# $\Lambda$(1405): brief theoretical review

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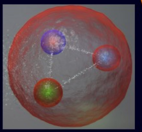
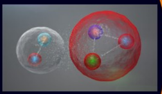
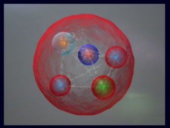
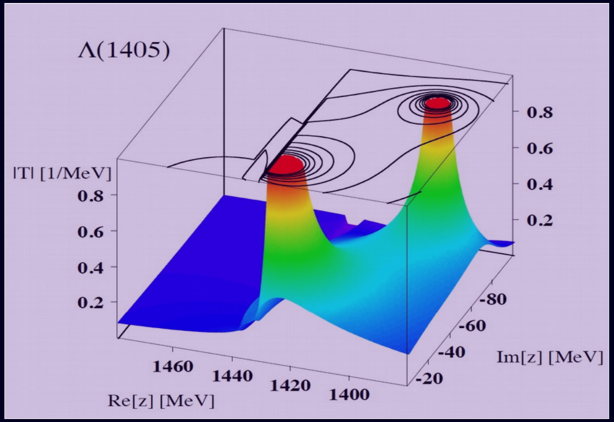
✓ A brief history of its nature and its double pole structure

$|\Lambda(1405)\rangle = \alpha_1 \Big|$  $\Big\rangle + \alpha_2 \Big|$  $\Big\rangle + \alpha_3 \Big|$  $\Big\rangle$

$+ \sum_i \alpha_i \,|\,\text{anything with same quantum numbers}\,\rangle$



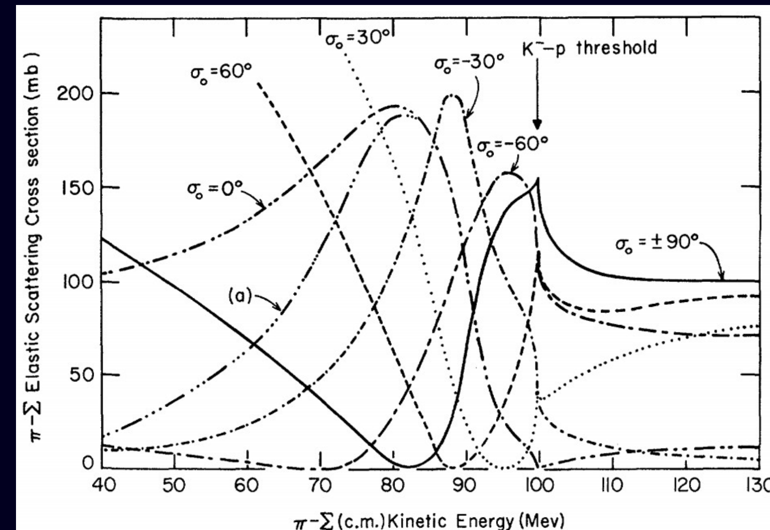

*PWA11/ATHOS6, Rio de Janeiro, September 3, 2019*

# Remarks on the $\Lambda(1405)$

✓ Predicted in 1959:

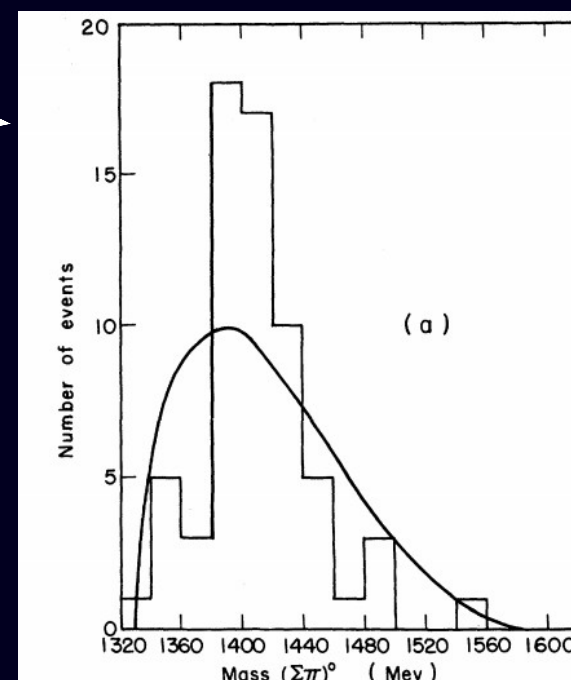
R.H. Dalitz and S.F. Tuan, PRL 2 (1959) 425, Ann Phys 10 (1960) 307

Input from $\bar{K}N$ scattering lengths and implement unitarity with $\bar{K}N$ - $\pi\Sigma$ coupled channels within K-matrix approach




✓ Discovered experimentally in 1961 Alston *et al. PRL 6,12 (1961)*

$$K^- + p \rightarrow \Sigma^+ + \pi^- + \pi^- + \pi^+,$$
$$K^- + p \rightarrow \Sigma^- + \pi^+ + \pi^+ + \pi^-,$$
$$K^- + p \rightarrow \Sigma^0 + \pi^0 + \pi^+ + \pi^-.$$



# The qqq conundrum:

✓ The Λ(1405) is the *ugly duckling* of the quark model:

**Isgur, Karl PRD18,11 (1978)**

$$H_{HO} = \frac{p_1^2}{2m} + \frac{p_2^2}{2m} + \frac{p_3^2}{2m'} + \tfrac{1}{2}K|\vec{r}_1 - \vec{r}_2|^2 + \tfrac{1}{2}K|\vec{r}_1 - \vec{r}_3|^2 + \tfrac{1}{2}K|\vec{r}_2 - \vec{r}_3|^2$$

