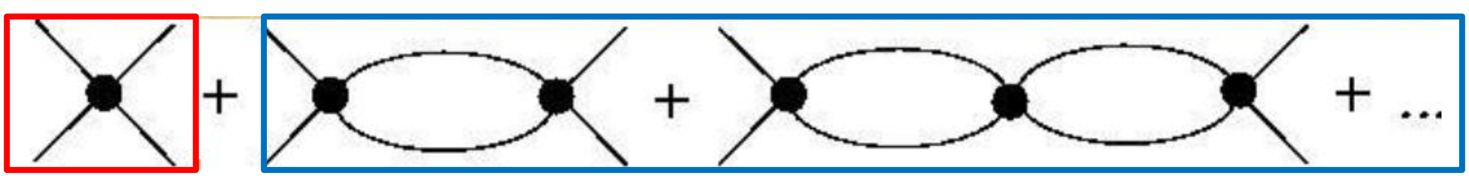
The only model parameter is **pion decay constant, f**

FORMALISM

Effective Chiral Lagrangian up to LO

C_{ij} coefficients are represented as a symmetric matrix where the indices i and j cover all the channels that conform the S=-1 sector.

	K^-p	$\bar{K}^0n$	$\pi^0\Lambda$	$\pi^0\Sigma^0$	$\eta\Lambda$	$\eta\Sigma^0$	$\pi^+\Sigma^-$	$\pi^-\Sigma^+$	$K^+\Xi^-$	$K^0\Xi^0$
K^-p	2	1	$\sqrt{3}/2$	1/2	3/2	$\sqrt{3}/2$	0	1	0	0
$\bar{K}^0n$		2	$-\sqrt{3}/2$	1/2	3/2	$-\sqrt{3}/2$	1	0	0	0
$\pi^0\Lambda$			0	0	0	0	0	0	$\sqrt{3}/2$	$-\sqrt{3}/2$
$\pi^0\Sigma^0$				0	0	0	2	2	1/2	1/2
$\eta\Lambda$					0	0	0	0	3/2	3/2
$\eta\Sigma^0$						0	0	0	$\sqrt{3}/2$	$-\sqrt{3}/2$
$\pi^+\Sigma^-$							2	0	1	0
$\pi^-\Sigma^+$								2	0	1
$K^+\Xi^-$									2	1
$K^0\Xi^0$										2



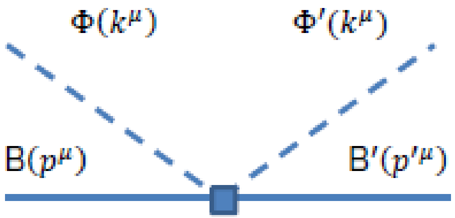
FORMALISM

Effective Chiral Lagrangian up to **NLO**

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

$$\mathcal{L}_{MB}^{(2)}(B,U) = b_D\langle \bar{B}\{\chi_+,B\}\rangle + b_F\langle \bar{B}[\chi_+,B]\rangle + b_0\langle \bar{B}B\rangle\langle\chi_+\rangle + d_1\langle \bar{B}\{u_\mu,[u^\mu,B]\}\rangle$$
$$+d_2\langle \bar{B}[u_\mu,[u^\mu,B]]\rangle + d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle$$

$$\chi = \begin{pmatrix} m_\pi^2 & 0 & 0 \\ 0 & m_\pi^2 & 0 \\ 0 & 0 & 2m_K^2 - m_\pi^2 \end{pmatrix}$$



- ***NLO, next – to – leading order term***

$$\mathcal{L}_{MB}^{(2)}(B,U) = -\frac{b_D}{4f^2}\langle \bar{B}(\Phi^2\chi + 2\Phi\chi\Phi + \chi\Phi^2)B + \bar{B}B(\Phi^2\chi + 2\Phi\chi\Phi + \chi\Phi^2)\rangle$$
$$-\frac{b_F}{4f^2}\langle \bar{B}(\Phi^2\chi + 2\Phi\chi\Phi + \chi\Phi^2)B - \bar{B}B(\Phi^2\chi + 2\Phi\chi\Phi + \chi\Phi^2)\rangle - \frac{b_0}{4f^2}\langle \bar{B}B\rangle\langle\Phi^2\chi + 2\Phi\chi\Phi + \chi\Phi^2\rangle +$$
$$\frac{2d_1}{f^2}\langle \bar{B}(\partial_\mu\Phi\partial^\mu\Phi B - \partial_\mu\Phi B\partial^\mu\Phi + \partial^\mu\Phi B\partial_\mu\Phi - B\partial^\mu\Phi\partial_\mu\Phi)\rangle +$$
$$\frac{2d_2}{f^2}\langle \bar{B}(\partial_\mu\Phi\partial^\mu\Phi B - \partial_\mu\Phi B\partial^\mu\Phi - \partial^\mu\Phi B\partial_\mu\Phi + B\partial^\mu\Phi\partial_\mu\Phi)\rangle + \frac{2d_3}{f^2}\langle \bar{B}\partial_\mu\Phi\rangle\langle\partial^\mu\Phi B\rangle + \frac{2d_4}{f^2}\langle \bar{B}B\rangle\langle\partial^\mu\Phi\partial_\mu\Phi\rangle$$

$$V_{ij}^{NLO} = \frac{1}{f^2}\left(D_{ij} - 2(k_\mu k'^\mu)L_{ij}\right)\sqrt{\frac{M_i+E_i}{2M_i}}\sqrt{\frac{M_j+E_j}{2M_j}}$$

7 new parameters to be fixed: b_D, b_F, b_0, d_1, d_2, d_3, d_4

FORMALISM

Effective Chiral Lagrangian up to **NLO**

D_{ij}

	K^-p	$\bar{K}^0n$	$\pi^0\Lambda$	$\pi^0\Sigma^0$	$\eta\Lambda$	$\eta\Sigma^0$	$\pi^+\Sigma^-$	$\pi^-\Sigma^+$	$K^+\Xi^-$	$K^0\Xi^0$
K^-p	$4(b_0+b_D)m_K^2$	$2(b_D+b_F)m_K^2$	$\frac{-(b_D+3b_F)\mu_1^2}{2\sqrt{3}}$	$\frac{(b_D-b_F)\mu_1^2}{2}$	0	$(b_D-b_F)\mu_1^2$	$\frac{(b_D+3b_F)\mu_2^2}{6}$	$-\frac{(b_D-b_F)\mu_2^2}{2\sqrt{3}}$	0	0
$\bar{K}^0n$		$4(b_0+b_D)m_K^2$	$\frac{(b_D+3b_F)\mu_1^2}{2\sqrt{3}}$	$\frac{(b_D-b_F)\mu_1^2}{2}$	$(b_D-b_F)\mu_1^2$	0	$\frac{(b_D+3b_F)\mu_2^2}{6}$	$\frac{(b_D-b_F)\mu_2^2}{2\sqrt{3}}$	0	0
$\pi^0\Lambda$			$\frac{4(3b_0+b_D)m_\pi^2}{3}$	0	0	0	0	$\frac{4b_Dm_\pi^2}{3}$	$-\frac{(b_D-3b_F)\mu_1^2}{2\sqrt{3}}$	$\frac{(b_D-3b_F)\mu_1^2}{2\sqrt{3}}$
$\pi^0\Sigma^0$				$4(b_0+b_D)m_\pi^2$	0	0	$\frac{4b_Dm_\pi^2}{3}$	0	$\frac{(b_D+b_F)\mu_1^2}{2}$	$\frac{(b_D+b_F)\mu_1^2}{2}$
$\eta\Lambda$					$4(b_0+b_D)m_\pi^2$	0	$\frac{4b_Dm_\pi^2}{3}$	$\frac{4b_Fm_\pi^2}{\sqrt{3}}$	$(b_D+b_F)\mu_1^2$	0
$\eta\Sigma^0$						$4(b_0+b_D)m_\pi^2$	$\frac{4b_Dm_\pi^2}{3}$	$-\frac{4b_Fm_\pi^2}{\sqrt{3}}$	0	$(b_D+b_F)\mu_1^2$
$\pi^+\Sigma^-$							$\frac{4(3b_0\mu_3^2+b_D\mu_4^2)}{9}$	0	$\frac{(b_D-3b_F)\mu_2^2}{6}$	$\frac{(b_D-3b_F)\mu_2^2}{6}$
$\pi^-\Sigma^+$								$\frac{4(b_0\mu_3^2+b_Dm_\pi^2)}{3}$	$\frac{(b_D+b_F)\mu_2^2}{2\sqrt{3}}$	$\frac{(b_D+b_F)\mu_2^2}{2\sqrt{3}}$
$K^+\Xi^-$									$4(b_0+b_D)m_K^2$	$2(b_D-b_F)m_K^2$
$K^0\Xi^0$										$4(b_0+b_D)m_K^2$

L_{ij}

	K^-p	$\bar{K}^0n$	$\pi^0\Lambda$	$\pi^0\Sigma^0$	$\eta\Lambda$	$\eta\Sigma^0$	$\pi^+\Sigma^-$	$\pi^-\Sigma^+$	$K^+\Xi^-$	$K^0\Xi^0$
K^-p	$2d_2+d_3+2d_4$	$d_1+d_2+d_3$	$-\frac{\sqrt{3}(d_1+d_2)}{2}$	$\frac{-d_1-d_2+2d_3}{2}$	$-2d_2+d_3$	$-d_1+d_2+d_3$	$\frac{d_1-3d_2+2d_3}{2}$	$\frac{d_1-3d_2}{2\sqrt{3}}$	$-4d_2+2d_3$	$-2d_2+d_3$
$\bar{K}^0n$		$2d_2+d_3+2d_4$	$\frac{\sqrt{3}(d_1+d_2)}{2}$	$\frac{-d_1-d_2+2d_3}{2}$	$-d_1+d_2+d_3$	$-2d_2+d_3$	$\frac{d_1-3d_2+2d_3}{2}$	$-\frac{(d_1-3d_2)}{2\sqrt{3}}$	$-2d_2+d_3$	$-4d_2+2d_3$
$\pi^0\Lambda$			$2d_4$	0	0	0	0	d_3	$\frac{\sqrt{3}(d_1-d_2)}{2}$	$-\frac{\sqrt{3}(d_1-d_2)}{2}$
$\pi^0\Sigma^0$				$2(d_3+d_4)$	$-2d_2+d_3$	$-2d_2+d_3$	d_3	0	$\frac{d_1-d_2+2d_3}{2}$	$\frac{d_1-d_2+2d_3}{2}$
$\eta\Lambda$					$2d_2+d_3+2d_4$	$-4d_2+2d_3$	d_3	$\frac{2d_1}{\sqrt{3}}$	$d_1+d_2+d_3$	$-2d_2+d_3$
$\eta\Sigma^0$						$2d_2+d_3+2d_4$	d_3	$-\frac{2d_1}{\sqrt{3}}$	$-2d_2+d_3$	$d_1+d_2+d_3$
$\pi^+\Sigma^-$							$2(d_3+d_4)$	0	$\frac{-d_1-3d_2+2d_3}{2}$	$\frac{-d_1-3d_2+2d_3}{2}$
$\pi^-\Sigma^+$								$2d_4$	$-\frac{(d_1+3d_2)}{2\sqrt{3}}$	$\frac{d_1+3d_2}{2\sqrt{3}}$
$K^+\Xi^-$									$2d_2+d_3+2d_4$	$-d_1+d_2+d_3$
$K^0\Xi^0$										$2d_2+d_3+2d_4$

FORMALISM

Effective Chiral Lagrangian up to **NLO**

$$V_{ij} = V_{ij}^{WT} + V_{ij}^{NLO} \Rightarrow \boxed{T = (1 - VG)^{-1} V} \Rightarrow T_{ij}^{NLO}$$

Fitting parameters:

- Decay constant f

  Its usual value, in real calculations, is between $1.15 - 1.2\, f_{\pi}^{exp}$ in order to simulate effects of higher order corrections . (f_{π}^{exp}=93.4MeV)

- 6 subtracting constants $a_{\bar{K}N}$, $a_{\pi\Lambda}$, $a_{\pi\Sigma}$, $a_{\eta\Lambda}$, $a_{\eta\Sigma}$, $a_{K\Xi}$

  These terms came from the regularization of the loop in LS equations.
  Isospin symmetry is taken into account.

