UNIVERSIDAD DE
MURCIA

On the double pole structure of the $\Lambda(1405)$

Luis Roca

University of Murcia (Spain)

L.R., E.Oset, Phys.Rev.C 87 (2013) 055201

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

L.R., M.Mai, E.Oset and U.G.Meißner, Eur.Phys.J.C 75 (2015) 5, 218

L.R., J.Nieves, E.Oset, arXiv:1507.04249 [hep-ph]

Index:

- ✓ Motivation
- ✓ $\Lambda(1405)$ in chiral unitary approach
- ✓ Extraction of the two pole positions from photoproduction
- ✓ The role in Λ_b decay and the CERN Pentaquark, $P_c(4450)^+$

HYP15, Sendai, September 8, 2015

Motivation

Citation: K.A. Olive *et al.* (Particle Data Group), Chin. Phys. **C38**, 090001 (2014) (URL: http://pdg.lbl.gov)

$\Lambda(1405)\ 1/2^-$

$I(J^P) = 0(\frac{1}{2}^-)$ Status: ∗∗∗∗

The nature of the $\Lambda(1405)$ has been a puzzle for decades: three-quark state or hybrid; two poles or one. We cannot here survey the rather extensive literature. See, for example, CIEPLY 10, KISSLINGER 11, SEKIHARA 11, and SHEVCHENKO 12A for discussions and earlier references.

It seems to be the universal opinion of the chiral-unitary community that there are two poles in the 1400-MeV region. ZYCHOR 08 presents experimental evidence against the two-pole model, but this is disputed by GENG 07A. See also REVAI 09, which finds little basis for choosing between one- and two-pole models; and IKEDA 12, which favors the two-pole model.

A single, ordinary three-quark $\Lambda(1405)$ fits nicely into a $J^P = 1/2^-$ SU(4) $\bar{4}$ multiplet, whose other members are the $\Lambda_c(2595)^+$, $\Xi_c(2790)^+$, and $\Xi_c(2790)^0$; see Fig. 1 of our note on "Charmed Baryons."

$\Lambda(1405)$ MASS

PRODUCTION EXPERIMENTS

VALUE (MeV)	*EVTS*	*DOCUMENT ID*		*TECN*	*COMMENT*
$1405.1^{+1.3}_{-1.0}$ OUR AVERAGE					
$1405\ ^{+11}_{-9}$		HASSANVAND	13	SPEC	$pp \to p\Lambda(1405)K^+$
$1405\ ^{+1.4}_{-1.0}$		ESMAILI	10	RVUE	^{4}He $K^- \to \Sigma^\pm \pi^\mp X$ at rest
1406.5 ± 4.0		[1] DALITZ	91		M-matrix fit
• • • We do not use the following data for averages, fits, limits, etc. • • •					
1391 ± 1	700	[1] HEMINGWAY	85	HBC	$K^- p$ 4.2 GeV/c
~ 1405	400	[2] THOMAS	73	HBC	$\pi^- p$ 1.69 GeV/c
1405	120	BARBARO-...	68B	DBC	$K^- d$ 2.1–2.7 GeV/c
1400 ± 5	67	BIRMINGHAM	66	HBC	$K^- p$ 3.5 GeV/c
1382 ± 8		ENGLER	65	HDBC	$\pi^- p$, $\pi^+ d$ 1.68 GeV/c
1400 ± 24		MUSGRAVE	65	HBC	$\bar{p}p$ 3–4 GeV/c
1410		ALEXANDER	62	HBC	$\pi^- p$ 2.1 GeV/c
1405		ALSTON	62	HBC	$K^- p$ 1.2–0.5 GeV/c
1405		ALSTON	61B	HBC	$K^- p$ 1.15 GeV/c

EXTRAPOLATIONS BELOW $N\bar{K}$ THRESHOLD

VALUE (MeV)	*DOCUMENT ID*		*TECN*	*COMMENT*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
1407.56 or 1407.50	[3] KIMURA	00		potential model
1411	[4] MARTIN	81		K-matrix fit
1406	[5] CHAO	73	DPWA	0–range fit (sol. B)
1421	MARTIN	70	RVUE	Constant K-matrix

On the Λ(1405)

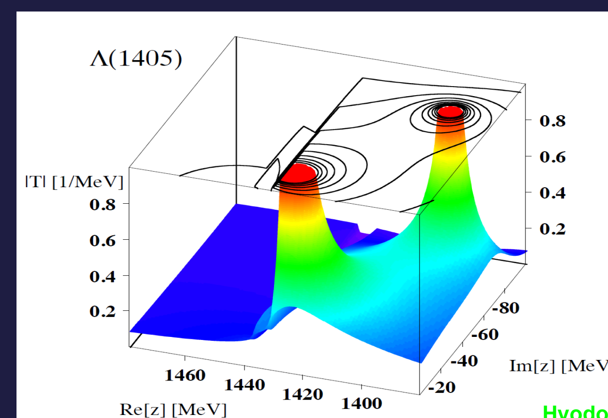
✓ Predicted in 1959 and discovered exp. in 1961
Dalitz, Tuang — Alston *et al.*

✓ Traditionally difficult to accomodate within quark models
Dalitz, Tuang — *i.e.*, Isgur *et al.*

(Λ(1405) (1/2⁻)is lighter than its nucleon counterpart N(1535)(1/2⁻)
and too large difference in mass with Λ(1520)(3/2⁺))

UChPT (chiral dynamics + unitarity) generates dynamically the Λ(1405)
Kaiser, Siegle, Weise, Oset, Ramos, Oller, Meissner, … and many more

✓ UChPT predicts a two-pole structure
(each having different values for the couplings to πΣ and $\bar{K}$N)
Jido, Oller, Oset, Ramos, Meissner,...



✓ Mass 30MeV below $\bar{K}$N threshold

Not possible in direct K beam exp.

✓ Current PDG mass value comes from
old πΣ production experiments

Basic idea of UChPT:

Oller, Oset, Dobado, Pelaez, Meissner, Kaiser, Weise, Ramos, Vicente-Vacas, Nieves, Ruiz-Arriola, Lutz, Hyodo, Jido, … ***and many more***

Input:

lowest order chiral Lagrangian
+ implementation of **unitarity** in coupled channels
+ exploitation of analytic properties

}

Extended range of applicability of ChPT to higher energies (resonance region)

Basic idea of UChPT:

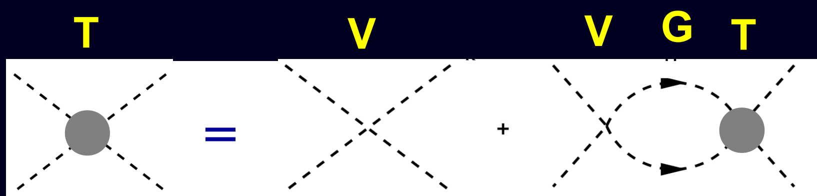
Oller, Oset, Dobado, Pelaez, Meissner, Kaiser, Weise, Ramos, Vicente-Vacas, Nieves, Ruiz-Arriola, Lutz, Hyodo, Jido, … *and many more*

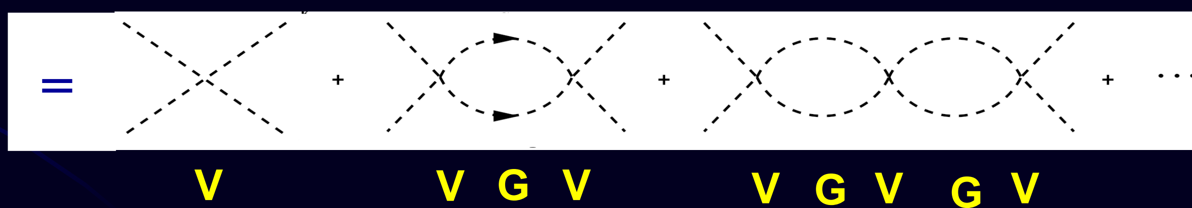
Input:

lowest order chiral Lagrangian
+ implementation of **unitarity** in coupled channels
+ exploitation of analytic properties

} Extended range of applicability of ChPT to higher energies (resonance region)

Unitarity of the S-matrix implies:





(Bethe-Salpeter eq.)