Theory

EXP

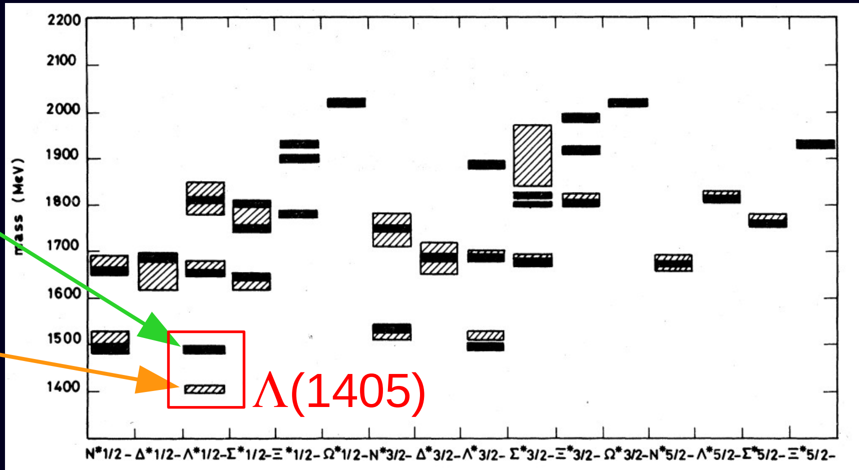



FIG. 1. Comparison of the predicted and observed spectrum of negative-parity baryons. The shaded regions correspond to the likely mass values of resonances; the solid bars are the predictions of the text, corresponding to the parameters $m_0 = 1610$ MeV, $\omega = 520$ MeV, $x = 0.6$, $\Delta m = 280$ MeV, and $\delta = 300$ MeV.

✓ Traditionally difficult to accomodate within quark models as qqq:

- Λ(1405)($1/2^-$) is the **lightest negative parity baryon,**

  in spite it has an **s** quark, it is lighter than its nucleon counterpart N(1535)($1/2^-$)

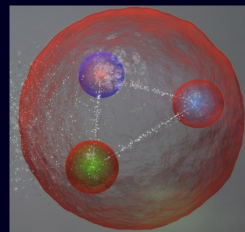
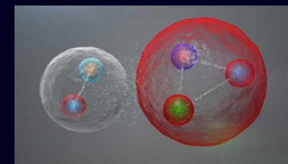
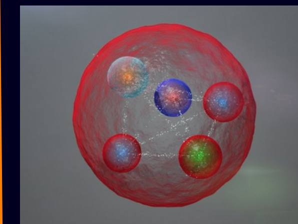
- Too large difference in mass with Λ(1520)($3/2^-$)

- **L=1** excitation costs around N(1535)-N(940)=**600 MeV** but Λ(1405)-Λ(1115)= 290 MeV

✓ Mass 200 MeV above experiment and πΣ width 5 times larger than exp in any realistic qqq picture

**Bijker et al. PRD94,07404(2016)**

Physical $\Lambda(1405)$ state is a mix of infinite contributions:

$|\Lambda(1405)\rangle = \alpha_1$ |  $\rangle + \alpha_2$ |  $\rangle + \alpha_3$ |  $\rangle$

$$+ \sum_i \alpha_i \,|\,\text{anything with same quantum numbers}\,\rangle$$

What is the weight $\alpha_i$ of the different contributions?

dominantly $\chi^\rho\psi^\lambda$ state[23] as predicted. Our belief is therefore that the poorly predicted mass of this state does not point to a fundamental flaw in our model, but rather to the fact that effects outside of the scope of the model can occasionally be significant. In this case we believe that the simplification we have made that is most likely faulty is our restriction to the $qqq$ sector of Fock space. Indeed,

Capstick, Isgur PRD 34,9 (1986)

- ✓ Cloudy bag model (dominant $\bar{K}N$ bound state + small qqq component   Jennings PLB176(1986)
- ✓ Hybrids (qqq-gluon)   Azizi et al. Eur.Phys.J.Plus 133 (2018) no.3, 121 , ...
- ✓ Pentaquarks   Inoue, Nucl.Phys. A790 (2007) 530, ...

# **Lattice**: supports $\overline{\text{K}}$N molecular picture

Hall et al, PRL114,132001 (2015)

Measures strange contribution to the magnetic form factor: if $\Lambda$(1405) is $\overline{\text{K}}$N molecule instead of qqq, then the s is in a spin-0 cluster (the $\overline{\text{K}}$) and cannot contribute to the form factor

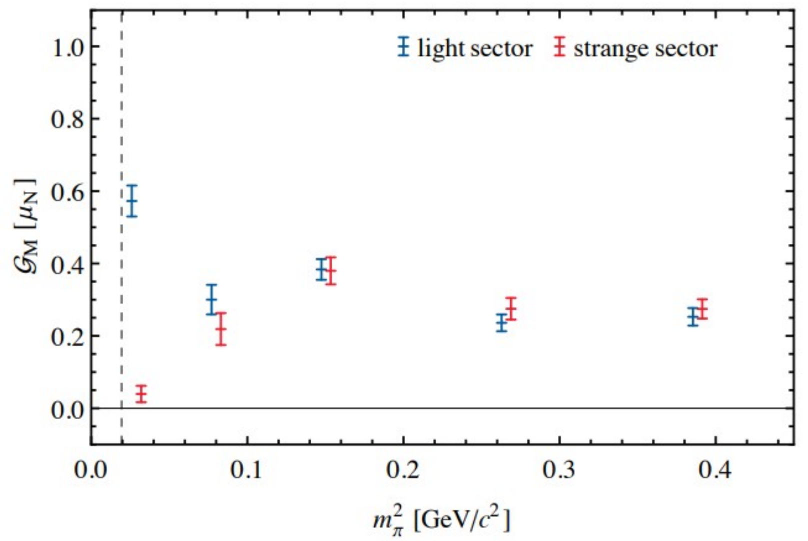



FIG. 3. The light ($u$ or $d$) and strange ($s$) quark contributions to the magnetic form factor of the $\Lambda(1405)$ at $Q^2 \simeq 0.16$ GeV$^2/c^2$ are presented as a function of the light $u$ and $d$ quark masses, indicated by the squared pion mass, $m_\pi^2$. Sector contributions are for single quarks of unit charge. The vertical dashed line indicates the physical pion mass.