- 7 coefficients of the NLO lagrangian terms $b_0, b_D, b_F, d_1, d_2, d_3, d_4$

Experimental data

- Cross sections for different channels

$$\sigma_{ij} = \frac{1}{4\pi}\frac{MM'}{s}\frac{k'}{k}\left|T_{ij}\right|^2$$

- Branching ratios

$$\gamma = \frac{\Gamma(K^-p \longrightarrow \pi^+\Sigma^-)}{\Gamma(K^-p \longrightarrow \pi^-\Sigma^+)} = \frac{\sigma_{\pi^+\Sigma^- \longrightarrow K^-p}}{\sigma_{\pi^-\Sigma^+ \longrightarrow K^-p}}$$

$$R_n = \frac{\Gamma(K^-p \longrightarrow \pi^0\Lambda)}{\Gamma(K^-p \longrightarrow neutral\ states)} = \frac{\sigma_{\pi^0\Lambda \longrightarrow K^-p}}{\sigma_{\pi^0\Lambda \longrightarrow K^-p} + \sigma_{\pi^0\Sigma^0 \longrightarrow K^-p}}$$

$$R_c = \frac{\Gamma(K^-p \longrightarrow \pi^+\Sigma^-, \pi^-\Sigma^+)}{\Gamma(K^-p \longrightarrow inelastic\ channels)} = \frac{\sigma_{\pi^+\Sigma^- \longrightarrow K^-p} + \sigma_{\pi^-\Sigma^+ \longrightarrow K^-p}}{\sigma_{\pi^+\Sigma^- \longrightarrow K^-p} + \sigma_{\pi^-\Sigma^+ \longrightarrow K^-p} + \sigma_{\pi^0\Lambda \longrightarrow K^-p} + \sigma_{\pi^0\Sigma^0 \longrightarrow K^-p}}$$

$K^- p \to K\Xi$ channels

These are particularly interesting for us, because

$K^- p \to K\Xi$ channels are very sensitive to the NLO terms in the Lagrangian

Also these channels are not included in the other fits!

B. Borasoy, R. Nißler, W. Wiese, **Eur. Phys. J. A25 (2005) 79**

Y. Ikeda, T. Hyodo, W. Wiese, **Phys. Lett. B706 (2011) 63; Nucl. Phys. A881 (2012) 98**

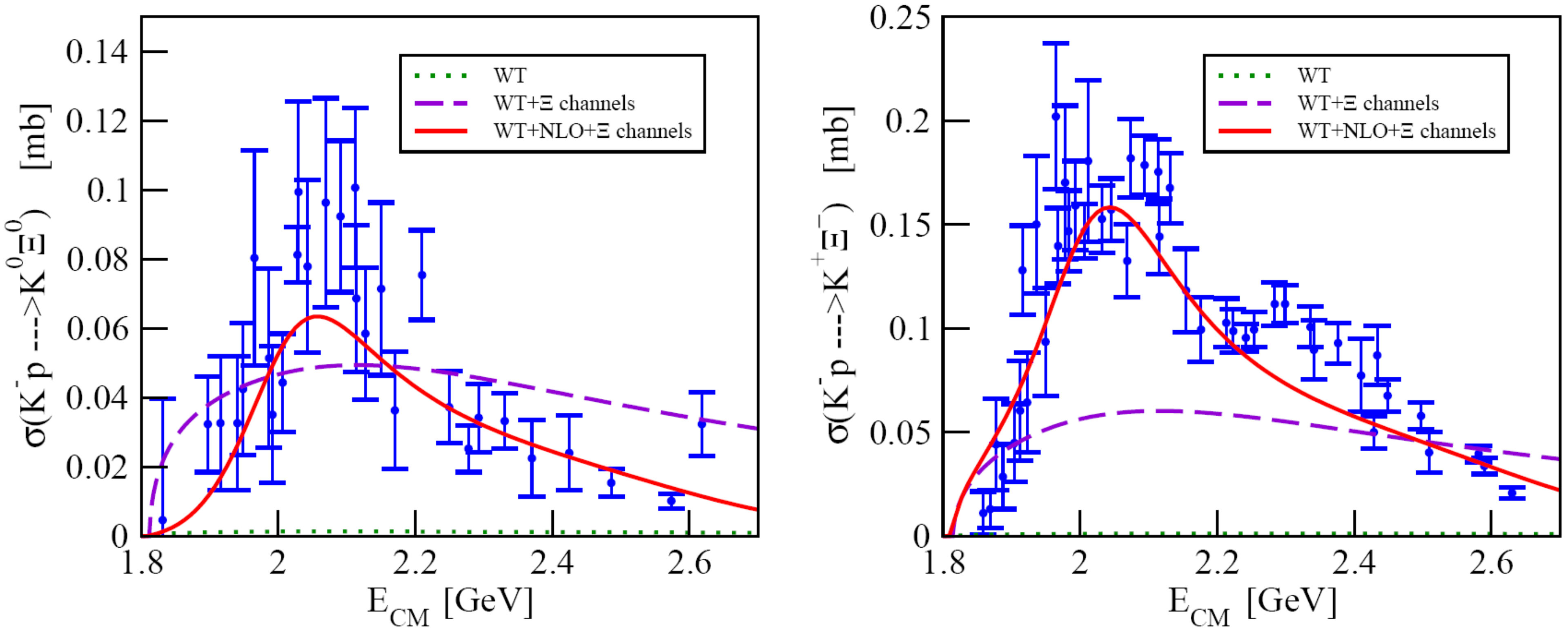
Z.-H. Guo, J.A. Oller, **Phys. Rev. C87 (2013) 035202**

M. Mai, U.G. Meissner, **Nucl. Phys. A900 (2013) 51**

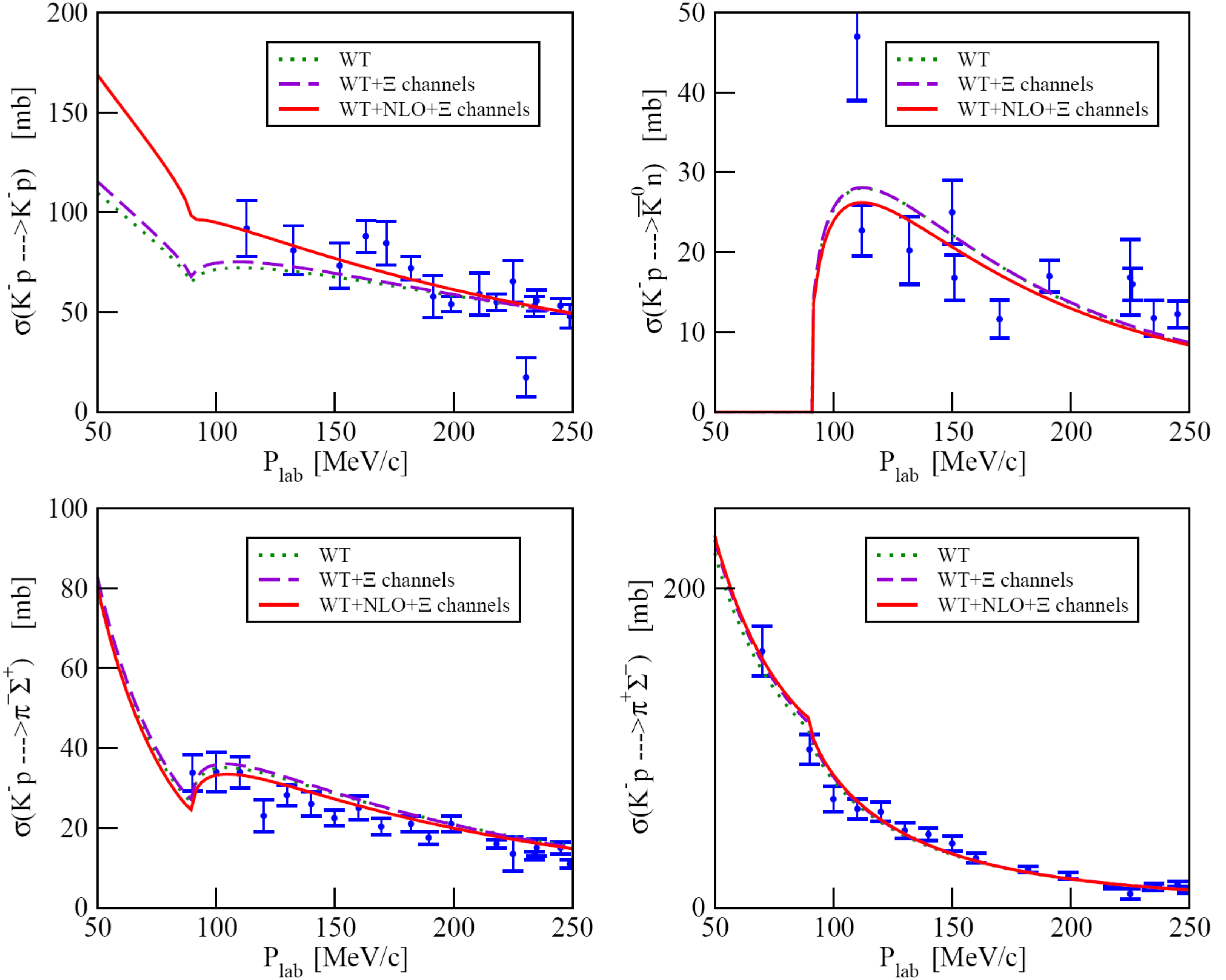
But studied in phenomenological model of

D. A. Sharov, V. L. Korotkikh, D. E. Lanskoy, **Eur. Phys. J. A47 (2011) 109**

$K^- p \to K\Xi$ channels



Results 1



WT
WT+Ξ channels
WT+NLO+Ξ channels
σ(K⁻p --->K⁻p) [mb]
σ(K⁻p --->K̄⁰n) [mb]
σ(K⁻p --->π⁻Σ⁺) [mb]
σ(K⁻p --->π⁺Σ⁻) [mb]
P_lab [MeV/c]
50
100
150
200
250
0
10
20
30
40
50
60
80