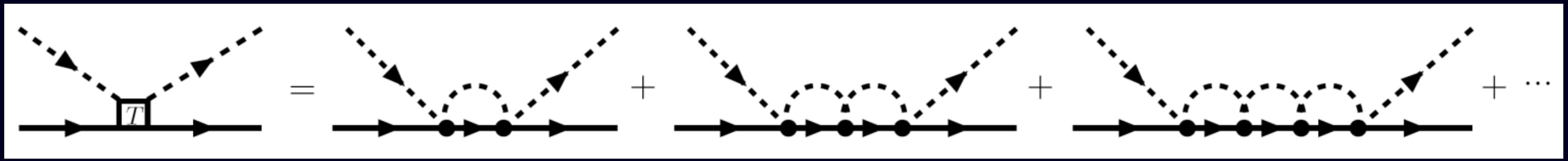
The kernel of the BS equation, **V**, is the lowest order ChPT Lagrangian

Effectively, one is summing this infinite series of diagrams

$$G = \frac{1}{16\pi^2}\left(\alpha + Log\frac{m_1^2}{\mu^2} + \frac{m_2^2 - m_1^2 + s}{2s} Log\frac{m_2^2}{m_1^2} + \frac{p}{\sqrt{s}}\left(Log\frac{s - m_2^2 + m_1^2 + 2p\sqrt{s}}{-s + m_2^2 - m_1^2 + 2p\sqrt{s}} + Log\frac{s + m_2^2 - m_1^2 + 2p\sqrt{s}}{-s - m_2^2 + m_1^2 + 2p\sqrt{s}}\right)\right)$$

$$G = \int_0^{q_{max}} \frac{q^2 dq}{(2\pi)^2} \frac{\omega_1 + \omega_2}{\omega_1\omega_2[(P^0)^2 - (\omega_1 + \omega_2)^2 + i\epsilon]}$$

Unitarized Meson-Baryon interaction



$$T = [1 - VG]^{-1}V$$

Kernel from lowest order Meson-Baryon chiral Lagrangian

Oset,Ramos'98; Oller,Meissner'01; Jido et al'03, Hyodo et.al'03, Garcia-Recio et al.'03, ...

$$L_1^{(B)} = \langle \bar{B} i\gamma^\mu \frac{1}{4f^2} [(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi) B - B(\Phi\partial_\mu\Phi - \partial_\mu\Phi\Phi)] \rangle$$

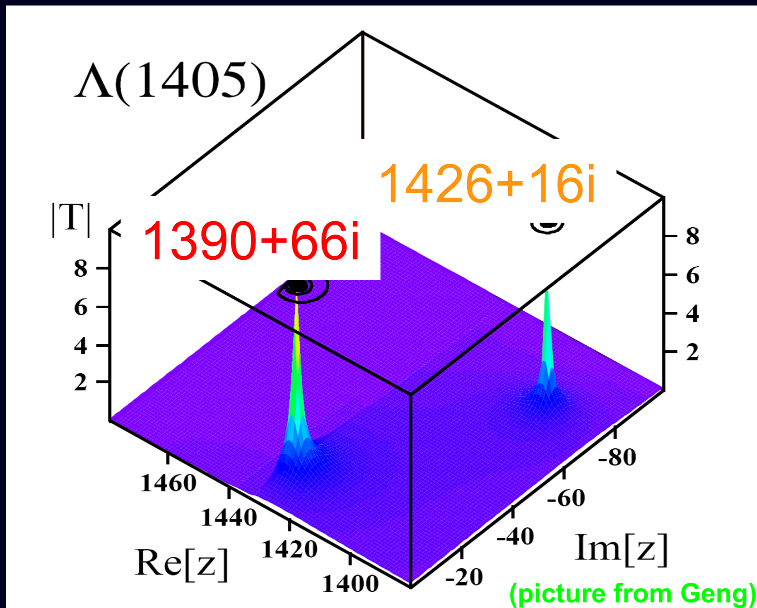
(Plus higher order terms **Borasoy et al.'05,'06; Oller et al.'05,'06, ...**)

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j) \times \left(\frac{M_i + E_i}{2M_i}\right)^{1/2} \left(\frac{M_j + E_j}{2M_j}\right)^{1/2}$$

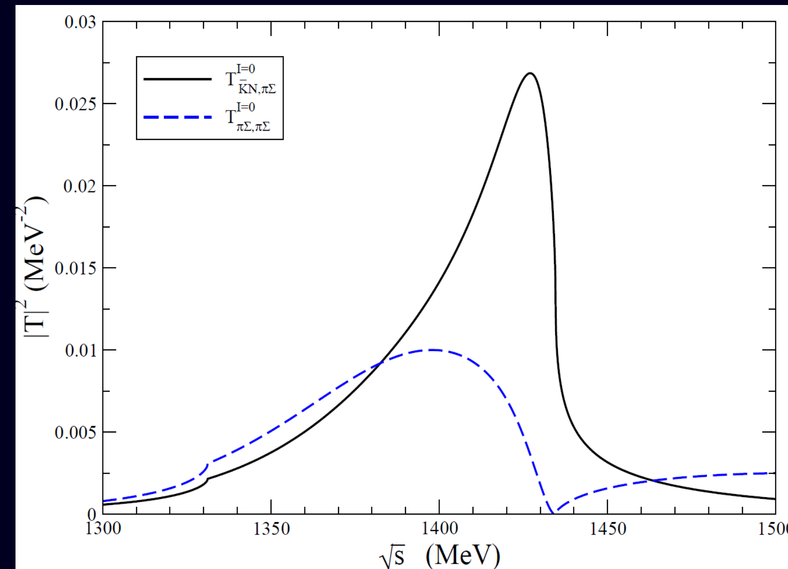
$$C_{ij} = \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix}$$

(only $\bar{K}N$ and $\pi\Sigma$ considered in this work. $\eta\Lambda$ and $K\Xi$ are small and their effect are encoded in the subtraction constants)

Two poles in the complex plane



Amplitudes in the real axis:



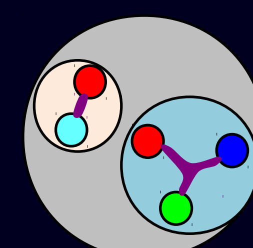
Couplings to different channels:

z_R $(I=0)$	$1390+66i$ g_i	$\|g_i\|$	$1426+16i$ g_i	$\|g_i\|$
$\pi\Sigma$	$-2.5-1.5i$	2.9	$0.42-1.4i$	1.5
$\bar{K}N$	$1.2+1.7i$	2.1	$-2.5+0.94i$	2.7
$\eta\Lambda$	$0.010+0.77i$	0.77	$-1.4+0.21i$	1.4
$K\Xi$	$-0.45-0.41i$	0.61	$0.11-0.33i$	0.35

Recall: no explicit resonances included!

(dynamically generated from chiral dynamics and unitarity)

Provide the actual shape of the amplituds. **Not Breit-Wigners!**



Lowest pole dominated by $\pi\Sigma$

Highest pole dominated by $\overline{K}N$

Resonance shape may be different for different reactions!