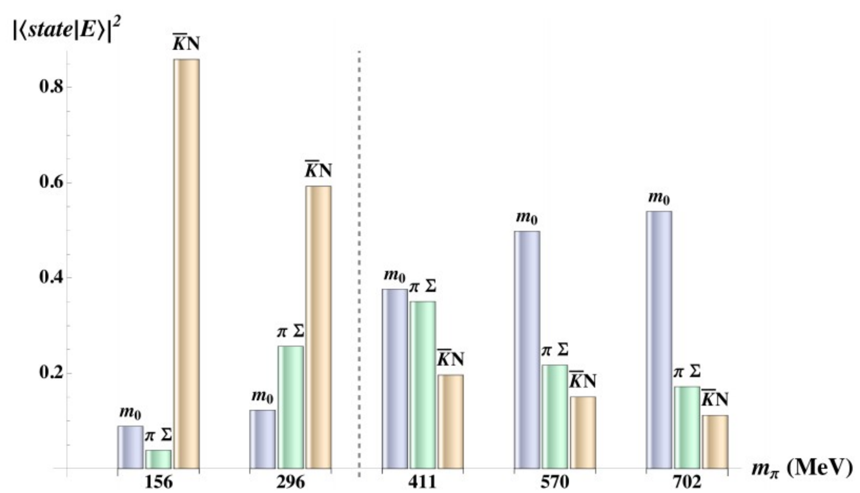
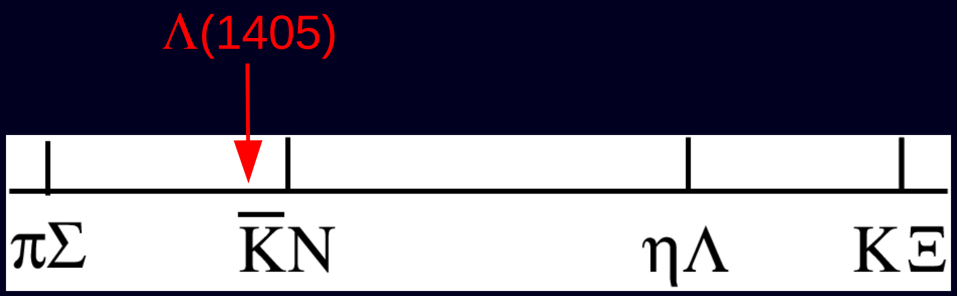



FIG. 4. The overlap of the basis state, $|state\rangle$, with the energy eigenstate $|E\rangle$ for the $\Lambda(1405)$, illustrating the composition of the $\Lambda(1405)$ as a function of pion mass. Basis states include the single particle state, denoted by $m_0$, and the two-particle states $\pi\Sigma$ and $\overline{K}N$. A sum over all two-particle momentum states is done in re-

(Not incompaible with two pole nature **Molina, Döring, PRD94 (2016)** )




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

- ✓ Couple channels is mandatory:

Crucial step forward: Chiral Lagrangians + unitarity (UChPT)

Kaiser, Siegel,Weise NPA (1995)

Basic idea of $\boxed{\text{UChPT:}}$

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)

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Kaiser, Siegel, Weise, NPA 594 (1995) 325

Input: MB chiral Lagrangian

$$\mathcal{L}^{(1)} = Tr(\overline{\Psi}_B(i\gamma_\mu D^\mu - M_0)\Psi_B) + F\,Tr(\overline{\Psi}_B\gamma_\mu\gamma_5[A^\mu,\Psi_B]) + D\,Tr(\overline{\Psi}_B\gamma_\mu\gamma_5\{A^\mu,\Psi_B\})$$

$$\mathcal{L}^{(1)}_{int} = \frac{i}{8f^2}Tr(\overline{B}[[\phi,\partial_0\phi],B]) \longrightarrow V_{ij}(\vec{r}) = \frac{C_{ij}}{2f^2}\sqrt{\frac{M_iM_j}{s\omega_i\omega_j}}\delta^3(\vec{r})$$

Chiral perturbation series not convergent (strong $\overline{\text{K}}$N-$\pi\Sigma$ coupling and pole below $\overline{\text{K}}$N threshold)

Resummation and regularization required: Lippmann-Schwinger:

$$T_{ij}(k_i,k_j) = V_{ij}(k_i,k_j) + \sum_n \int_0^\infty \frac{q^2 dq\, 2\omega_n V_{in}(k_i,q)T_{nj}(q,k_j)}{q^2 - k_n^2 + i\epsilon}$$

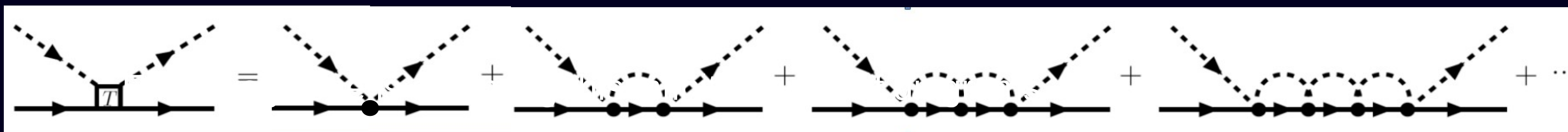
**$\Lambda$(1405) dynamically generated**

$\Lambda$(1405) predicted as a $\overline{\text{K}}$N bound state coupled to the open $\pi\Sigma$ channel

Oset, Ramos NPA635 (1998)