Results 1

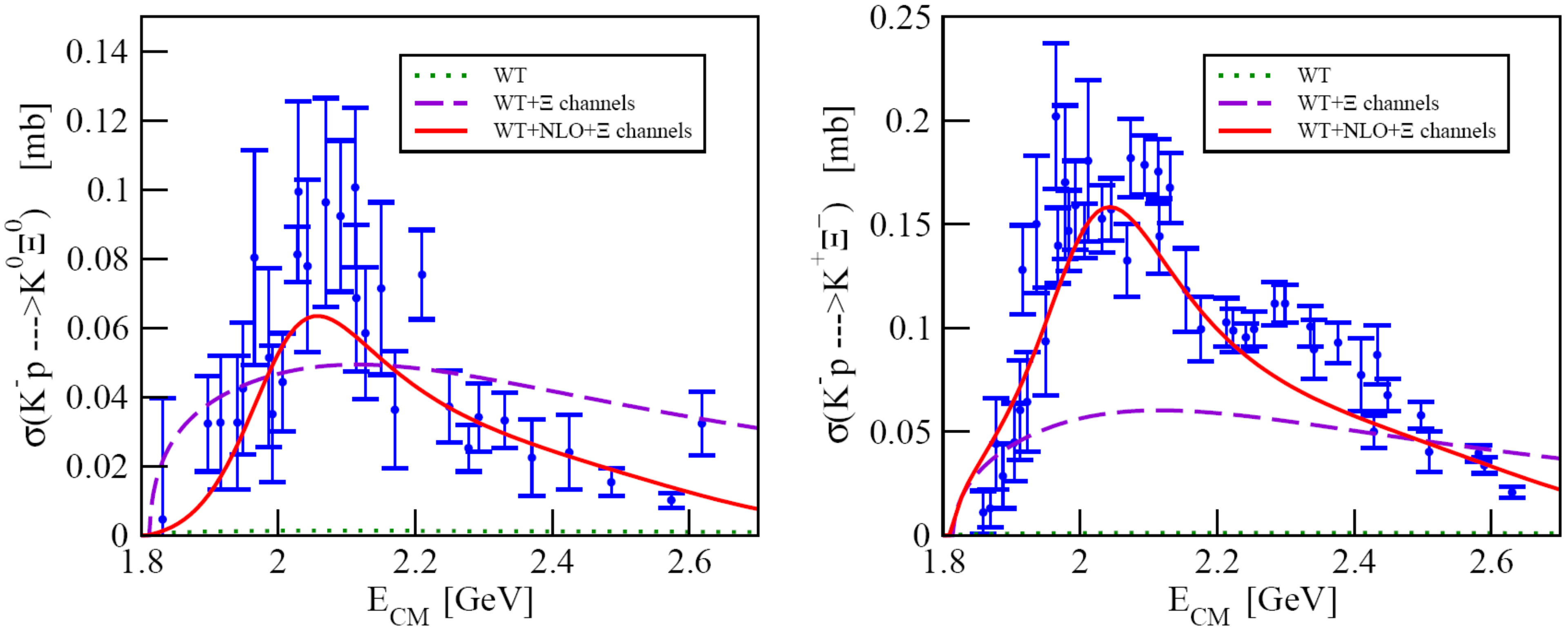
- ***Branching ratios***

MODEL	γ	R_n	R_c
WT	2.34	0.185	0.665
WT+Ξ channels	2.30	0.185	0.665
WT+ NLO+Ξ channels	2.31	0.186	0.660
Experimental	2.36 ± 0.04	0.189 ± 0.015	0.664 ± 0.011

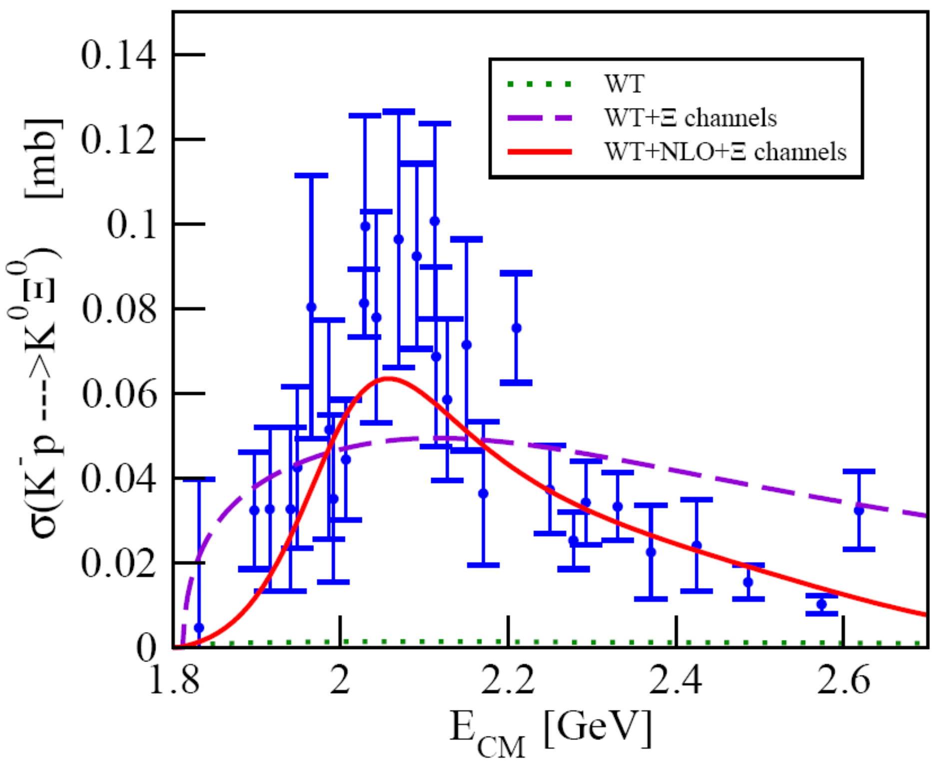
Fitting parameters 1

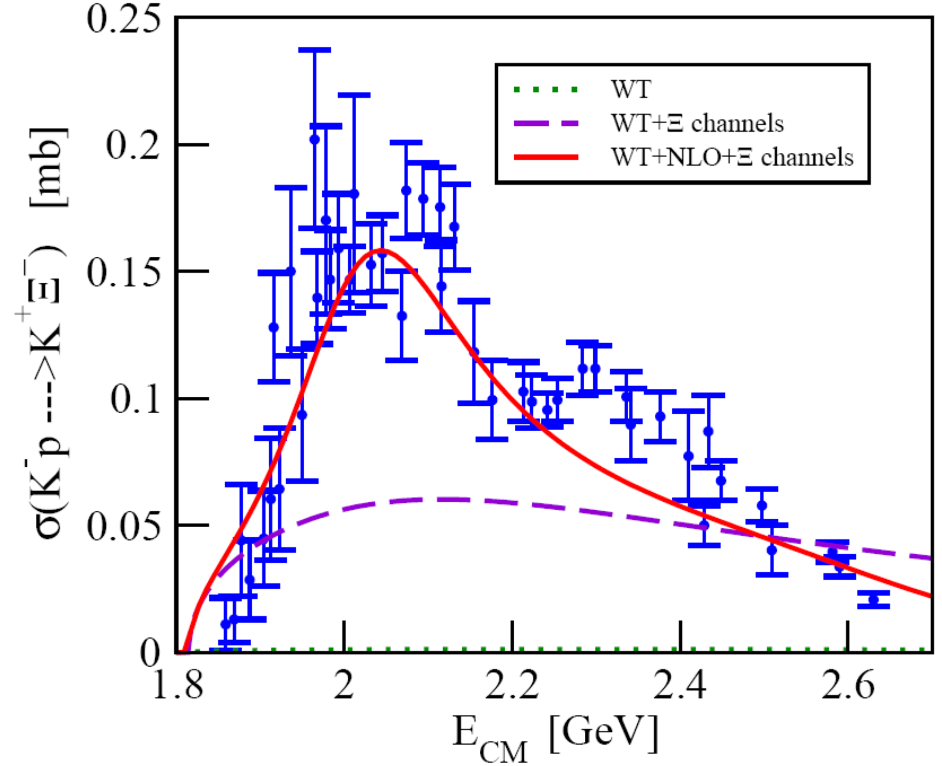
	WT	WT+Ξ channels	WT+ NLO+Ξ channels
$a_{\bar{K}N}$ (10^{-3})	-1.79	-1.95	4.13
$a_{\pi\Lambda}$ (10^{-3})	-39.83	-222.69	26.03
$a_{\pi\Sigma}$ (10^{-3})	0.06	0.40	0.37
$a_{\eta\Lambda}$ (10^{-3})	1.18	1.49	4.50
$a_{\eta\Sigma}$ (10^{-3})	38.04	247.17	-16.00
$a_{K\Xi}$ (10^{-3})	239.0	32.26	51.60
f (MeV)	$1.21 f_\pi$	$1.21 f_\pi$	$1.21 f_\pi$
b_0 (GeV^{-1})	–	–	-0.58
b_D (GeV^{-1})	–	–	0.28
b_F (GeV^{-1})	–	–	0.39
d_1 (GeV^{-1})	–	–	0.36
d_2 (GeV^{-1})	–	–	0.49
d_3 (GeV^{-1})	–	–	0.95
d_4 (GeV^{-1})	–	–	-0.68
$\chi^2_{d.o.f.}$	1.23 (no Ξ!)	3.56	1.79

$K^- p \to K\Xi$ channels



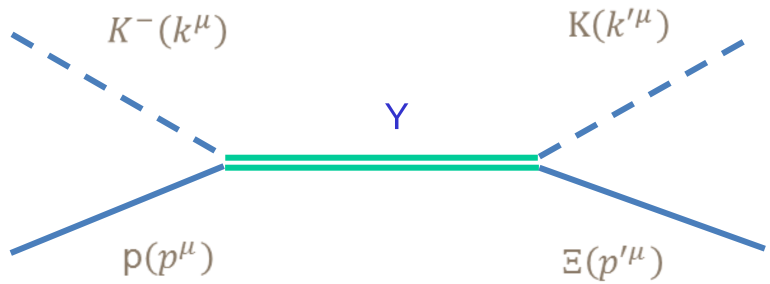
$K^- p \to K\Xi$ channels





- Missing contribution from the heavy high spin resonances

$$K^- p \to Y \to K\Xi$$

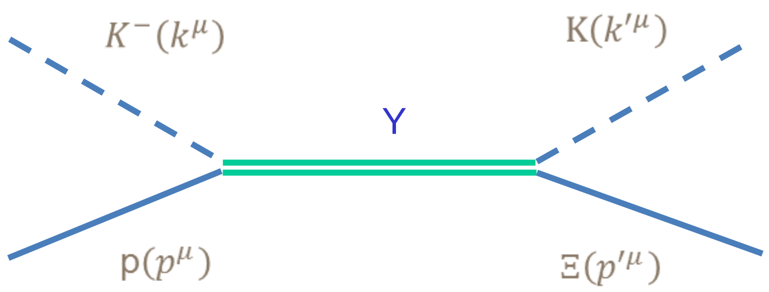


$K^-p \to K\Xi$ channels

Resonancia	$I(J^P)$	Mass (MeV)	Γ (MeV)	Fraction ($\Gamma_{K\Xi}/\Gamma$)
$\Lambda(1890)$	$0\left(\frac{3}{2}^+\right)$	$1850-1910$	$60-200$	_
$\Lambda(2100)$	$0\left(\frac{7}{2}^-\right)$	$2090-2110$	$100-250$	$< 3\%$
$\Lambda(2110)$	$0\left(\frac{5}{2}^+\right)$	$2090-2140$	$150-250$	_
$\Lambda(2350)$	$0\left(\frac{9}{2}^+\right)$	$2340-2370$	$100-250$	_
$\Sigma(1915)$	$1\left(\frac{5}{2}^+\right)$	$1900-1935$	$80-160$	_
$\Sigma(1940)$	$1\left(\frac{3}{2}^-\right)$	$1900-1950$	$150-300$	_
$\Sigma(2030)$	$1\left(\frac{7}{2}^+\right)$	$2025-2040$	$150-200$	$< 2\%$
$\Sigma(2250)$	$1(?^?)$ $\left(\frac{5}{2}^-\right)$	$2210-2280$	$60-150$	_

Sharov, Korotkikh, Lanskoy, ***EPJ A47 (11) 109:***
trying different combinations, the author conclude that **Σ(2030)** and **Σ(2250)** give the better fit to the data

Inclusion of hyperonic resonances in $K^- p \to K\Xi$ channels



K. Nakayama, Y. Oh, H. Habertzettl, Phys. Rev. C74, 035205 (2006)
K. Shing Man, Y. Oh, K. Nakayama,, Phys. Rev. C83, 055201 (2011)

Y= $\Sigma(2030)$, $\Sigma(2250)$

$\Sigma(2030)$, $J^P = \frac{7}{2}^+$, $T^{7/2^+}$

$$\mathscr{L}^{7/2^\pm}_{BYK}(q) = -\frac{g_{BY_{7/2}K}}{m_K^3}\bar{B}\Gamma^{(\mp)}Y^{\mu\nu\alpha}_{7/2}\partial_\mu\partial_\nu\partial_\alpha K + H.c.$$

$$v^{7/2^\pm}_{BYK} = -\frac{g_{BY_{7/2}K}}{m_K^3}k_\mu k_\nu k_\sigma \Gamma^{(\mp)}$$

$$S_{7/2}(q) = \frac{i}{\not{q} - M_{Y_{7/2}} + i\Gamma_{7/2}/2}\Delta^{\beta_1\beta_2\beta_3}_{\alpha_1\alpha_2\alpha_3}$$