Fit to photoproduction data

L.R., E.Oset, Phys.Rev.C 87 (2013) 055201

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

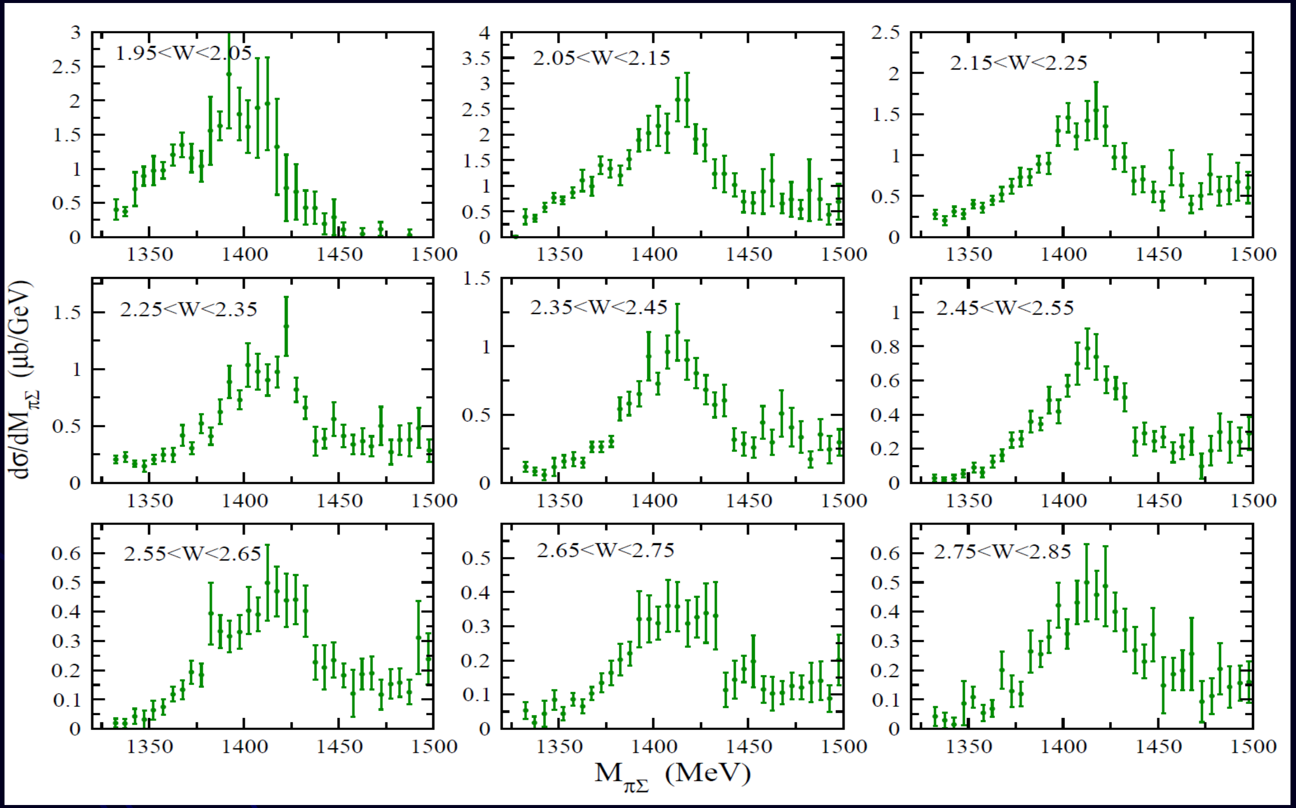
Aim of this work:

How to extract both pole positions from experimental photoproduction data

Experimental data:

$\gamma p \rightarrow K^+ \pi^0 \Sigma^0$

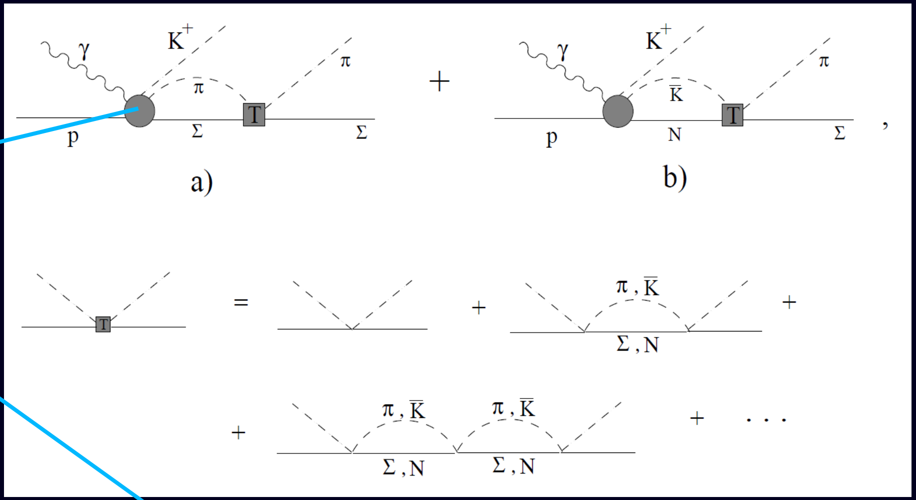
Exp data from Moriya et al., [CLAS coll. @Jlab] PhysRev. C.87 (2013) 3, 035206



Clear Λ(1405) shape, but how to extract its physical properties given its double pole structure?

Our analysis:

Idea: as model independent as possible
but double pole from chiral dynamics



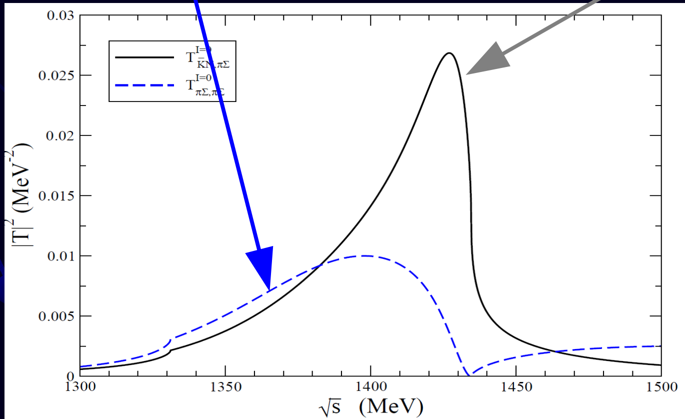
Production mechanism
(whatever)

General expression for the photoproduction scattering amplitude:

$$t(W) = b(W) G_{\pi\Sigma} T^{I=0}_{\pi\Sigma,\pi\Sigma} + c(W) G_{\bar{K}N} T^{I=0}_{\bar{K}N,\pi\Sigma}$$

$\gamma p \rightarrow K^+ \pi^0 \Sigma^0$

only I=0



b and *c* (complex) coefficients
fitted for each energy!

Next we allow for a small variation of the kernel of the unitarization procedure:

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j) \times \left(\frac{M_i + E_i}{2M_i}\right)^{1/2}\left(\frac{M_j + E_j}{2M_j}\right)^{1/2}$$

$$C_{ij} = \begin{pmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{pmatrix} \longrightarrow C_{ij} = \begin{pmatrix} 3\alpha_1 & -\sqrt{\frac{3}{2}}\alpha_2 \\ -\sqrt{\frac{3}{2}}\alpha_2 & 4\alpha_3 \end{pmatrix}$$

(coefficients of the potential fitted but of natural order ~1)

Also:

$$a_{KN} \rightarrow \alpha_4 a_{KN}, \; a_{\pi\Sigma} \rightarrow \alpha_5 a_{\pi\Sigma}$$

(subtraction constants)

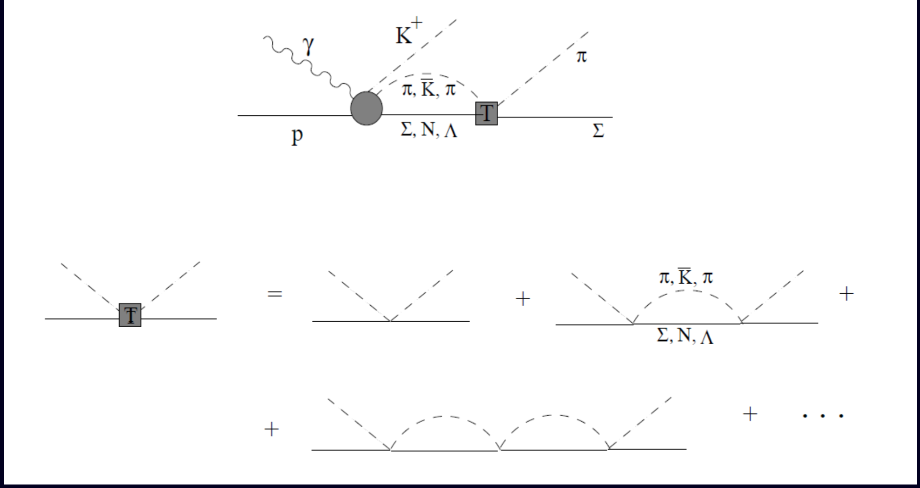
α_i coefficients are fitted

For $\gamma p \to K^+ \pi^\pm \Sigma^\mp$ also I=1 contributes:

$$|\pi^0\Sigma^0\rangle = \sqrt{\frac{2}{3}}|2\,0\rangle - \frac{1}{\sqrt{3}}|0\,0\rangle,$$

$$|\pi^+\Sigma^-\rangle = -\frac{1}{\sqrt{6}}|2\,0\rangle - \frac{1}{\sqrt{2}}|1\,0\rangle - \frac{1}{\sqrt{3}}|0\,0\rangle$$

$$|\pi^-\Sigma^+\rangle = -\frac{1}{\sqrt{6}}|2\,0\rangle + \frac{1}{\sqrt{2}}|1\,0\rangle - \frac{1}{\sqrt{3}}|0\,0\rangle$$