**Unitarity** of the S-matrix implies :

Effectively, one is summing this infinite series of diagrams




T V VGV VGVGV

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

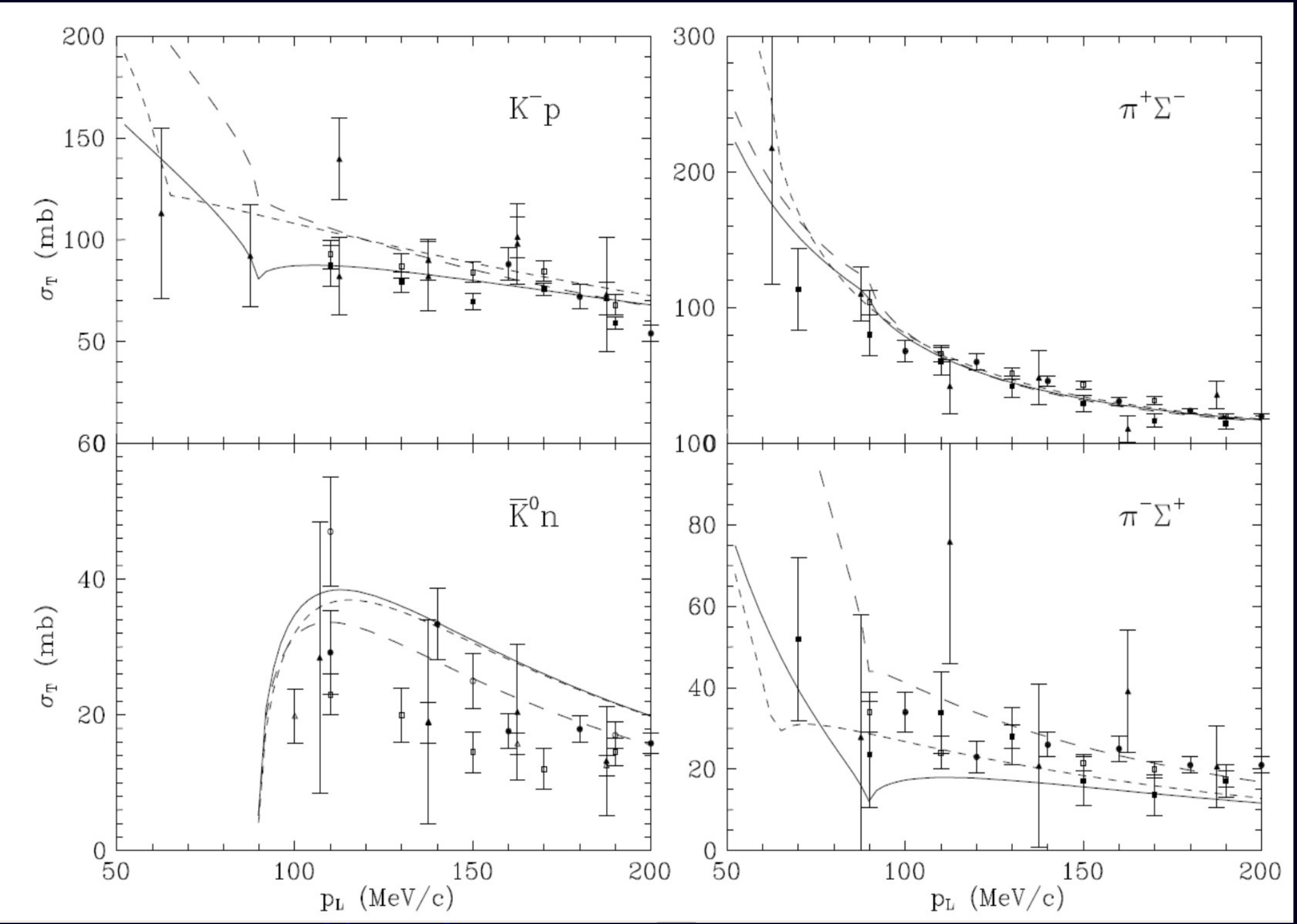
(...+ $\pi\Lambda$ + $\eta\Sigma$ + $K\Xi$)

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

On-shell approximation: off-shell effects are reabsorbed in renormalization of the couplings

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

Algebraic equation!




Oset, Ramos NPA635 (1998)

Oller, Meissner PLB500,263 (2001)

Subtracted dispersion relations: removes sensibility to the regulator

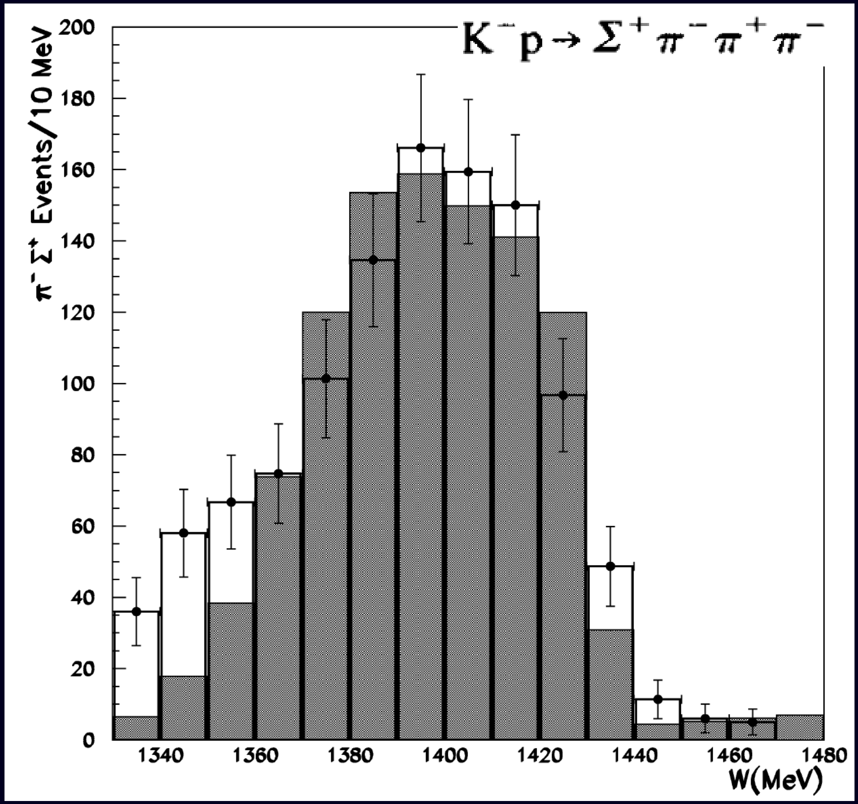
$$T^{-1}(W)_{ij} = -\delta_{ij}\overbrace{\left\{\widetilde{a}_i(s_0) + \frac{s-s_0}{\pi}\int_{s_i}^{\infty} ds' \frac{\rho(s')_i}{(s'-s)(s'-s_0)}\right\}}^{g(s)} + \mathcal{T}^{-1}(W)_{ij},$$

$$\mathrm{Im}\, T^{-1}(W)_{ij} = -\rho(W)_i \delta_{ij}$$

$$T(W) = [I + \mathcal{T}(W)\cdot g(s)]^{-1}\cdot \mathcal{T}(W)$$

Allows matching with ChPT amplitudes order by order

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




( Data from Hemingway, NPB253,742(1985) )

✓ First appearance of the **double pole** structure in UChPT!