$\Sigma(2250)$, $J^P = \frac{5}{2}^-$, $T^{5/2^-}$

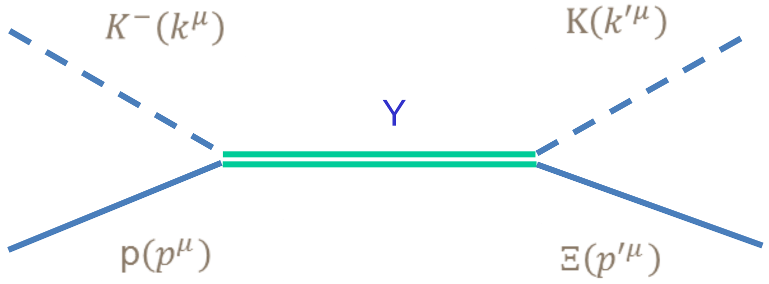
$$\mathscr{L}^{5/2^\pm}_{BYK}(q) = i\frac{g_{BY_{5/2}K}}{m_K^2}\bar{B}\Gamma^{(\pm)}Y^{\mu\nu}_{5/2}\partial_\mu\partial_\nu K + H.c.$$

$$v^{5/2^\pm}_{BYK} = i\frac{g_{BY_{5/2}K}}{m_K^2}k_\mu k_\nu \Gamma^{(\pm)}$$

$$S_{5/2}(q) = \frac{i}{\not{q} - M_{Y_{5/2}} + i\Gamma_{5/2}/2}\Delta^{\beta_1\beta_2}_{\alpha_1\alpha_2}$$

$$\Gamma^{(\pm)} = \binom{\gamma_5}{1}$$

Inclusion of hyperonic resonances in $K^- p \to K\Xi$ channels



K. Nakayama, Y. Oh, H. Habertzettl, Phys. Rev. C74, 035205 (2006)
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Y= $\Sigma(2030)$, $\Sigma(2250)$

$\Sigma(2030)$, $J^P = \frac{7}{2}^+$, $T^{7/2^+}$

$\Sigma(2250)$, $J^P = \frac{5}{2}^-$, $T^{5/2^-}$

$$S_{5/2}(p) = \frac{i}{\not{p} - m_R + i\Gamma/2}\Delta^{\beta_1\beta_2}_{\alpha_1\alpha_2},$$

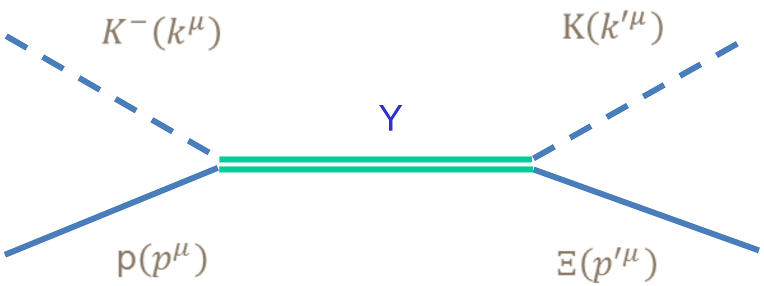
$$S_{7/2}(p) = \frac{i}{\not{p} - m_R + i\Gamma/2}\Delta^{\beta_1\beta_2\beta_3}_{\alpha_1\alpha_2\alpha_3}$$

$$\Delta^{\beta_1\beta_2}_{\alpha_1\alpha_2}(\tfrac{5}{2}) = \frac{1}{2}\left(\theta^{\beta_1}_{\alpha_1}\theta^{\beta_2}_{\alpha_2} + \theta^{\beta_2}_{\alpha_1}\theta^{\beta_1}_{\alpha_2}\right) - \frac{1}{5}\theta_{\alpha_1\alpha_2}\theta^{\beta_1\beta_2} - \frac{1}{10}\left(\bar{\gamma}_{\alpha_1}\bar{\gamma}^{\beta_1}\theta^{\beta_2}_{\alpha_2} + \bar{\gamma}_{\alpha_1}\bar{\gamma}^{\beta_2}\theta^{\beta_1}_{\alpha_2} + \bar{\gamma}_{\alpha_2}\bar{\gamma}^{\beta_1}\theta^{\beta_2}_{\alpha_1} + \bar{\gamma}_{\alpha_2}\bar{\gamma}^{\beta_2}\theta^{\beta_1}_{\alpha_1}\right)$$

$$\Delta^{\beta_1\beta_2\beta_3}_{\alpha_1\alpha_2\alpha_3}(\tfrac{7}{2}) = \frac{1}{36}\sum_{P(\alpha),P(\beta)}\left\{\theta^{\beta_1}_{\alpha_1}\theta^{\beta_2}_{\alpha_2}\theta^{\beta_3}_{\alpha_3} - \frac{3}{7}\theta^{\beta_1}_{\alpha_1}\theta_{\alpha_2\alpha_3}\theta^{\beta_2\beta_3} - \frac{3}{7}\bar{\gamma}_{\alpha_1}\bar{\gamma}^{\beta_1}\theta^{\beta_2}_{\alpha_2}\theta^{\beta_3}_{\alpha_3} + \frac{3}{35}\bar{\gamma}_{\alpha_1}\bar{\gamma}^{\beta_1}\theta_{\alpha_2\alpha_3}\theta^{\beta_2\beta_3}\right\},$$

$$\theta^{\nu}_{\mu} = g^{\nu}_{\mu} - \frac{p_\mu p^\nu}{M^2}, \qquad \bar{\gamma}_\mu = \gamma_\mu - \frac{p_\mu \not{p}}{M^2}$$

Inclusion of hyperonic resonances in $K^- p \to K\Xi$ channels



Y= $\Sigma(2030)$, $\Sigma(2250)$

Finally, the scattering amplitudes related to the resonances can be obtained in the following way :

$$T^{5/2^-}(s',s) = \frac{g_{\Xi Y_{5/2} K}\, g_{N Y_{5/2} \bar{K}}}{m_K^4}\, \bar{u}^{s'}_{\Xi}(p')\, \frac{k'_{\beta_1} k'_{\beta_2} \Delta^{\beta_1 \beta_2}_{\alpha_1 \alpha_2} k^{\alpha_1} k^{\alpha_2}}{\not{q} - M_{Y_{5/2}} + i\Gamma_{5/2}/2}\, u^s_N(p)\, \boxed{\exp\left(-\vec{k}^2/\Lambda^2_{5/2}\right)}\, \boxed{\exp\left(-\vec{k}'^2/\Lambda^2_{5/2}\right)}$$

$$T^{7/2^+}(s',s) = \frac{g_{\Xi Y_{7/2} K}\, g_{N Y_{7/2} \bar{K}}}{m_K^6}\, \bar{u}^{s'}_{\Xi}(p')\, \frac{k'_{\beta_1} k'_{\beta_2} k'_{\beta_2} \Delta^{\beta_1 \beta_2 \beta_3}_{\alpha_1 \alpha_2 \alpha_3} k^{\alpha_1} k^{\alpha_2} k^{\alpha_3}}{\not{q} - M_{Y_{7/2}} + i\Gamma_{7/2}/2}\, u^s_N(p)\, \boxed{\exp\left(-\vec{k}^2/\Lambda^2_{7/2}\right)}\, \boxed{\exp\left(-\vec{k}'^2/\Lambda^2_{7/2}\right)}$$

Note that a form factor has been included in each vertex of the diagram, we chose exponential form factor due to the high dependence in momentum of the scattering amplitudes.

Inclusion of hyperonic resonances in $K^- p \to K\Xi$ channels

Taking into account the scattering amplitude given by LS equations for a NLO Chiral Lagrangian and the phenomenological contributions from the resonances, the total scattering amplitude for the $\bar{K}N \longrightarrow K\Xi$ reaction should be written as:

$$T^{tot}_{ij,s,s\prime} = T^{LS}_{ij,s,s\prime} + T^{5/2^-}_{s,s\prime} + T^{7/2^+}_{s,s\prime}$$

Fitting parameters:

- Decay constant f

  Its usual value, in real calculations, is between $1.15 - 1.2\ f^{exp}_{\pi}$ in order to simulate effects of higher order corrections . (f^{exp}_{π}=93.4MeV)

- Subtracting constants $a_{\bar{K}N}$, $a_{\pi\Lambda}$, $a_{\pi\Sigma}$, $a_{\eta\Lambda}$, $a_{\eta\Sigma}$, $a_{K\Xi}$

  These terms came from the regularization of the loop in LS equations.
  Isospin symmetry is taken into account.

- Coefficients of the NLO lagrangian terms $b_0, b_D, b_F, d_1, d_2, d_3, d_4$

- Masses and width of the resonances $M_{Y_{5/2}}, M_{Y_{7/2}}, \Gamma_{5/2}, \Gamma_{7/2}$

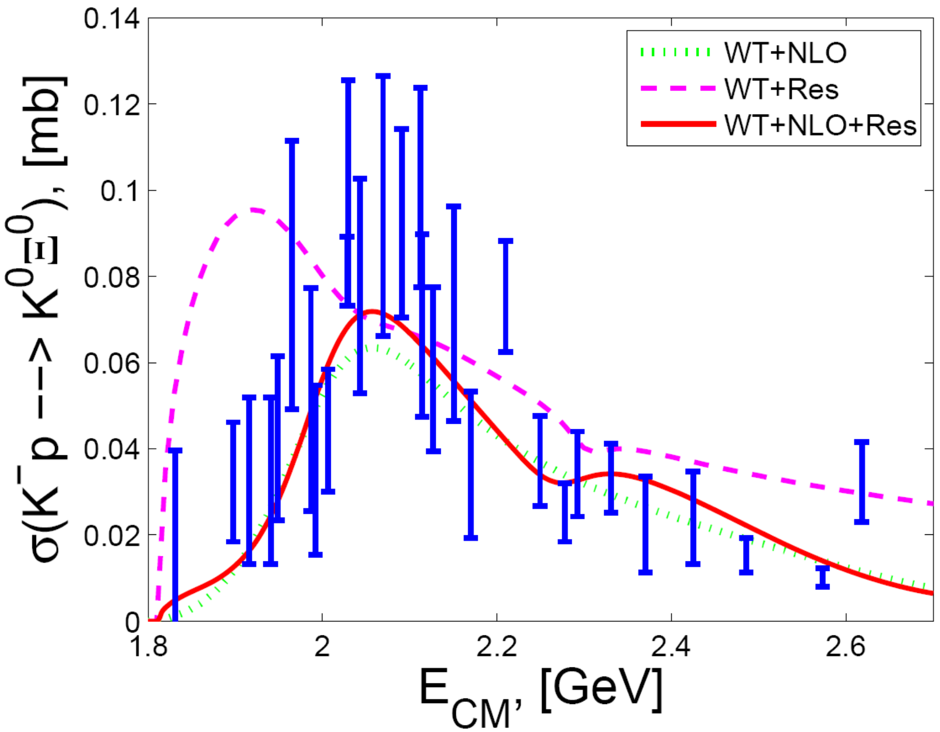
  Not free at all, their values are constrained according to PDG summary