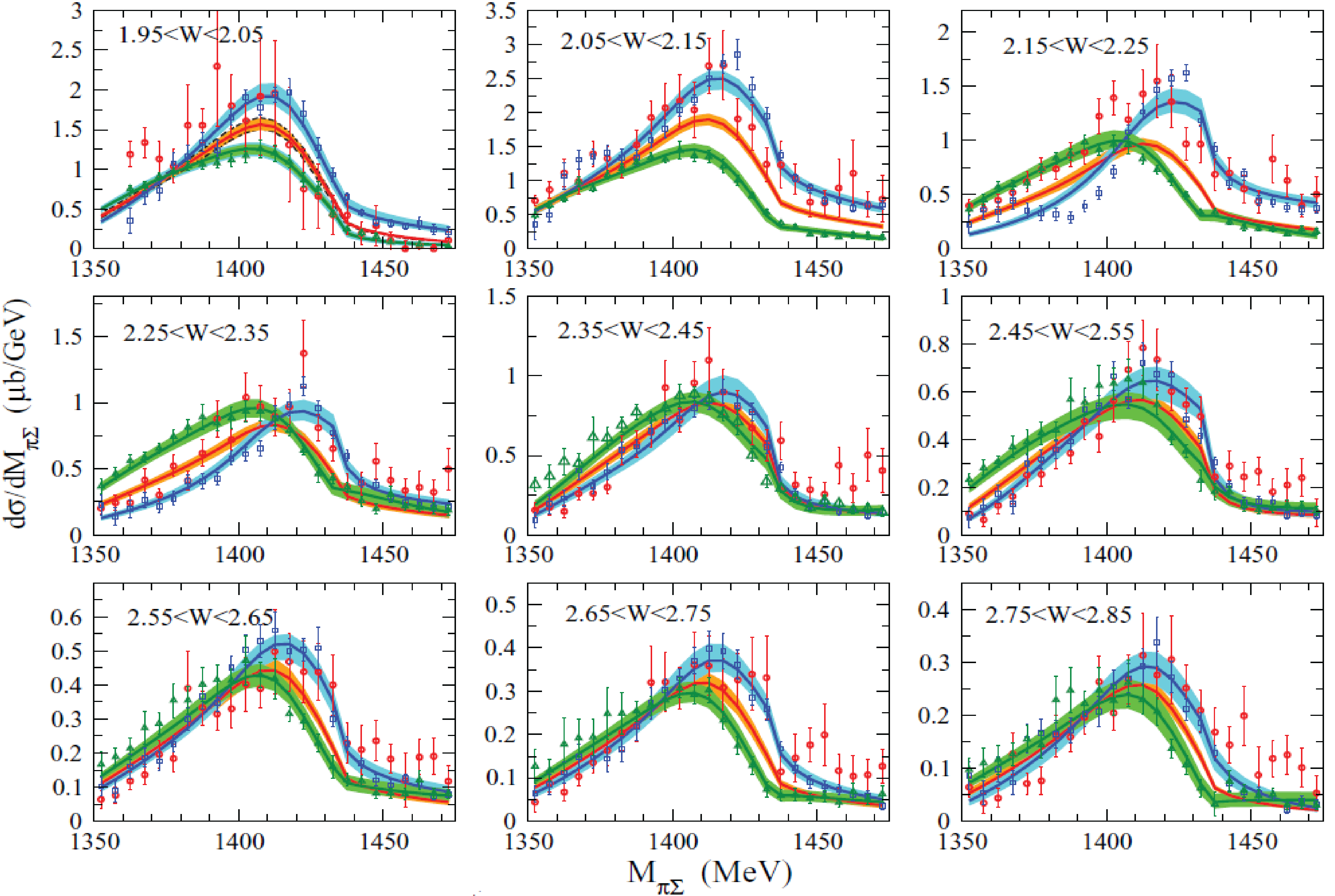
$$t_{\gamma p \to K^+\pi^0\Sigma^0}(W) = b_0(W) G^{I=0}_{\pi\Sigma} T^{I=0}_{\pi\Sigma,\pi\Sigma} + c_0(W) G^{I=0}_{\bar{K}N} T^{I=0}_{\bar{K}N,\pi\Sigma},$$

$$t_{\gamma p \to K^+\pi^\pm\Sigma^\mp}(W) = b_0(W) G^{I=0}_{\pi\Sigma} T^{I=0}_{\pi\Sigma,\pi\Sigma} + c_0(W) G^{I=0}_{\bar{K}N} T^{I=0}_{\bar{K}N,\pi\Sigma}$$
$$\pm\sqrt{\frac{3}{2}}\Big(b_1(W) G^{I=1}_{\pi\Sigma} T^{I=1}_{\pi\Sigma,\pi\Sigma} + c_1(W) G^{I=1}_{\bar{K}N} T^{I=1}_{\bar{K}N,\pi\Sigma} + d_1(W) G^{I=1}_{\pi\Lambda} T^{I=1}_{\pi\Lambda,\pi\Sigma}\Big),$$

$$C^1_{ij} = \begin{pmatrix} 3\alpha^1_{11} & -\alpha^1_{12} & -\sqrt{\frac{3}{2}}\alpha^1_{13} \\ -\alpha^1_{12} & 2\alpha^1_{22} & 0 \\ -\sqrt{\frac{3}{2}}\alpha^1_{13} & 0 & 0 \end{pmatrix}$$

$a_{KN} \to \beta_1 a_{KN}$, $a_{\pi\Sigma} \to \beta_2 a_{\pi\Sigma}$

and $a_{\pi\Lambda} \to \beta_3 a_{\pi\Lambda}$



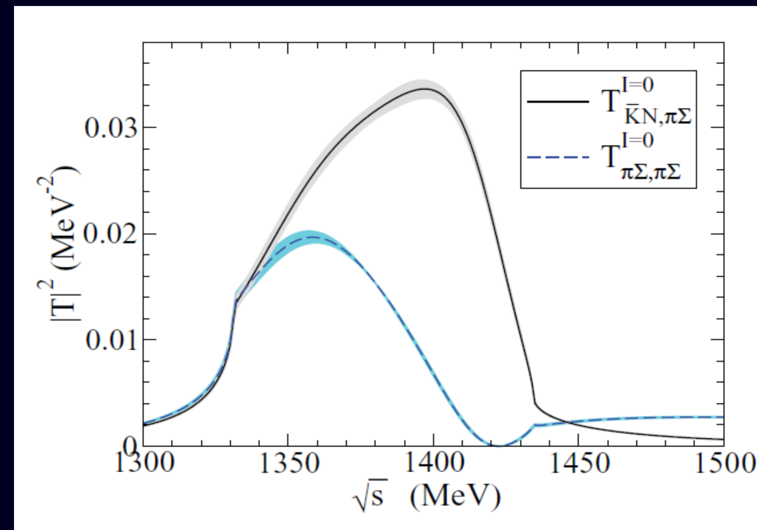
Red: $\pi^0\Sigma^0$; blue: $\pi^-\Sigma^+$, green: $\pi^+\Sigma^-$

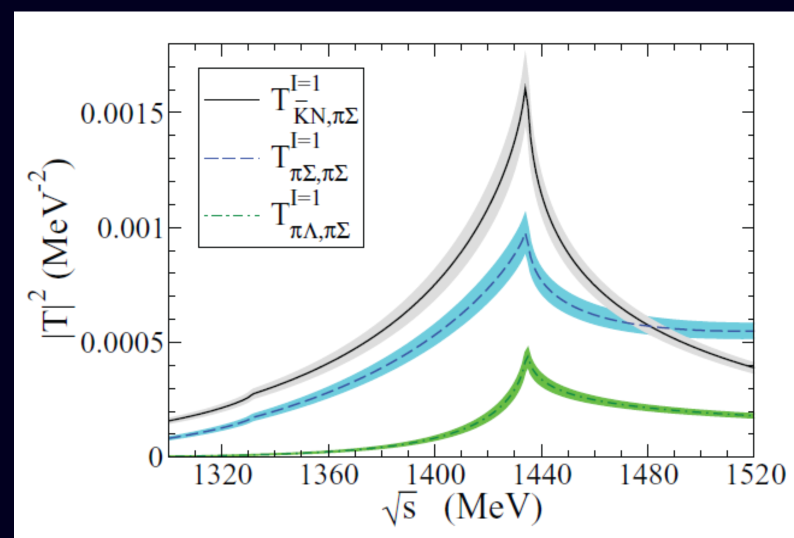
Results of the global fit:

α_{11}^0	α_{12}^0	α_{22}^0	α_{11}^1	α_{12}^1	α_{13}^1	α_{22}^1	β_1	β_2	β_3
1.037	1.466	1.668	0.85	0.93	1.056	0.77	1.187	0.722	1.119

(order 1)

	$I=0$		$I=1$
poles	$1352-48i$	$1419-29i$	–
$\lvert g_{\bar{K}N}\rvert$	2.71	3.06	–
$\lvert g_{\pi\Sigma}\rvert$	2.96	1.96	–





No poles for I=1 are found, but amplitudes ressemble much the shape of the $a_0(980)$ “resonance”.