> pole positions change appreciably from one sheet to the other, which is a clear indication of a large meson–baryon component. For the second and third sheets, which are the closest ones to the physical sheet, we have the following pole positions. Sheet II: $(1379.2 - i\,27.6)$ MeV, $(1433.7 - i\,11.0)$ MeV $(I = 0)$ and

Oller, Meissner PLB500,263 (2001)

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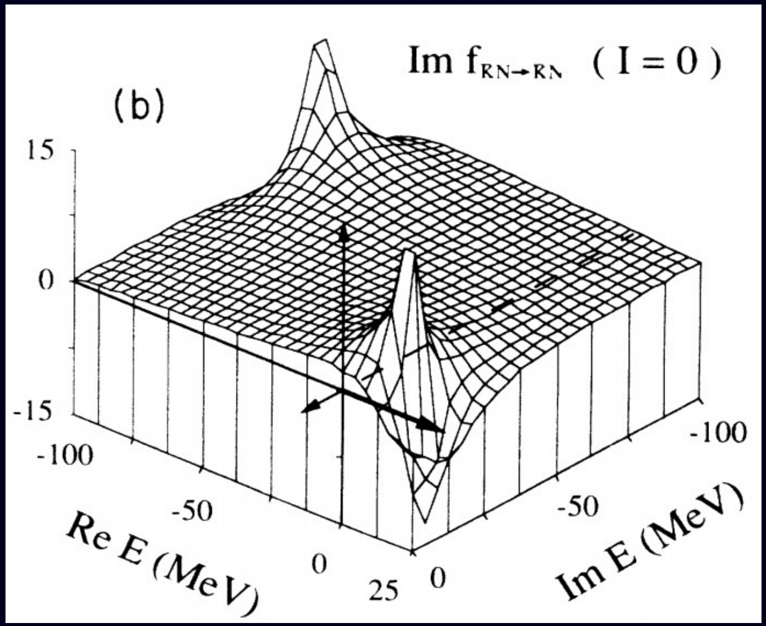
✓ But **double pole** already obtained before in 1990 with potential from cloudy bag model!

Fink, He, Landau, Schnick PRC41,6 (1990)

> $$\bar{K}N, \Sigma\pi, \Lambda\pi, \quad (I=0,1)\ . \tag{5}$$
>
> The dynamics arise from the coupled Lippmann-Schwinger equations
>
> $$T(k',k;E) = V(k',k) + \frac{2}{\pi}\int_0^\infty dp\, p^2 V(k',p) G_E(p) T(p,k;E)\ ,$$



# PDG 2014

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) $\overline{4}$ 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 | $^4\mathrm{He}\,K^- \to \Sigma^\pm\pi^\mp X$ at rest |
| $1406.5\pm4.0$ | | [1] DALITZ 91 | | M-matrix fit |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $1391\pm1$ | 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/$c$ |
| $1400\pm5$ | 67 | BIRMINGHAM 66 | HBC | $K^-p$ 3.5 GeV/$c$ |
| $1382\pm8$ | | ENGLER 65 | HDBC | $\pi^-p$, $\pi^+d$ 1.68 GeV/$c$ |
| $1400\pm24$ | | MUSGRAVE 65 | HBC | $\overline{p}p$ 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 $N\overline{K}$ THRESHOLD**

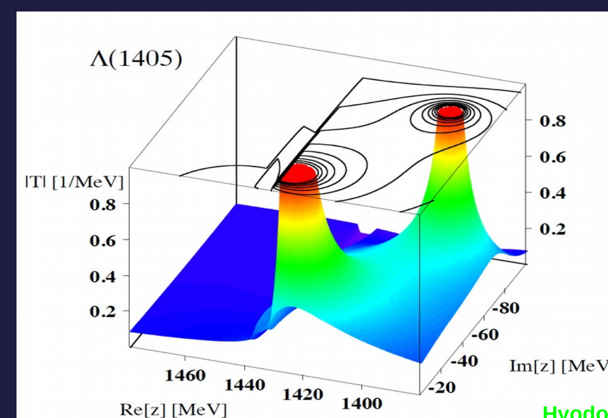
| VALUE (MeV) | DOCUMENT ID | TECN | COMMENT |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| 1407.56 or 1407.50 | [3] KIMURA 00 | | potential model |
| 1411 | [4] MARTIN 81 | | K-matrix fit |
| 1406 | [5] CHAO 73 | DPWA | 0–range fit (sol.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

**UChPT** (chiral dynamics + unitarity) generates dynamically the $\Lambda(1405)$

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

✓ UChPT predicts a two-pole structure
(each having different values for the couplings to $\pi\Sigma$ and $\overline{K}N$)

Jido, Oller, Oset, Ramos, Meissner,...




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

Not possible in direct K beam exp.