- Cutoff parameters from the form factor $\Lambda_{5/2}, \Lambda_{7/2}$

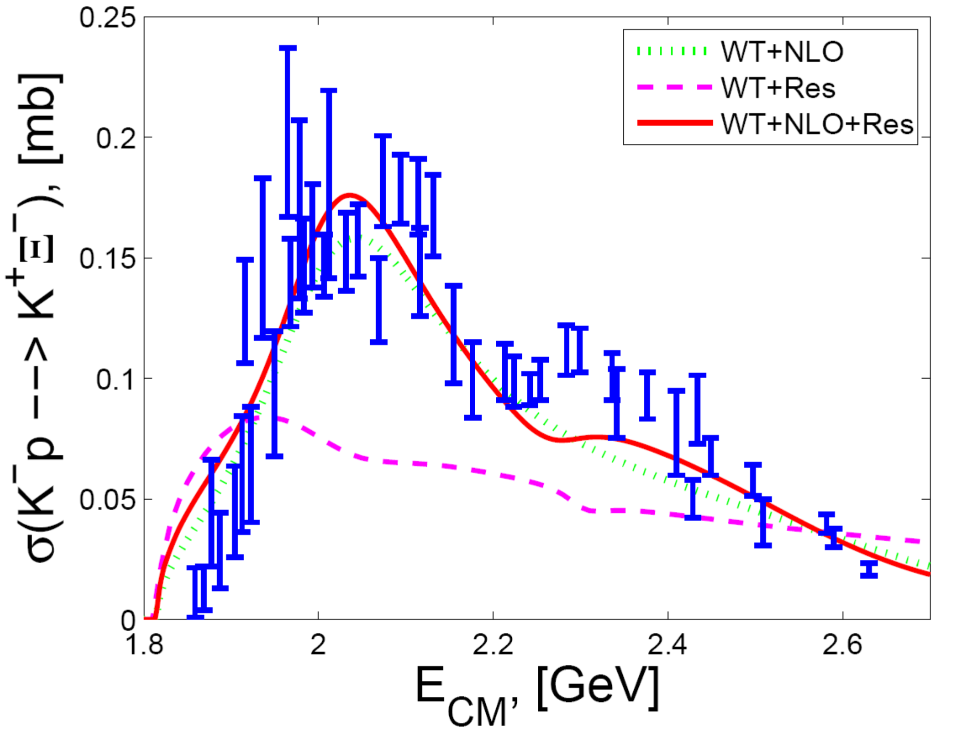
- Product of the coupling constants (one for each vertex) for both resonances

  $g_{\Xi Y_{5/2}K} \cdot g_{NY_{5/2}\bar{K}}$, $g_{\Xi Y_{7/2}K} \cdot g_{NY_{7/2}\bar{K}}$

Results 2

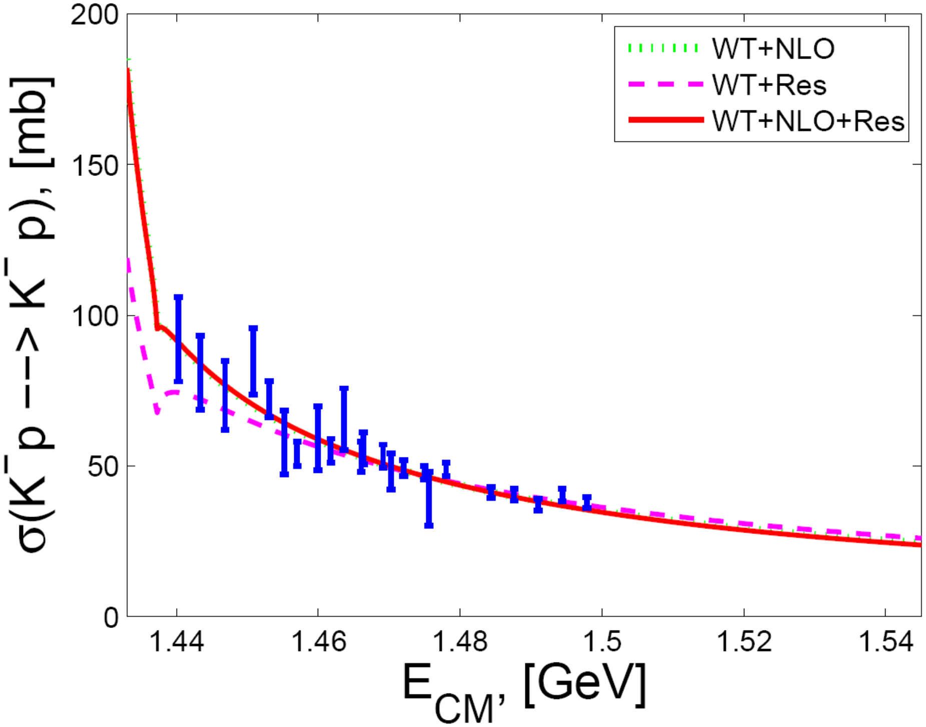


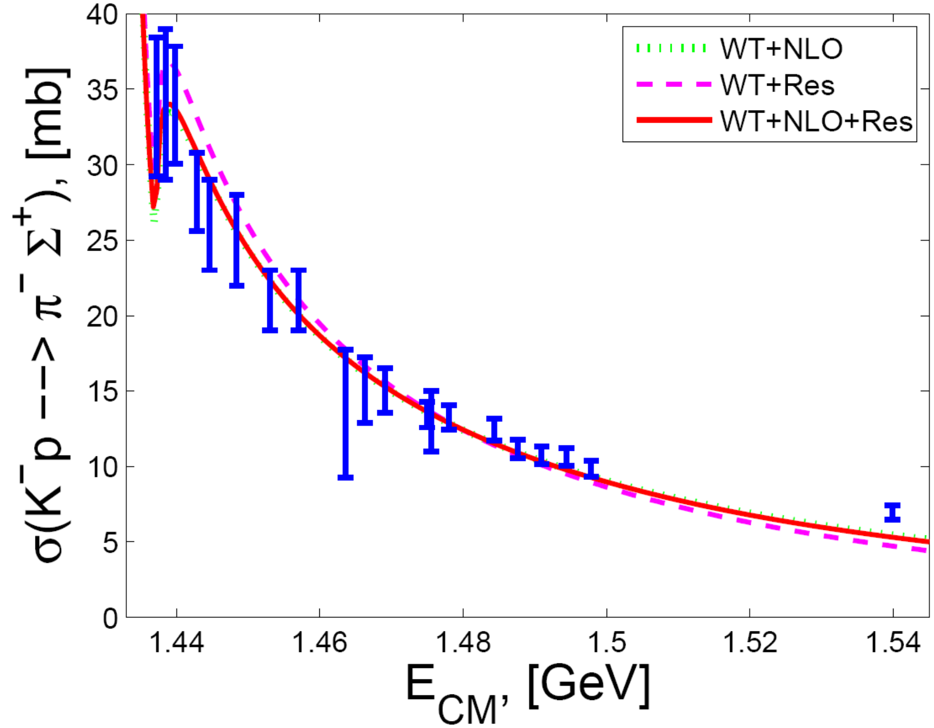
WT+NLO
WT+Res
WT+NLO+Res
σ(K⁻p --> K⁰Ξ⁰), [mb]
E_CM, [GeV]



WT+NLO
WT+Res
WT+NLO+Res
σ(K⁻p --> K⁺Ξ⁻), [mb]
E_CM, [GeV]

Results 2





- ***Branching ratios***

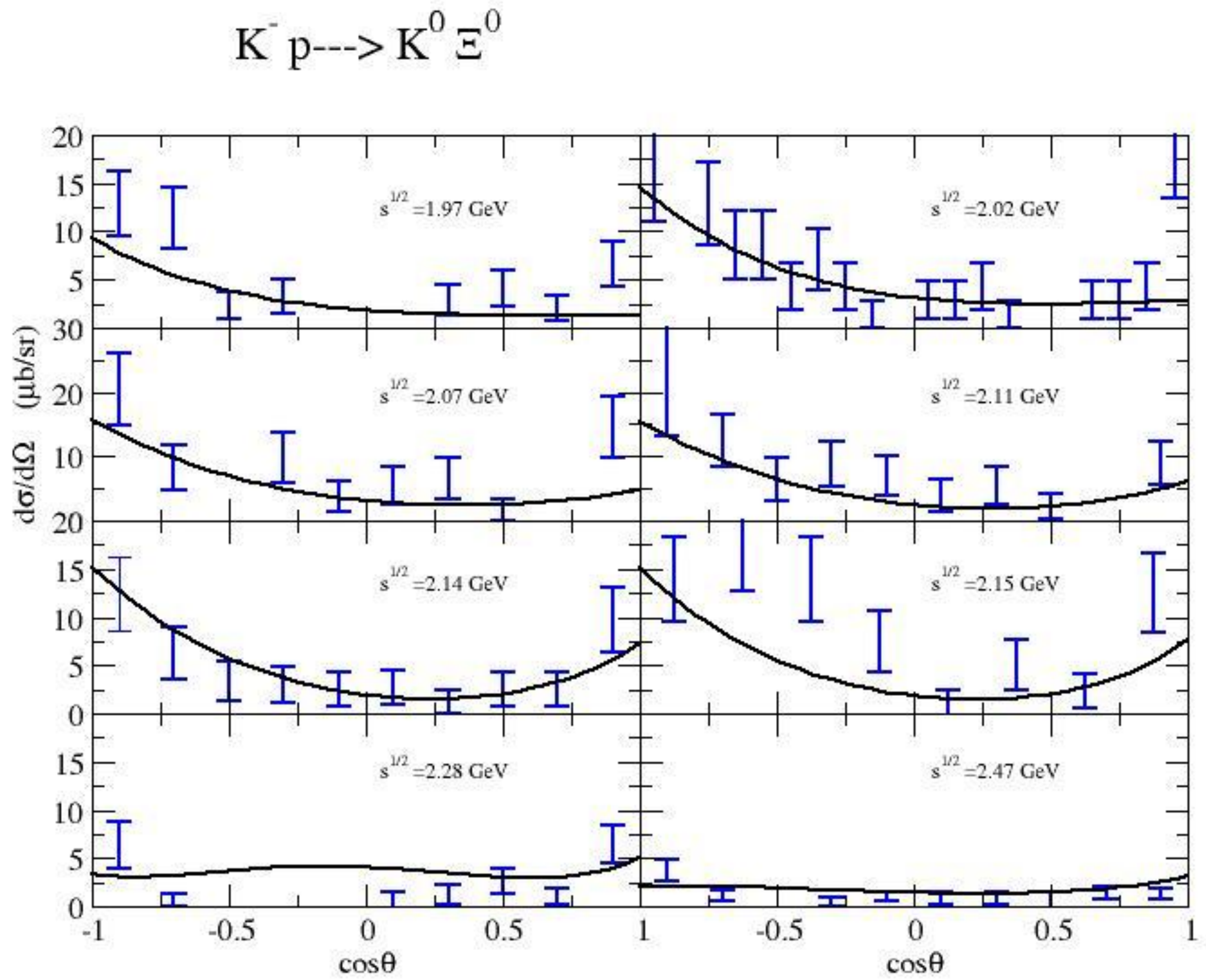
MODEL	γ	R_n	R_c
WT +RES	2.48	0.202	0.667
WT+ NLO	2.31	0.186	0.660
WT+NLO+RES	2.50	0.188	0.664
Experimental	2.36 ± 0.04	0.189 ± 0.015	0.664 ± 0.011