Prediction. Not fitted!

1s kaonic hydrogen energy shift:

$$\Delta E - i\Gamma/2 =$$

$$(194 \pm 4) - i(301 \pm 9)\ \text{eV}$$

Exp.: SIDDHARTA exp. @ Daphne, PLB704, 113 (2011)

$$(283 \pm 42) - i(271 \pm 55)\ \text{eV}.$$

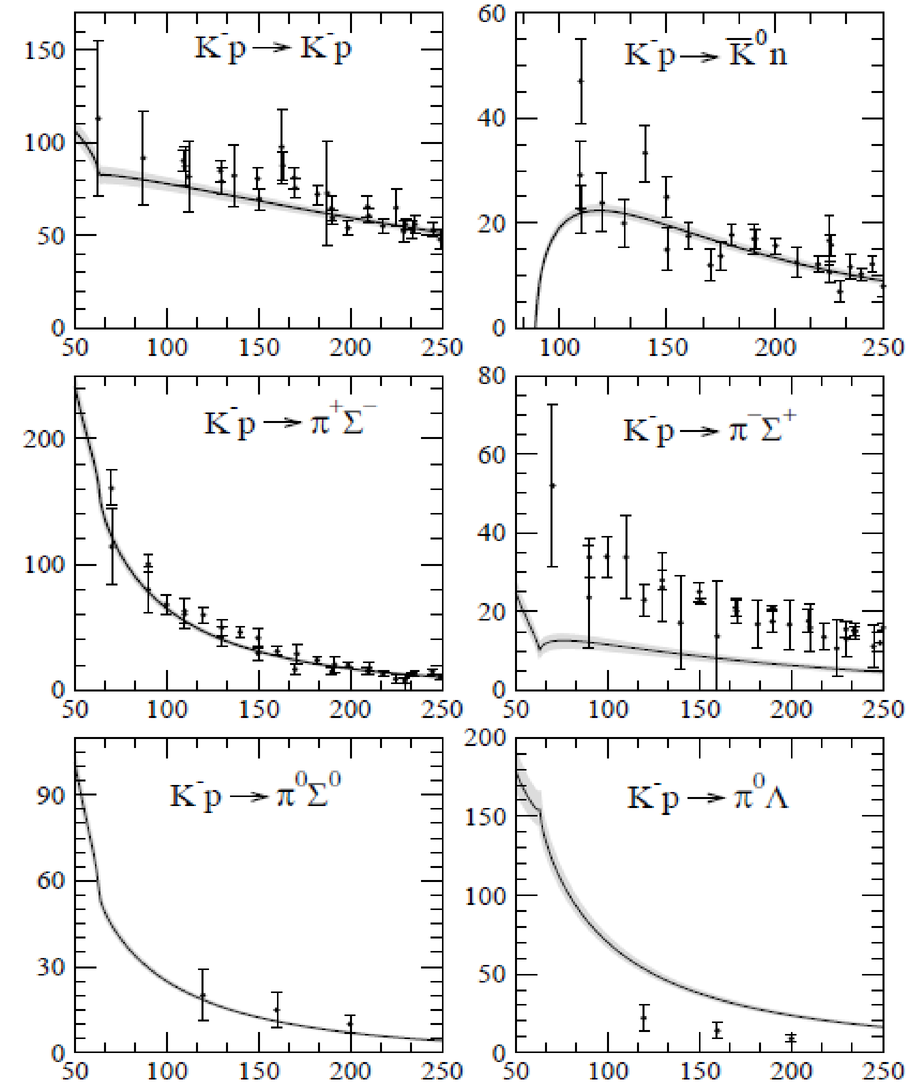
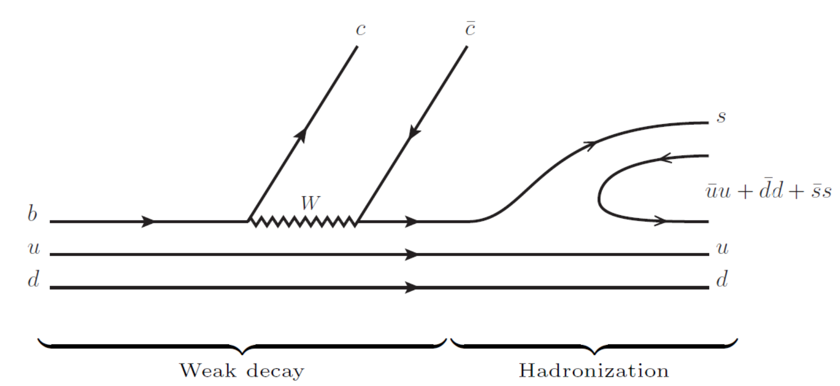


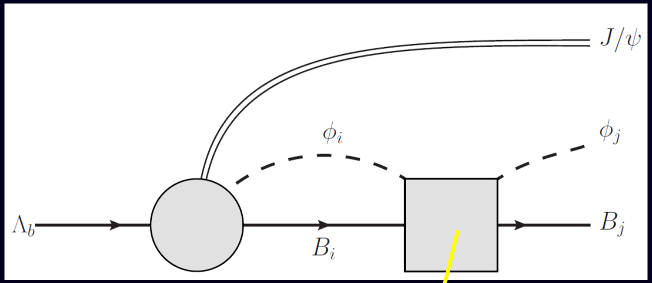
FIG. 10. Predicted $K^- p$ cross sections (in mb). Experimental data from ref. [53].

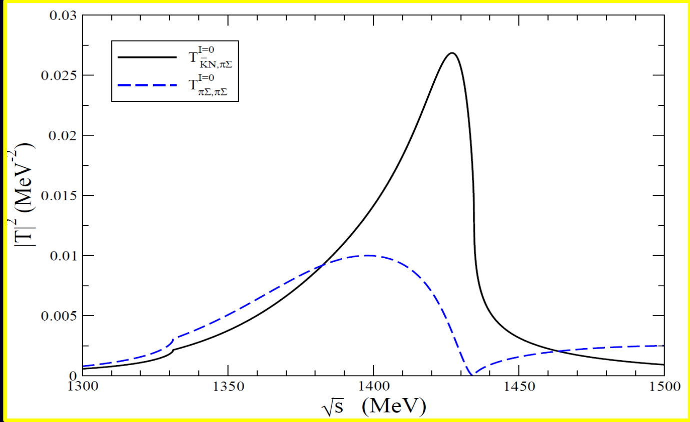
The Λ(1405) in $\Lambda_b \to J/\psi\ \Lambda(1405)$

L.R., M.Mai, E.Oset and U.G.Meißner, Eur.Phys.J.C 75 (2015) 5, 218

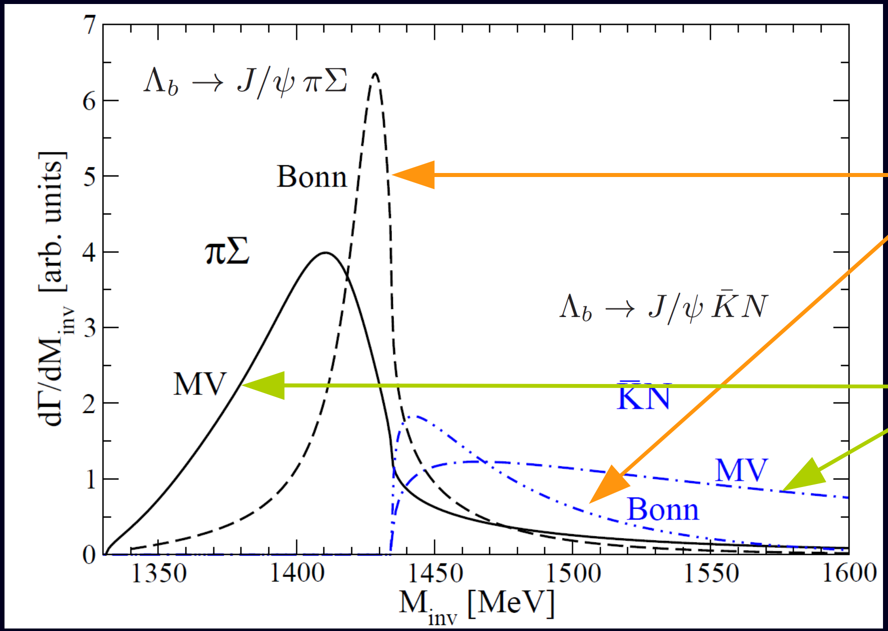
$\Lambda_b \to J/\psi\,\pi\Sigma$ $\Lambda_b \to J/\psi\,\bar{K}N$