✓ Current PDG mass value comes from old $\pi\Sigma$ production experiments

PDG 2019

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

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

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the $N$-$\overline{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that this behavior "is characteristic of $S$-wave coupling; the other below threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its $N$-$\overline{K}$ coupling is $P$-wave. For $\Lambda(1405)$ this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

A recent measurement by the CLAS collaboration, MORIYA 14, definitively established the long-assumed $J^P = 1/2^-$ spin-parity assignment of the $\Lambda(1405)$. The experiment produced the $\Lambda(1405)$ spin-polarized in the photoproduction process $\gamma p \to K^+ \Lambda(1405)$ and measured the decay of the $\Lambda(1405)$(polarized) $\to \Sigma^+$(polarized)$\pi^-$. The observed isotropic decay of $\Lambda(1405)$ is consistent with spin $J = 1/2$. The polarization transfer to the $\Sigma^+$(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

**See the related review(s):**

Pole Structure of the $\Lambda(1405)$ Region   Hyodo, Meissner

## $\Lambda(1405)$ REGION POLE POSITIONS

### REAL PART

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $1429^{+8}_{-7}$ | [1] MAI | 15 | DPWA |
| $1325^{+15}_{-15}$ | [2] MAI | 15 | DPWA |
| $1434^{+2}_{-2}$ | [3] MAI | 15 | DPWA |
| $1330^{+4}_{-5}$ | [4] MAI | 15 | DPWA |
| $1421^{+3}_{-2}$ | [5] GUO | 13 | DPWA |
| $1388 \pm 9$ | [6] GUO | 13 | DPWA |
| $1424^{+7}_{-23}$ | [7] IKEDA | 12 | DPWA |
| $1381^{+18}_{-6}$ | [8] IKEDA | 12 | DPWA |

# Why **two poles**?

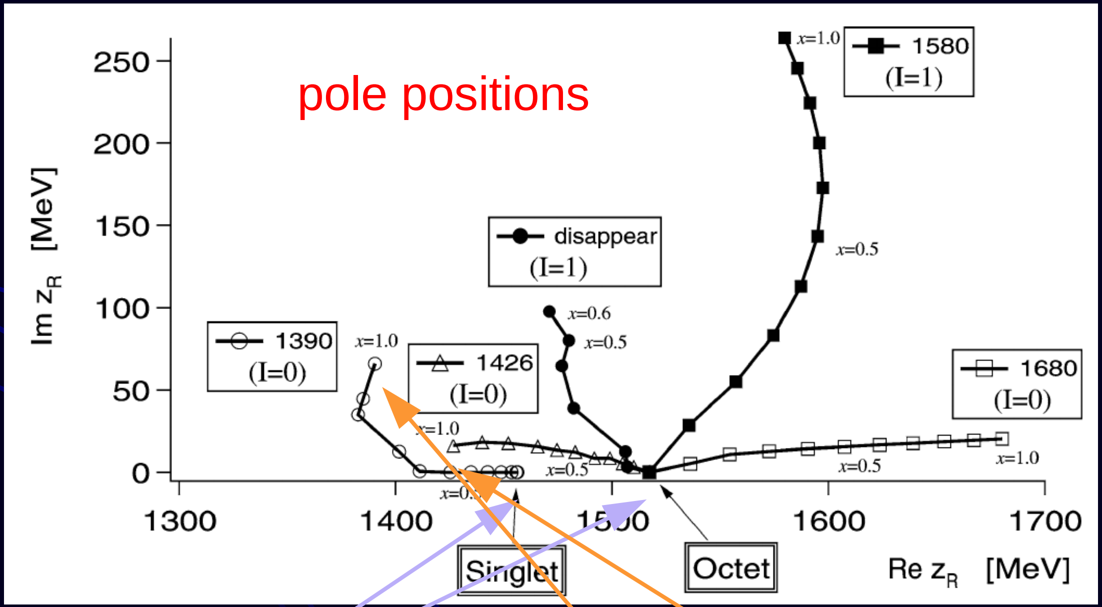
Octet mesons x octet baryons: $8 \otimes 8 = 1 \oplus 8_s \oplus 8_a \oplus 10 \oplus \overline{10} \oplus 27$

Potential from ChPT in SU(3) basis: $V_{\alpha\beta} = \mathrm{diag}(6, 3, 3, 0, 0, -2)$

Attractive for 1, $8_s$ and $8_a$: expect 3 bound states!

**UNAVOIDABLE** from chiral symmetry + unitarity!

Jido, Oller, Oset, Ramos, Meissner NPA635 (2003)




$$M_i(x) = M_0 + x(M_i - M_0),$$
$$m_i^2(x) = m_0^2 + x(m_i^2 - m_0^2),$$
$$a_i(x) = a_0 + x(a_i - a_0),$$

$x \in [0,1]$

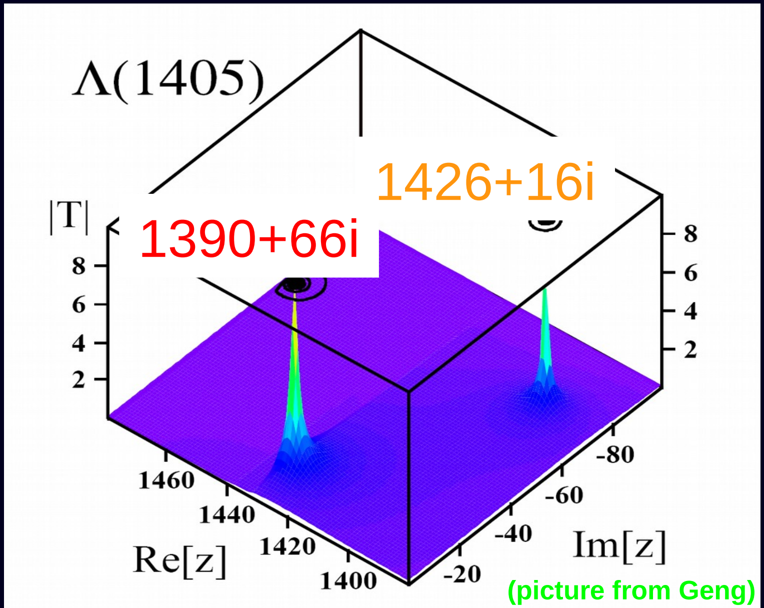
Exact SU(3) limit

SU(3) broken (physical)