Fitting parameters 2

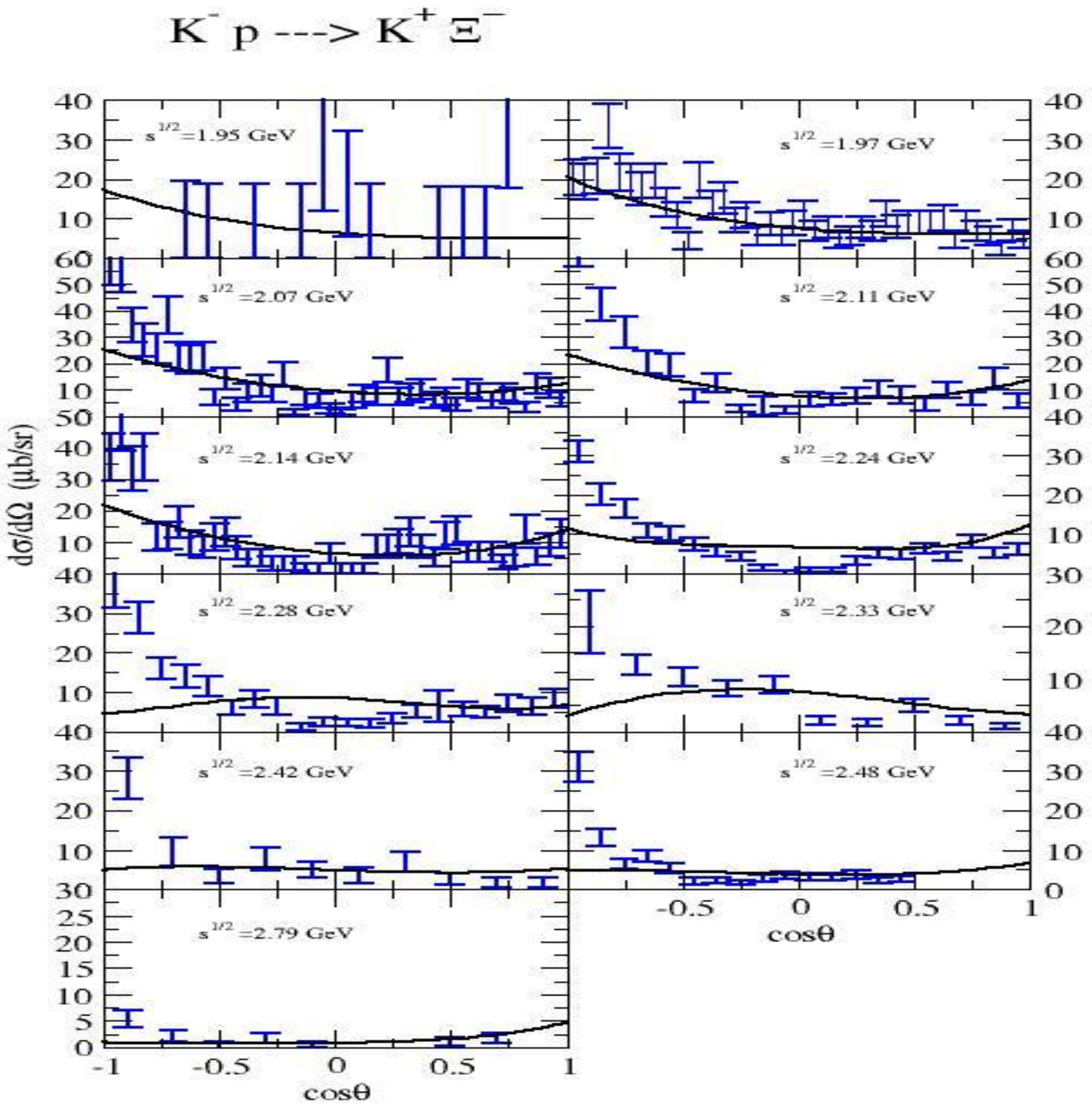
	WT+RES	WT+ NLO	WT+ NLO +RES
$a_{\bar{K}N}$ (10^{-3})	-1.87	4.13	4.03
$a_{\pi\Lambda}$ (10^{-3})	-202.56	26.03	26.89
$a_{\pi\Sigma}$ (10^{-3})	0.29	0.37	0.16
$a_{\eta\Lambda}$ (10^{-3})	1.42	4.50	5.10
$a_{\eta\Sigma}$ (10^{-3})	224.53	-16.00	-37.03
$a_{K\Xi}$ (10^{-3})	36.05	51.60	58.397
f (MeV)	$1.20f_\pi$	$1.21f_\pi$	$1.21f_\pi$
b_0 (GeV^{-1})	_	-0.58	-0.52
b_D (GeV^{-1})	_	0.28	0.26
b_F (GeV^{-1})	_	0.39	0.43
d_1 (GeV^{-1})	_	0.36	0.41
d_2 (GeV^{-1})	_	0.49	0.45
d_3 (GeV^{-1})	_	0.95	0.85
d_4 (GeV^{-1})	_	-0.68	-0.59
$g_{\Xi Y_{5/2}K} \cdot g_{NY_{5/2}\bar{K}}$	-6.0	_	3.65
$g_{\Xi Y_{7/2}K} \cdot g_{NY_{7/2}\bar{K}}$	-6.59	_	0.12
$\Lambda_{5/2}(MeV)$	506.50	_	578.94
$\Lambda_{7/2}(MeV)$	484.05	_	862.25
$M_{Y_{5/2}}(MeV)$	2300.0	_	2275.2
$M_{Y_{7/2}}(MeV)$	2025.0	_	2040.0
$\Gamma_{5/2}(MeV)$	60.0	_	130.71
$\Gamma_{7/2}(MeV)$	200.0	_	200.00
$\chi^2_{d.o.f.}$	3.19	1.79	1.34

Variations within 10-20%

Results 2


K⁻ p---> K⁰ Ξ⁰
s^1/2 =1.97 GeV
s^1/2 =2.02 GeV
s^1/2 =2.07 GeV
s^1/2 =2.11 GeV
s^1/2 =2.14 GeV
s^1/2 =2.15 GeV
s^1/2 =2.28 GeV
s^1/2 =2.47 GeV
dσ/dΩ (μb/sr)
cosθ
cosθ

Results 2


K⁻ p ---> K⁺ Ξ⁻
s^1/2 =1.95 GeV
s^1/2 =1.97 GeV
s^1/2 =2.07 GeV
s^1/2 =2.11 GeV
s^1/2 =2.14 GeV
s^1/2 =2.24 GeV
s^1/2 =2.28 GeV
s^1/2 =2.33 GeV
s^1/2 =2.42 GeV
s^1/2 =2.48 GeV
s^1/2 =2.79 GeV
dσ/dΩ (μb/sr)
cosθ

Production of Ξ in nuclei: (K^-,K^+) reaction on nuclear targets

- These reaction may inform us about the size of the Ξ optical potential in the nucleus
- They are employed to produce Ξ hypernuclei and double Λ hypernuclei

Production of Ξ in nuclei: (K^-,K^+) reaction on nuclear targets

$$K^-(p_{lab}) + A \Rightarrow K^+(p') + A'_{\Xi^-}$$

K- is absorbed by the nucleon with momenta randomly chosen within the local Fermi sea

$$\sigma_{A_\Xi} = \int d^3r \rho_p(r) \sigma_\Xi(p_{lab}, k) = 2\int d^3r \int \frac{d^3k}{(2\pi)^3} \Theta(k_F(r) - k) \sigma_\Xi(p_{lab}, k)$$

$$K^-(p_{lab}) + p(k) \Rightarrow K^+(p') + \Xi^-(k')$$

$$d\sigma_\Xi(p_{lab}, k) = \frac{(2\pi)^4}{4m_p p_{lab}} |T|^2 \frac{d^3p'}{(2\pi)^3 E_K} \frac{d^3k'}{(2\pi)^3 E_\Xi} \delta(p_{Lab} + k - p' - k')$$

where $T \equiv T^{tot}_{K^-p \to K^+\Xi^-}$

$$E_\Xi = \sqrt{M_\Xi^{\ 2} + k'^2} - V_\Xi(r), \qquad V_\Xi = -V_0 \, \rho(r)/\rho_0, \qquad \text{with} \qquad V_0 \approx -15 - 20\,MeV$$

Production of Ξ in nuclei: (K^-,K^+) reaction on nuclear targets

Exp. Data of **T.Iijima et al. Nucl.Phys. A546 (1992) 588**

$K^- A \rightarrow K^+ \Xi^- A'$ $\qquad p_{K^-} = 1.65$ GeV

Forward reaction: $1.7° < \Theta_{K^+}\big|_{lab} < 13.6°$

ISI - eikonal approximation

$$e^{-\int_{-\infty}^{z} \sigma_{K^- N}(p_{lab})\rho(\sqrt{b^2+z'^2})dz'} \qquad \sigma_{K^- N} = \frac{1}{2}(\sigma^{tot}_{K^- p} + \sigma^{tot}_{K^- n})$$

FSI - eikonal approximation

$$e^{-\int_{z}^{\infty} \sigma_{K^+ N}(p')\rho(r')dl} \qquad \text{where} \qquad \vec{r}' = \vec{r} + l\,\frac{\vec{p}'}{p'}$$

$$\sigma_{K^+ N} = \frac{1}{2}(\sigma^{tot}_{K^+ p} + \sigma^{tot}_{K^+ n})$$

Production of Ξ in nuclei: (K^-,K^+) reaction on nuclear targets

Exp. Data of **T.Iijima et al. Nucl.Phys. A546 (1992) 588**

$K^- A \rightarrow K^+ \Xi^- A'$ $\qquad p_{K^-} = 1.65$ GeV

Forward reaction: $1.7° < \Theta_{K^+}\big|_{lab} < 13.6°$

$$T^{tot}_{K^- p \rightarrow K^+ \Xi^-} \Rightarrow \left(\frac{d\sigma}{d\Omega}\right)^{forward}_{lab} \approx 35 mb$$