Reflects the highest mass Λ(1405) pole



Two different UChPT models:

- ✓ Higher order meson-baryon Lagrangians fitted to photoproduction and meson-baryon cross sections

  Bruns, Mai, Meißner, Phys.Lett. B697 (2011) 254

- ✓ Lowest order chiral Lagrangian with modified kernel

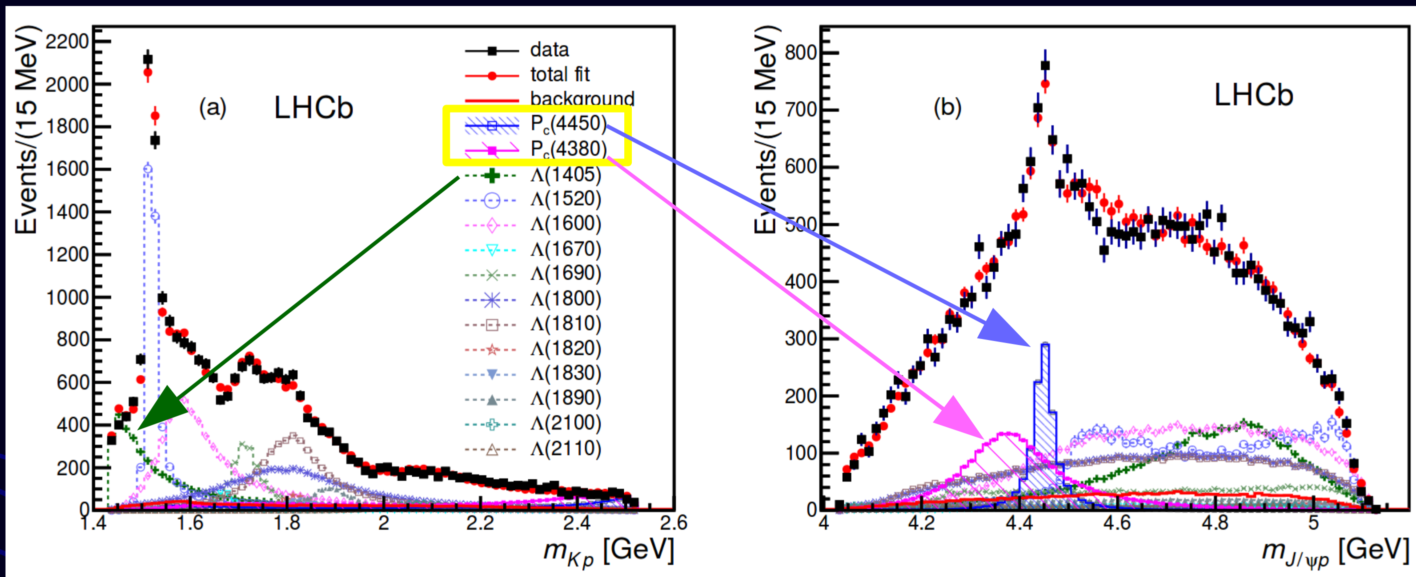
  (Our model explained above)

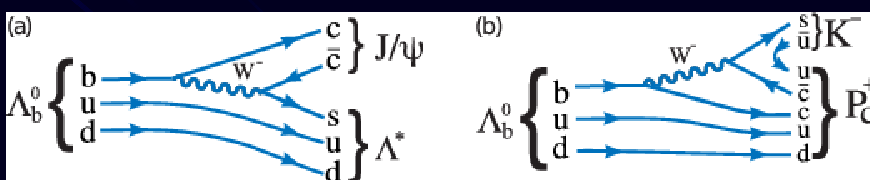
  L.R., E.Oset, Phys.Rev.C 88 (2013) 055206

The LHCb pentaquark, $P_c(4450)^+$

The $\Lambda_b \rightarrow J/\psi K^- p$ reaction has recently been used to report the existence of a pentaquark by the LHCb collaboration at CERN

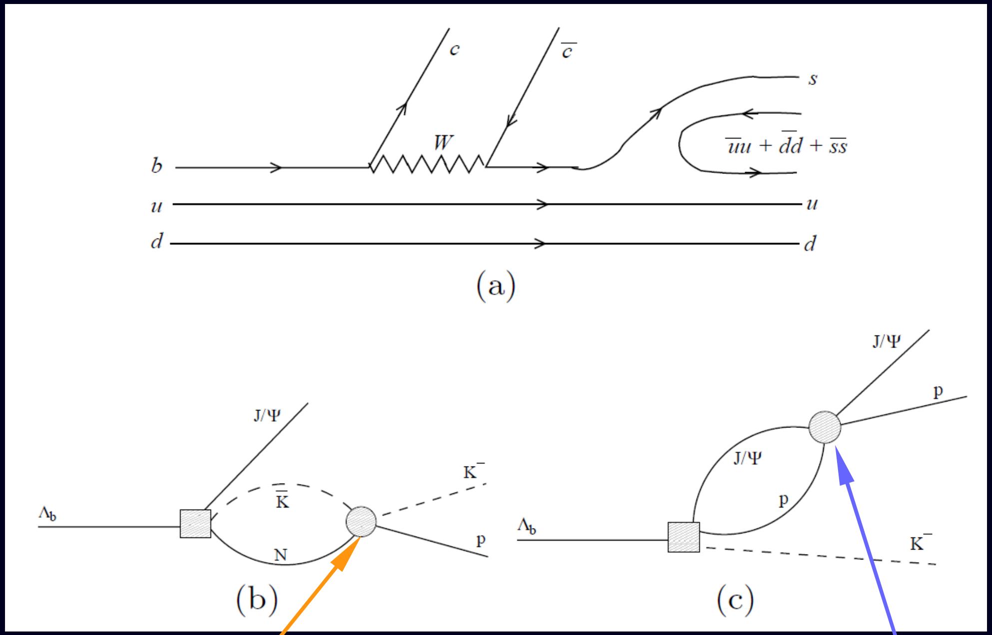
LHCb Coll. (CERN), Phys.Rev.Lett. 115 (2015) 7, 072001





First claimed hidden-charm baryon

Our model: L.R., J.Nieves, E.Oset, arXiv:1507.04249 [hep-ph].