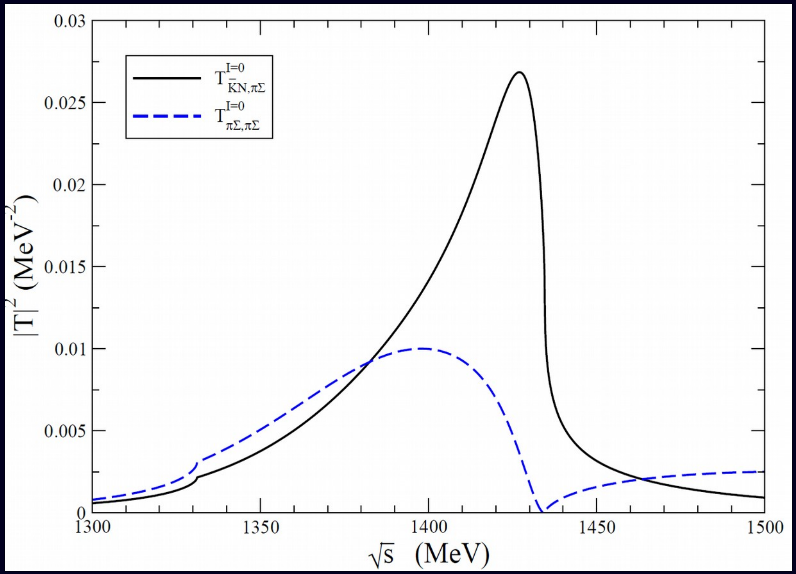
In SU(3) limit there is 1 pole for the singlet and 2 degenerate poles for the octet

In the physical limit they mix producing two poles close to $\overline{K}N$ threshold and one for the $\Lambda(1670)$

**Two poles** in the complex plane




Amplitudes in the real axis:




**Couplings** to different channels:

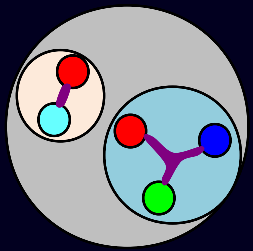
| $z_R$ $(I=0)$ | $1390+66i$ $g_i$ | $\lvert g_i \rvert$ | $1426+16i$ $g_i$ | $\lvert g_i \rvert$ |
|---|---|---|---|---|
| $\pi\Sigma$ | $-2.5-1.5i$ | 2.9 | $0.42-1.4i$ | 1.5 |
| $\bar{K}N$ | $1.2+1.7i$ | 2.1 | $-2.5+0.94i$ | 2.7 |
| $\eta\Lambda$ | $0.010+0.77i$ | 0.77 | $-1.4+0.21i$ | 1.4 |
| $K\Xi$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

Lowest pole dominated by $\pi\Sigma$

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

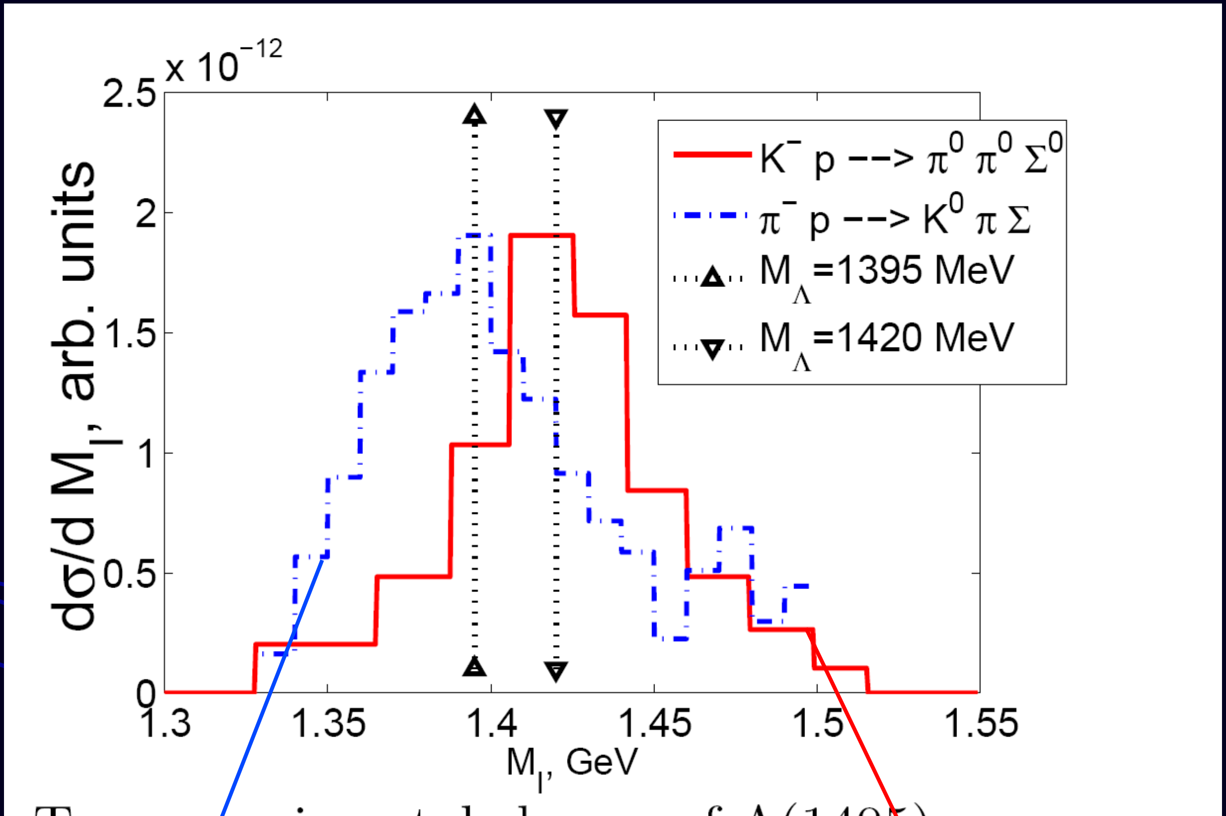
Recall: no explicit resonances included!
(dynamically generated from chiral dynamics and unitarity)

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



Resonance shape may be different for different reactions!