Practically constant

$$|\vec{p}| \leq k_F(\rho_0)$$

ISI: $\sigma_{K^- N} \approx 29 mb$

Practically constant

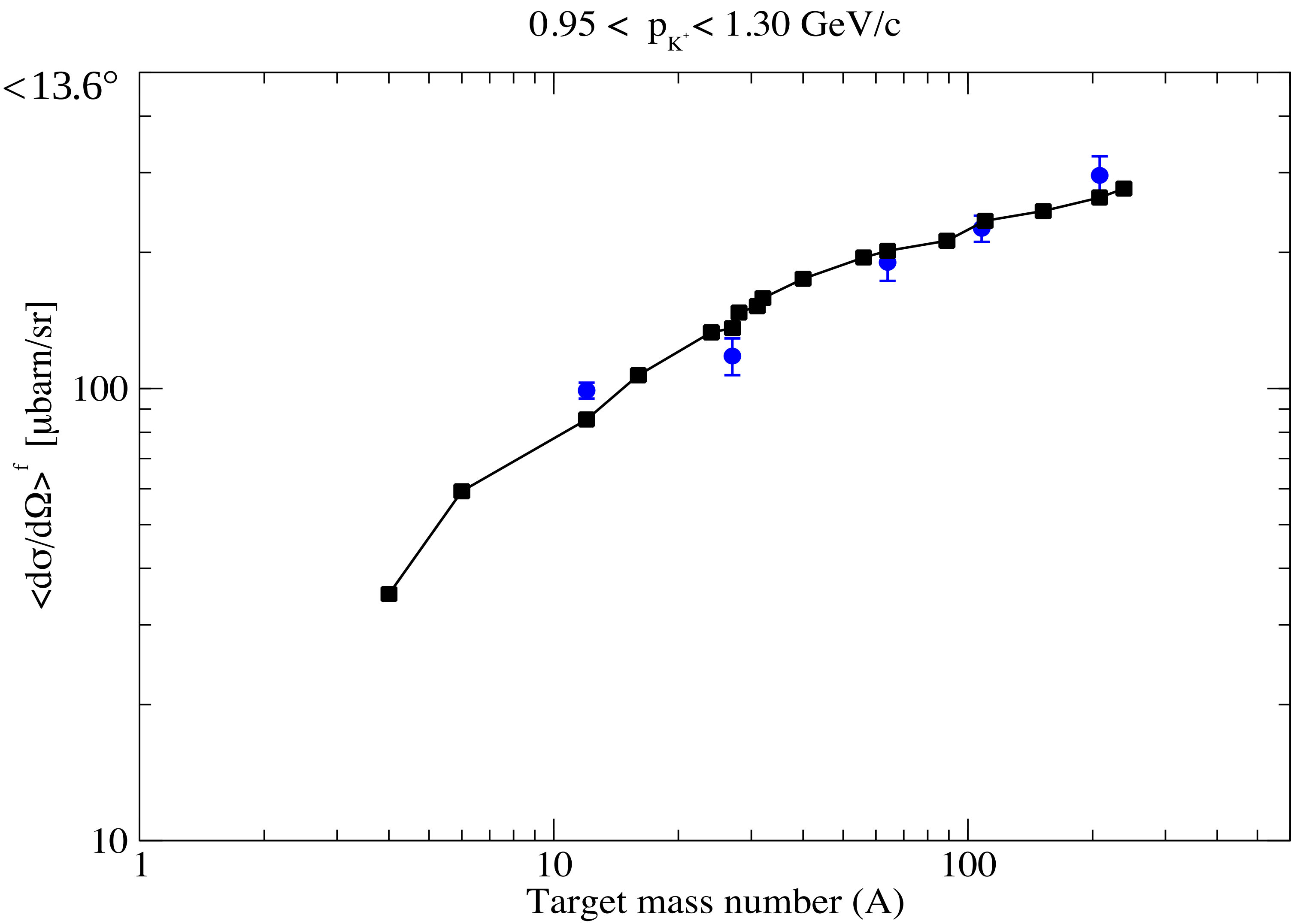
FSI: $\sigma_{K^+ N} \approx 18.4 mb$

Exp. Data of **T.Iijima et al. Nucl.Phys. A546 (1992) 588**

$K^- A \rightarrow K^+ \Xi^- A'$

$p_{K^-} = 1.65$ GeV

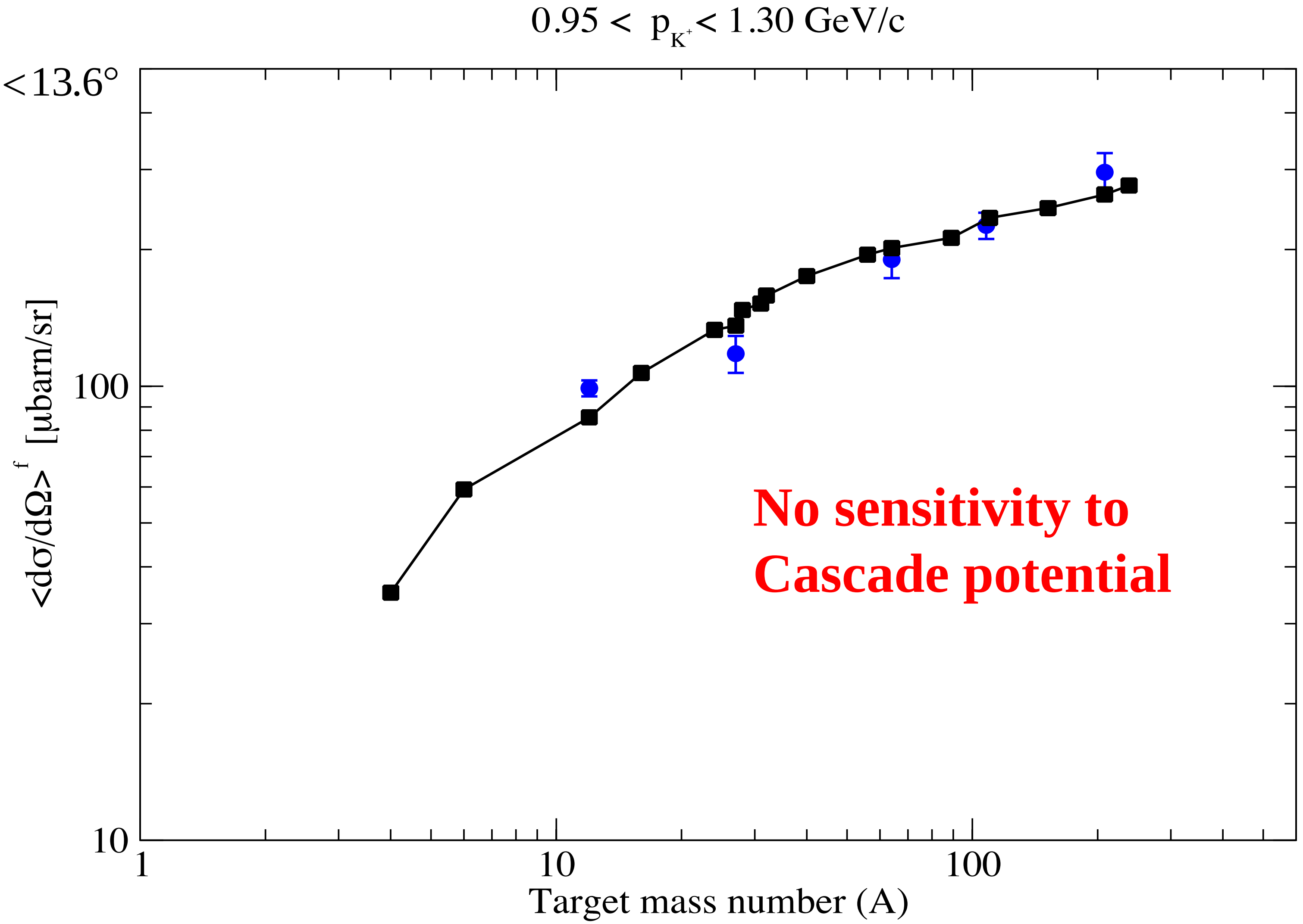
$1.7° < \Theta_{K^+}\big|_{lab} < 13.6°$



Exp. Data of **T.Iijima et al. Nucl.Phys. A546 (1992) 588**

$K^- A \rightarrow K^+ \Xi^- A'$

$p_{K^-} = 1.65$ GeV



Ξ-hypernuclei production

We add the condition: **$E_{ext} < 0$**

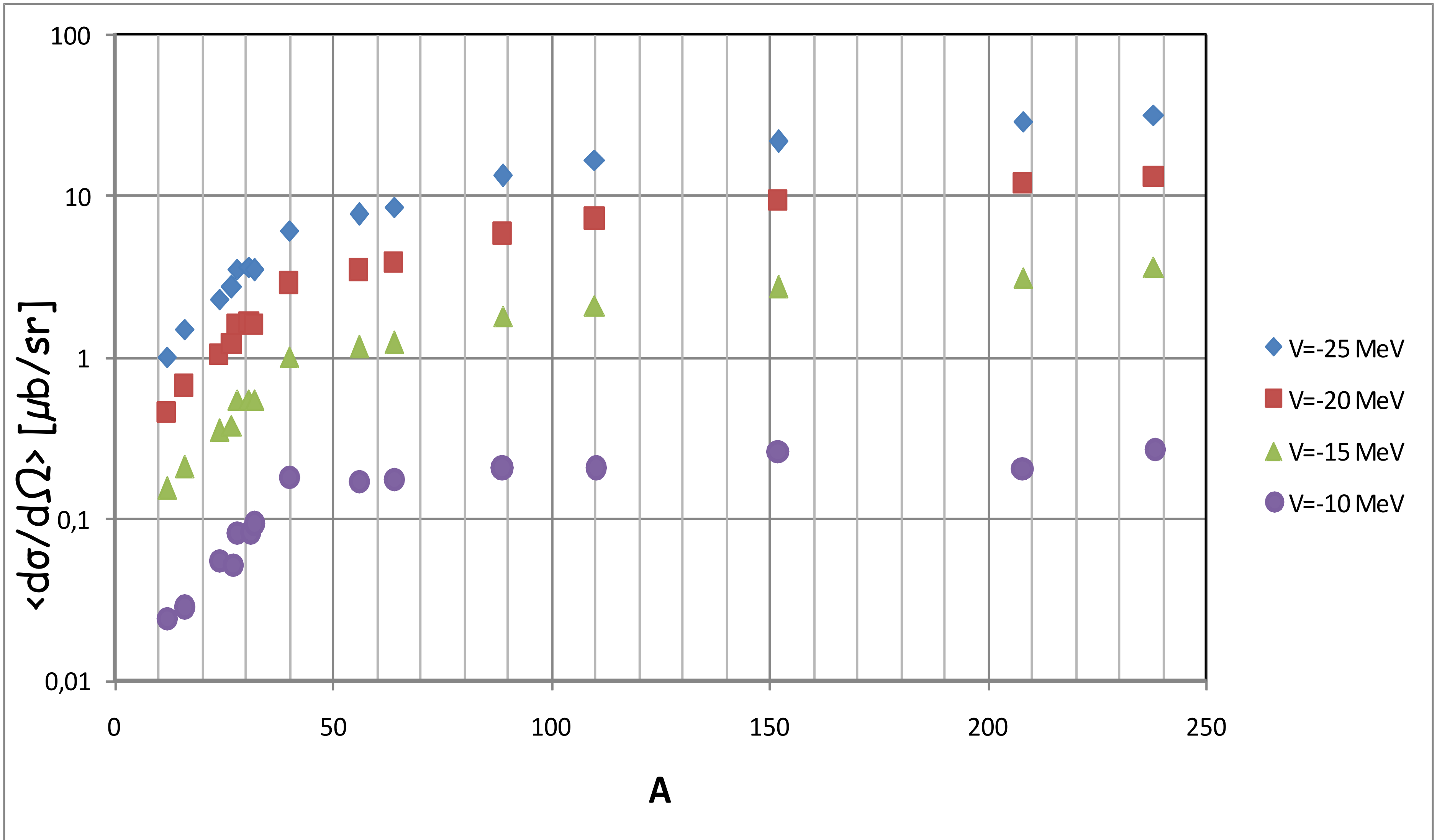
$$E_{ext} = E_x - M_{gs}^{A'} - M_{\Xi^-} = \left[E_{K^-} + M_{gs}^{A} - E_{K^+} \right] - M_{gs}^{A'} - M_{\Xi^-}$$