UChPT as explained before: $\Lambda(1405)$

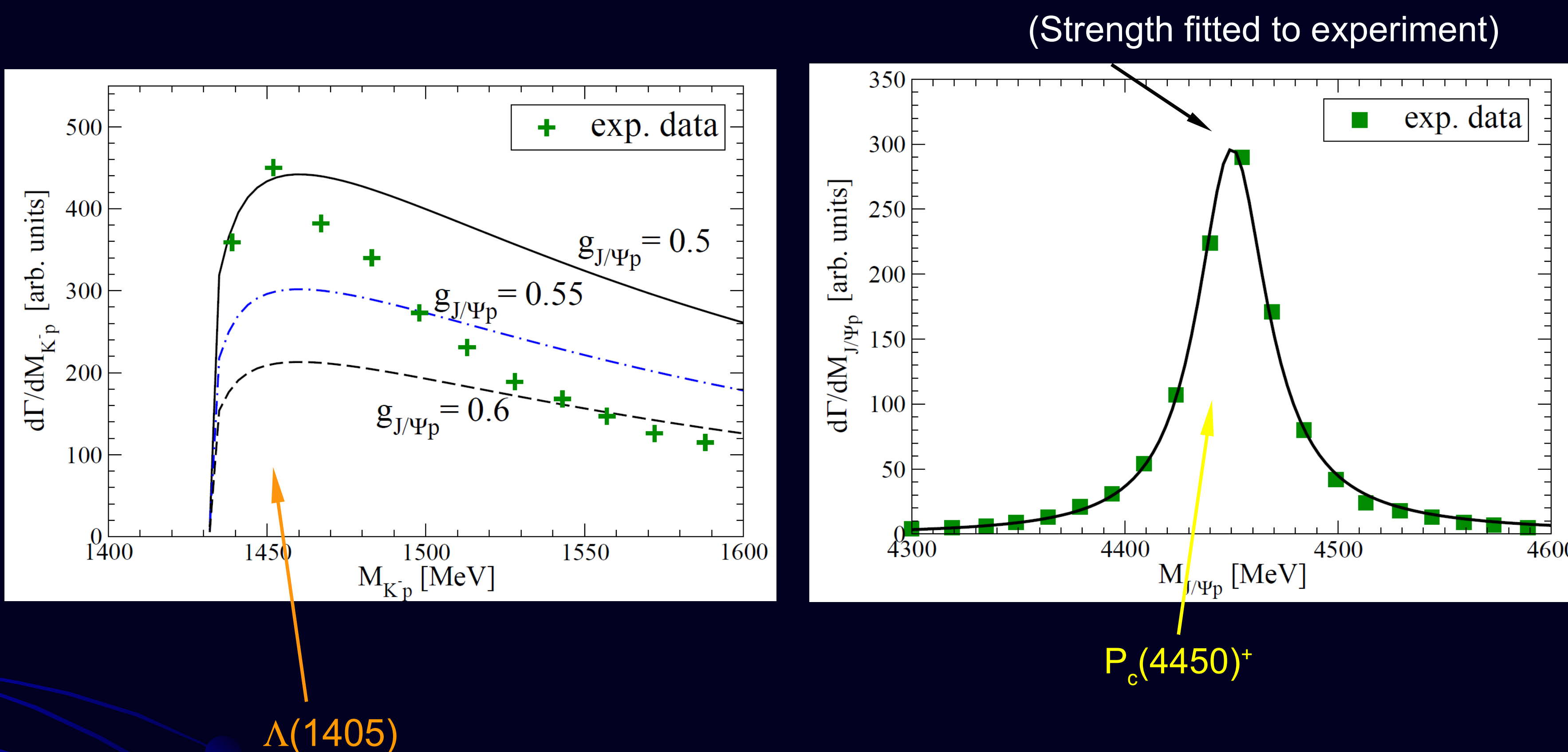
$J/\psi N,\ \bar{D}^*\Lambda_c,\ \bar{D}^*\Sigma_c,\ \bar{D}\Sigma_c^*$ and $\bar{D}^*\Sigma_c^*$ coupled channels

Xiao, Nieves, Oset, PRD88 (2013) 056012

Poles at $4334 + 19i$ MeV, $4417 + 4i$ MeV and $4481 + 17i$ MeV

with $J^P = 3/2^-,\ I = 1/2$

Dominant coupling to $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$



Relative strength between both panels is not trivial at all and is a genuine prediction from our theory

We predict the $P_c(4450)^+$ to be $J^P=3/2^-$ $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$ molecule

Experimental fit allows $J^P=5/2^+, 5/2^-, 3/2^-$

Summary

- $\Lambda(1405)$ well established but until recently poorly understood

- UChPT predicts a double pole structure, dynamically generated from $\pi\Sigma$ and $\bar{K}N$ (basically)

Different reactions can weigh differently the different channels and, therefore, the different poles.
In general, the amplitude is a combination of both, and has a shape very different to a Breit-Wigner

- We have done a fit to CLAS photoproduction data based on the unitarized amplitudes

→ Double pole appears naturally and produces actual shapes of the mass distribution in the real axis (not just Breit-Wigner like combinations)

- We obtain good fits for which we get the $\Lambda(1405)$ pole positions 1352-48i, 1419-29i

- Crucial role of the $\Lambda(1405)$ in $\Lambda_b \to J/\psi\, \pi\Sigma$ and $\Lambda_b \to J/\psi\, \bar{K} N$

- The LHCb pentaquark, $P_c(4450)^+$: matches our theoretical $\Lambda(1405)$ production in $\Lambda_b \to J/\psi K^- p$ if the pentaquark is $J^P=3/2^-$ $\bar{D}^*\Sigma_c - \bar{D}^*\Sigma_c^*$ molecule

TABLE II. The coupling constants to various channels for certain poles in the $J = 3/2$, $I = 1/2$ sector.

$4334.45 + i19.41$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.31 - i0.18$	$0.16 - i0.23$	$0.20 - i0.48$	$2.97 - i0.36$	$0.24 - i0.76$
$\|g_i\|$	1.32	0.28	0.52	2.99	0.80
$4417.04 + i4.11$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$0.53 - i0.07$	$0.08 - i0.07$	$2.81 - i0.07$	$0.12 - i0.10$	$0.11 - i0.51$
$\|g_i\|$	0.53	0.11	2.81	0.16	0.52
$4481.04 + i17.38$	$J/\psi N$	$\bar{D}^*\Lambda_c$	$\bar{D}^*\Sigma_c$	$\bar{D}\Sigma_c^*$	$\bar{D}^*\Sigma_c^*$
g_i	$1.05 + i0.10$	$0.18 - i0.09$	$0.12 - i0.10$	$0.22 - i0.05$	$2.84 - i0.34$
$\|g_i\|$	1.05	0.20	0.16	0.22	2.86

Fits done by **CLAS**:

- Including only one I=0 amplitude:

Amplitude	Centroid m_R (MeV/c^2)	Width $\Gamma^0_{I,1}$ (MeV/c^2)	Phase $\Delta\Phi_I$ (radians)	Flatté Factor γ
$I=0$	1338 ± 10	85 ± 10	N/A	0.91 ± 0.20
$I=1$ (narrow)	1413 ± 10	52 ± 10	2.0 ± 0.2	0.41 ± 0.20
$I=1$ (broad)	1394 ± 20	149 ± 40	0.1 ± 0.3	N/A

Moriya et al., [CLAS coll. @Jlab] PhysRevC.87.035206

- Including two I=0 amplitudes: Schumacher, Moriya, arXiv:1301.5000

Amplitude	Centroid m_R (MeV)	Width Γ_0 (MeV)	Phase $\Delta\Phi_I$ (radians)	Flatté γ Factor
$I=0$ (low mass)	1338 ± 10	44 ± 10	N/A	0.94 ± 0.20
$I=0$ (high mass)	1384 ± 10	76 ± 10	1.8 ± 0.4	N/A
$I=1$	1367 ± 20	54 ± 10	2.2 ± 0.4	1.19 ± 0.20

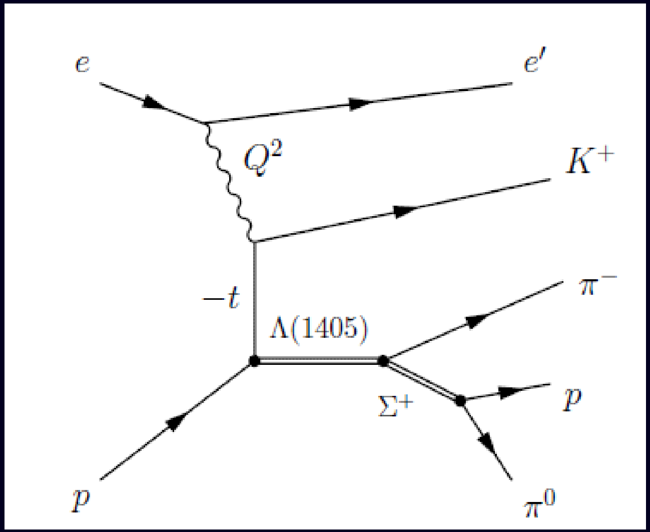
Fit only to $\pi^0\Sigma^0$ channel:

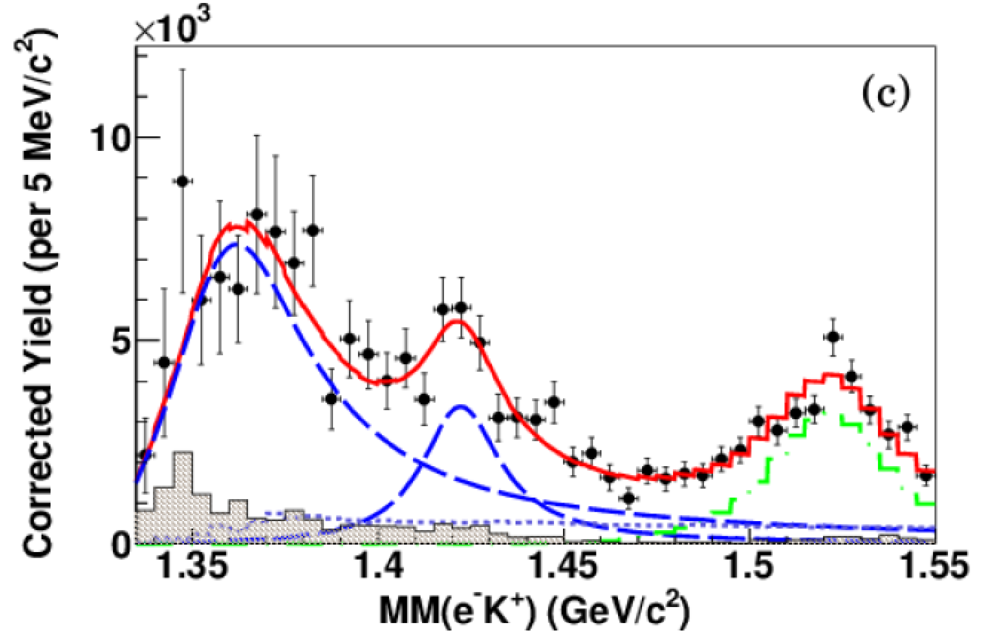
Amplitude	Centroid m_R (MeV)	Width Γ_0 (MeV)	Phase $\Delta\Phi_I$ (radians)	Flatté γ Factor
$I=0$	1329 ± 10	20 ± 10	N/A	1.5 ± 0.3
$I=0$	1390 ± 10	174 ± 20	-0.2 ± 0.3	N/A

Our fit:

	α_1	α_2	α_3	α_4	α_5	$\Lambda(1405)$ poles [MeV]	
solution 1	1.15	1.17	1.15	1.03	0.88	1385-68i	1419-22i
solution 2	1.88	1.89	1.57	0.93	0.87	1347-28i	1409-33i

Experimental results from **electroproduction**: Lu, Schumacher, et al., [CLAS coll. @Jlab] PhysRevC.88.0452062

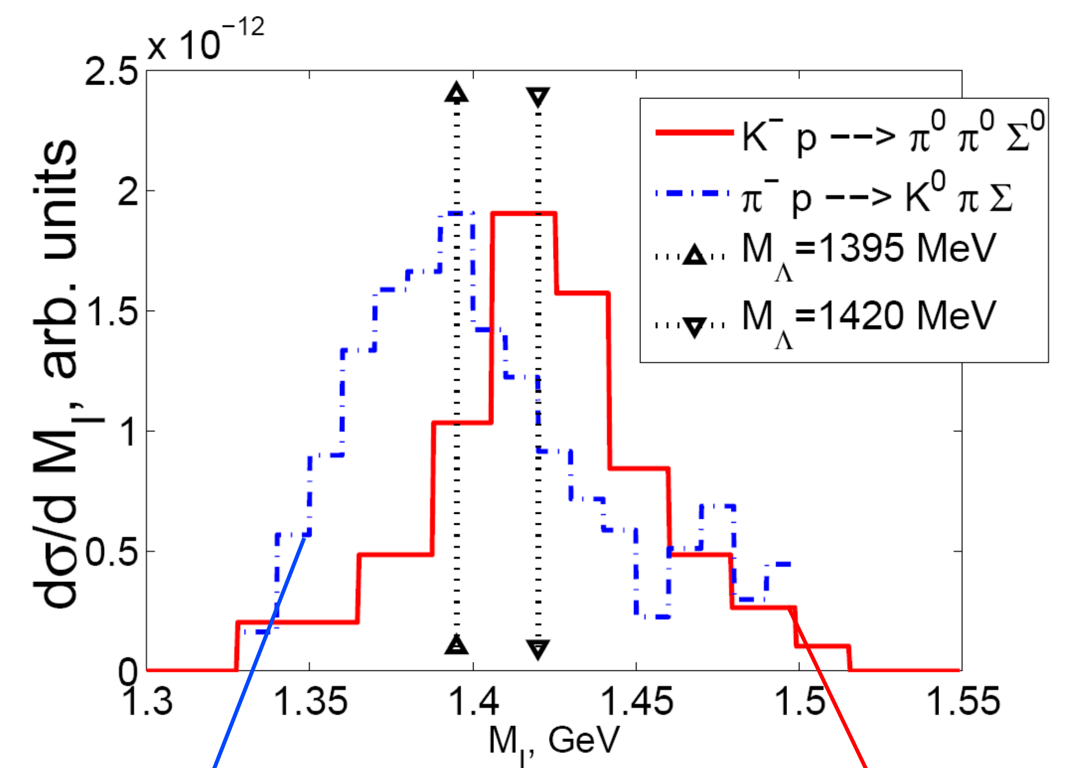




$m_0^{low} = 1.365 \pm 0.002 \ \mathrm{GeV/c^2}$ $m_0^{high} = 1.422 \pm 0.002 \ \mathrm{GeV/c^2}$

	$I=0$		$I=1$
poles	$1352 - 48i$	$1419 - 29i$	–
$\lvert g_{\bar{K}N} \rvert$	2.71	3.06	–
$\lvert g_{\pi\Sigma} \rvert$	2.96	1.96	–

Magas, Oset, Ramos. PRL'05



Two experimental shapes of $\Lambda(1405)$ resonance.

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

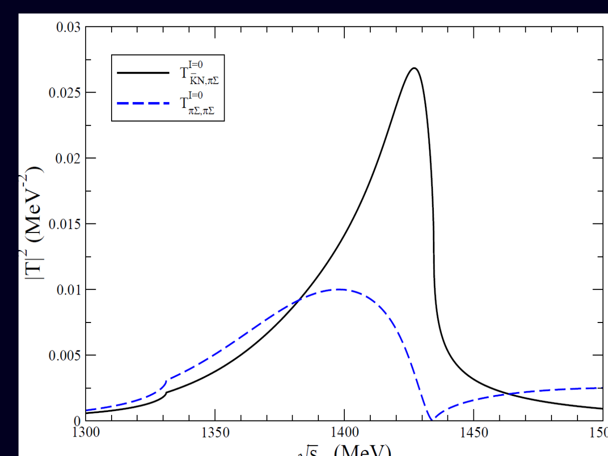
S. Prakhov et al. (Crystall Ball Collaboration) PRC 70, 034605 (2004)

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

D. W. Thomas et al,NPB 56, 15 (1973)

Dominated by $\pi\Sigma \longrightarrow \pi\Sigma$

Dominated by $\bar{K}N \longrightarrow \pi\Sigma$



Motivation

On the Λ(1405)

✓ Predicted in 1959 and discovered exp. in 1961
Dalitz, Tuang **Alston *et al.***

✓ Traditionally difficult to accomodate within quark models **_i.e._, Isgur _et al._**

(Λ(1405) ($1/2^-$)is lighter than its nucleon counterpart N(1535)($1/2^-$) and too large difference in mass with Λ(1520)($3/2^+$))

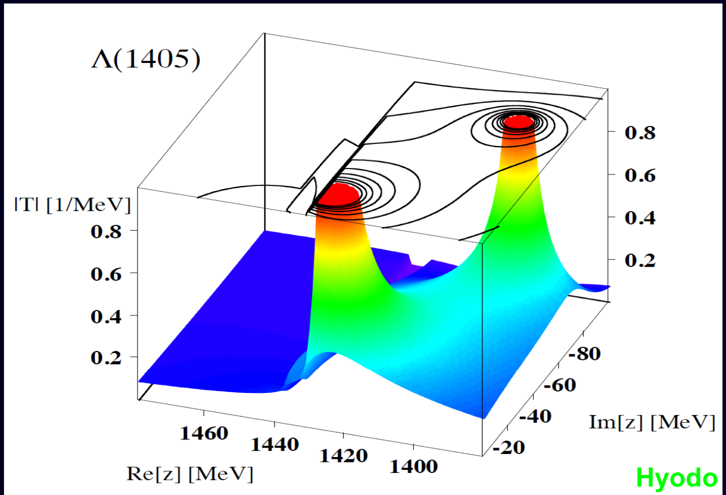
✓ Mass 30MeV below $K\bar{N}$ threshold

✓ Current PDG mass value comes from old πΣ production experiments

UChPT (chiral dynamics + unitarity) generates dynamically the Λ(1405)

Kaiser, Siegle, Weise, Oset, Ramos, Oller, Meissner, … and many more

✓ UChPT predicts a two-pole structure
(each having different values for the couplings to πΣ and $K\bar{N}$)
Jido, Oller, Oset, Ramos, Meissner,…



Hyodo