Ξ-hypernuclei production

$p_{K^-} = 1.65\ \text{GeV}$

$E_{ext} < 0$

$1.7° < \Theta_{K^+}\big|_{lab} < 13.6°$

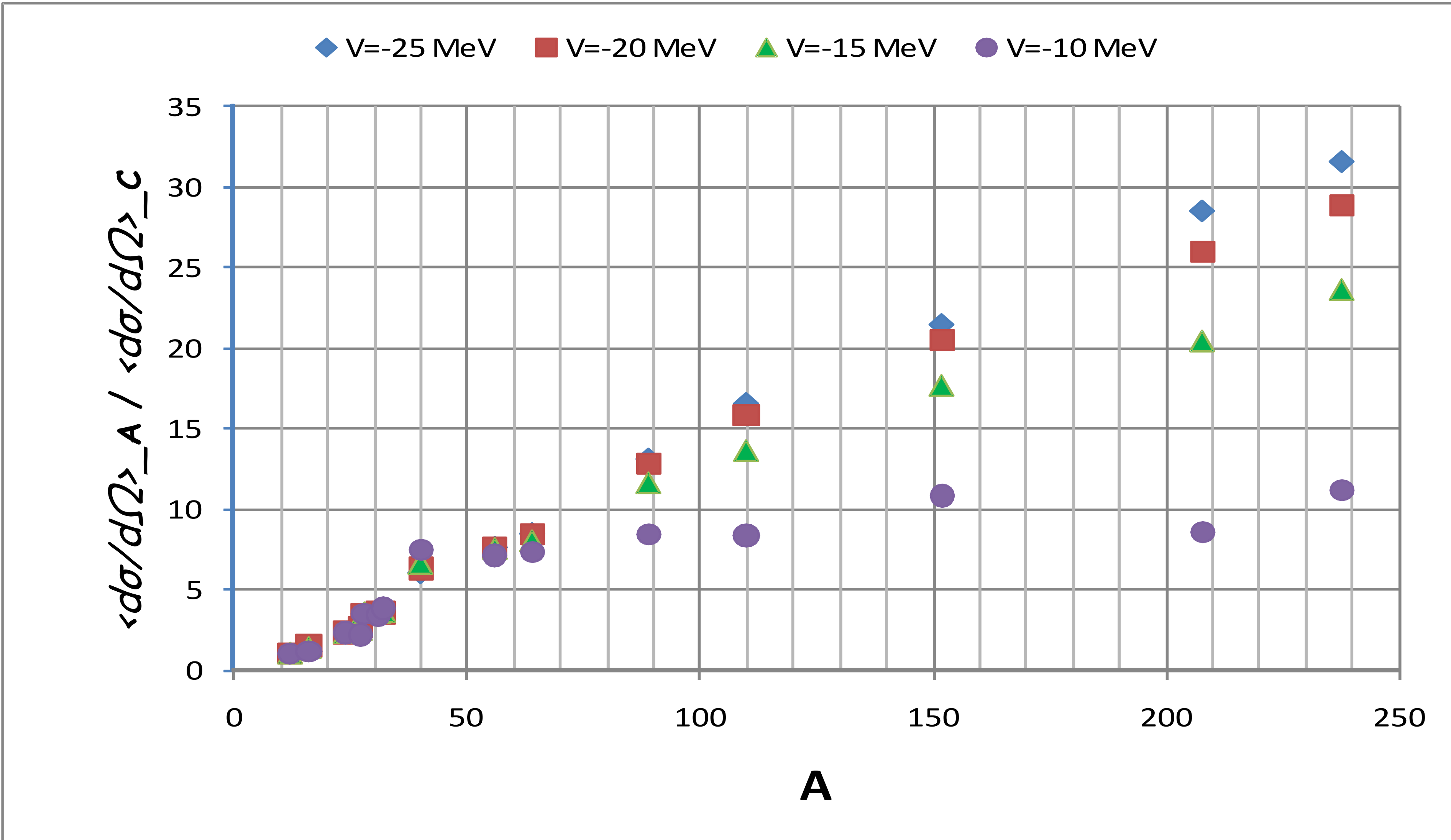


Ξ-hypernuclei production

$p_{K^-} = 1.65\ \text{GeV}$

$E_{ext} < 0$

$1.7° < \Theta_{K^+}\big|_{lab} < 13.6°$



Conclusions

Chiral Perturbation Theory with unitarization in coupled channels is a very powerful technique to describe low energy hadron dynamics

Next – to – leading order calculations are now possible

NLO terms in the Lagrangian do improve agreement with data

$K^- p \to K\Xi$ channels *are very interesting and important for fitting NLO parameters*

Our results can be useful to study Ξ-hypernuclei production

Work in progress…

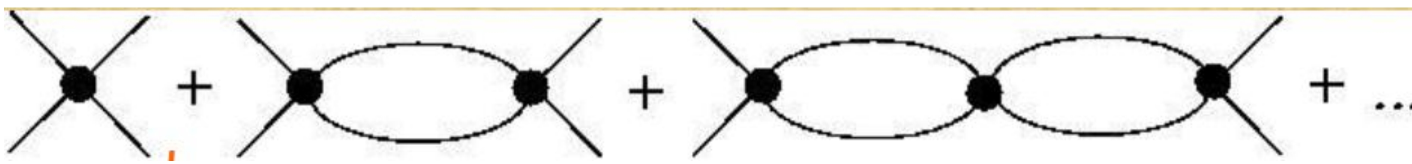
BACKUP SLIDES

Λ(1405) as a dynamically generated resonance

Jones, Dalitz and Horgan, Nucl. Phys. B129 (1977) 45 –
Λ(1405) is dynamical generated

Boost in unitary extensions of chiral perturbation theory $(U\chi PT)$

1995-2003: Kaiser, Oset, Ramos, Oller, Meissner, Jido, Hosaka, Garcia-Recio, Vicente Vacas



Λ(1405) as a dynamically generated resonance

Jones, Dalitz and Horgan, Nucl. Phys. B129 (1977) 45 –
Λ(1405) is dynamical generated

Boost in unitary extensions of chiral perturbation theory $(U\chi PT)$

1995-2003: Kaiser, Oset, Ramos, Oller, Meissner, Jido, Hosaka, Garcia-Recio, Vicente Vacas

→ Surprisingly there are **two poles** in the neighborhood of the Lambda(1405) both contributing to the final experimental invariant mass distribution

$\pi\Sigma$

Mass ~ 1390 MeV
Width ~ 130 MeV

$\bar{K}N$

Mass ~ 1425 MeV
Width ~ 30 MeV

Λ(1405) as a dynamically generated resonance

The observed shapes are in good agreement with corresponding chiral unitarity model calculations:

$$K^- p \rightarrow \pi^0 \pi^0 \Sigma^0$$

→ Magas, Oset, Ramos, Phys. Rev. Lett. 95 (05) 052301

$$\pi^- p \rightarrow K^0 \pi \ \Sigma$$

→ Thomas et al., Nucl. Phys. B56 (1973) 15

This combined study gives the first **experimental evidence** of the two-pole nature of the Λ(1405)

Crystall Ball Collaboration data from

$$K^- p \to \pi^0 \pi^0 \Sigma^0$$

(Width ~ 38 MeV)

versus

Thomas et al., NP B 56 (1973) 15

$$\pi^- p \to K^0 \pi \Sigma$$

(Width ~ 60 MeV)

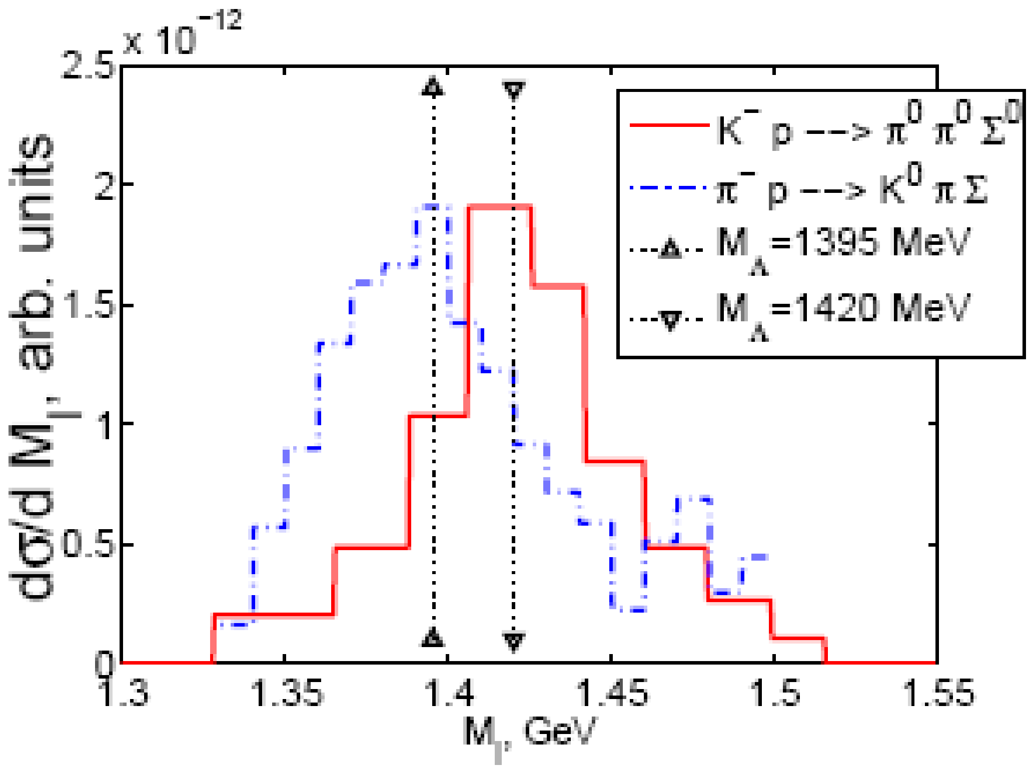


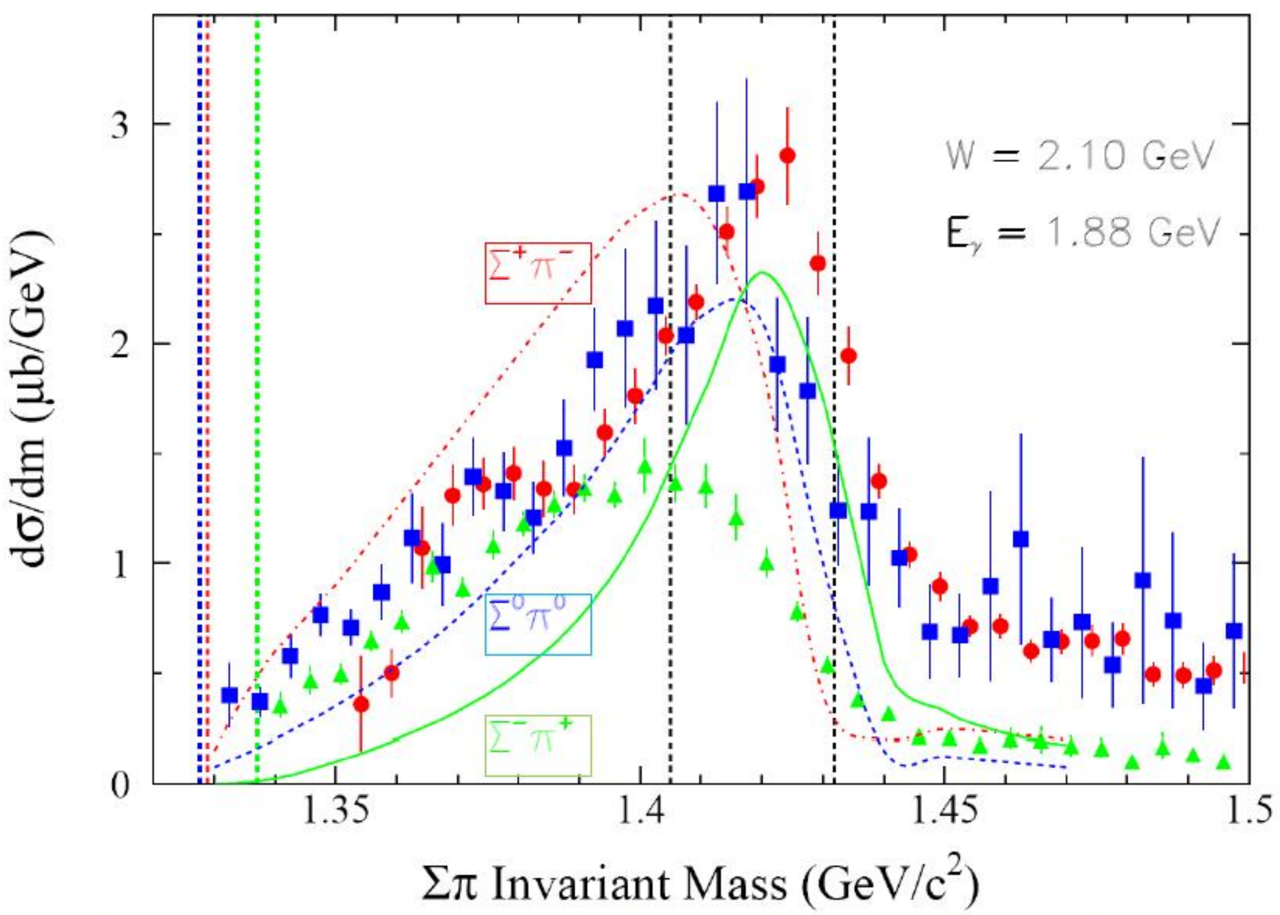
FIG. 5: Two experimental shapes of $\Lambda(1405)$ resonance. See text for more details.

Magas, Oset, Ramos, PRL 95 (2005) 052301

Fine-tuning of the model

Large I=1 effects have been detected in the photoproduction experiment at CLAS, Moriya *et al., Phys.Rev.C87,035206 (2013)*

$$\gamma p \longrightarrow K^{+}\pi\Sigma$$



Line Curves, Nacher et al. Better reproduction for $\pi^0\Sigma^0$ But not for the charged modes with I=1