If $\Lambda(1405)$ is dynamically generated we have to produce first the meson-baryon pair and then the rescattering produces the $\Lambda(1405)$.
Scattering data is not enough
Magas, Oset, Ramos. PRL'05



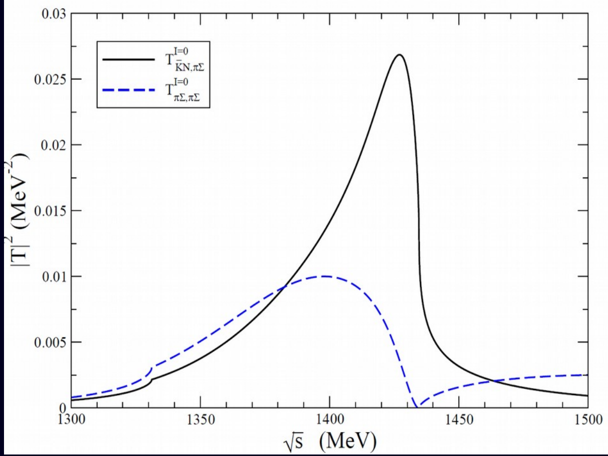
Two experimental shapes of $\Lambda(1405)$ resonance.

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

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

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

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




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

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

## Two poles always found by all groups using chiral unitary approach:

García-Recio, Nieves, Ruiz-Arriola, Vicente-Vacas,PRD67, 076009 (2003)

Hyodo, Nam, Jido, Hosaka PRC68, 018201(2003)

Borasoy, Niessler, Weise, EPJA27,79(2005)

Hyodo, Weise, PRC77,035204 (2008)

Ikeda, Hyodo, Weise, NPA881,98 (2012)

Guo, Oller, PRC87,035202 (2013)

Mai, Meissner, EPJA51,30 (2015)

Molina, Döring, PRD94 (2016)

## Two poles always found by all groups using chiral unitary approach:

García-Recio, Nieves, Ruiz-Arriola, Vicente-Vacas,PRD67, 076009 (2003)
Hyodo, Nam, Jido, Hosaka PRC68, 018201(2003)
Borasoy, Niessler, Weise, EPJA27,79(2005)
Hyodo, Weise, PRC77,035204 (2008)
Ikeda, Hyodo, Weise, NPA881,98 (2012)
Guo, Oller, PRC87,035202 (2013)
Mai, Meissner, EPJA51,30 (2015)
Molina, Döring, PRD94 (2016)

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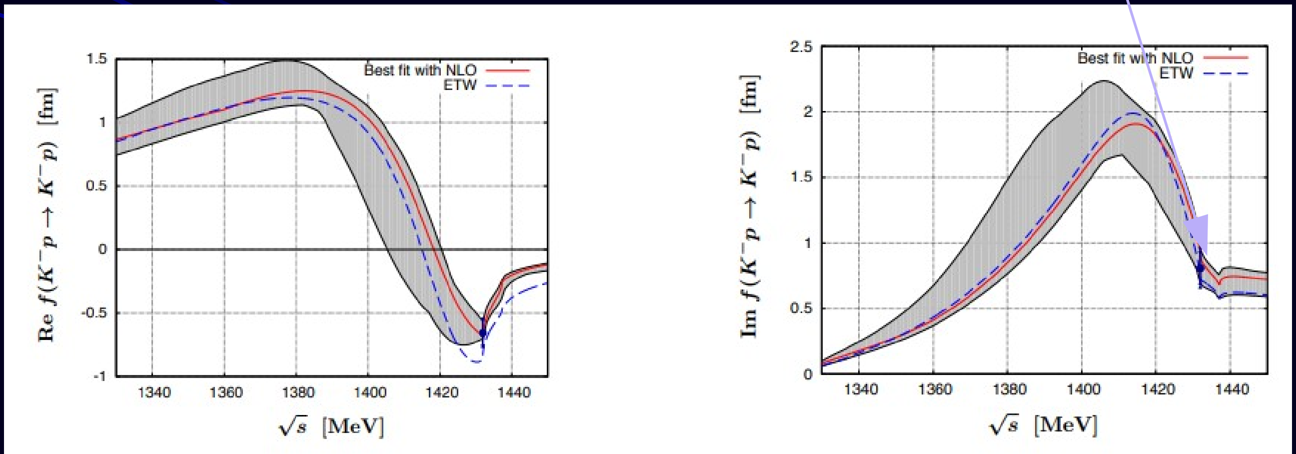
Ikeda, Hyodo, Weise, NPA881,98 (2012)

$$\begin{aligned}\mathcal{L}_{MB}^{(2)} =& b_0 \,\mathrm{Tr}(\bar{\mathcal{B}}\,\mathcal{B})\,\mathrm{Tr}(\chi_+) + b_D\,\mathrm{Tr}(\bar{\mathcal{B}}\{\chi_+,\mathcal{B}\}) + b_F\,\mathrm{Tr}(\bar{\mathcal{B}}[\chi_+,\mathcal{B}])\\ &+ d_1\,\mathrm{Tr}(\bar{\mathcal{B}}\,\{u_\mu,[u^\mu,\mathcal{B}]\}) + d_2\,\mathrm{Tr}(\bar{\mathcal{B}}\,[u_\mu,[u^\mu,\mathcal{B}]])\\ &+ d_3\,\mathrm{Tr}(\bar{\mathcal{B}}\,u_\mu)\,\mathrm{Tr}(\mathcal{B}\,u^\mu) + d_4\,\mathrm{Tr}(\bar{\mathcal{B}}\,\mathcal{B})\,\mathrm{Tr}(u_\mu\,u^\mu)\quad ,\end{aligned}$$

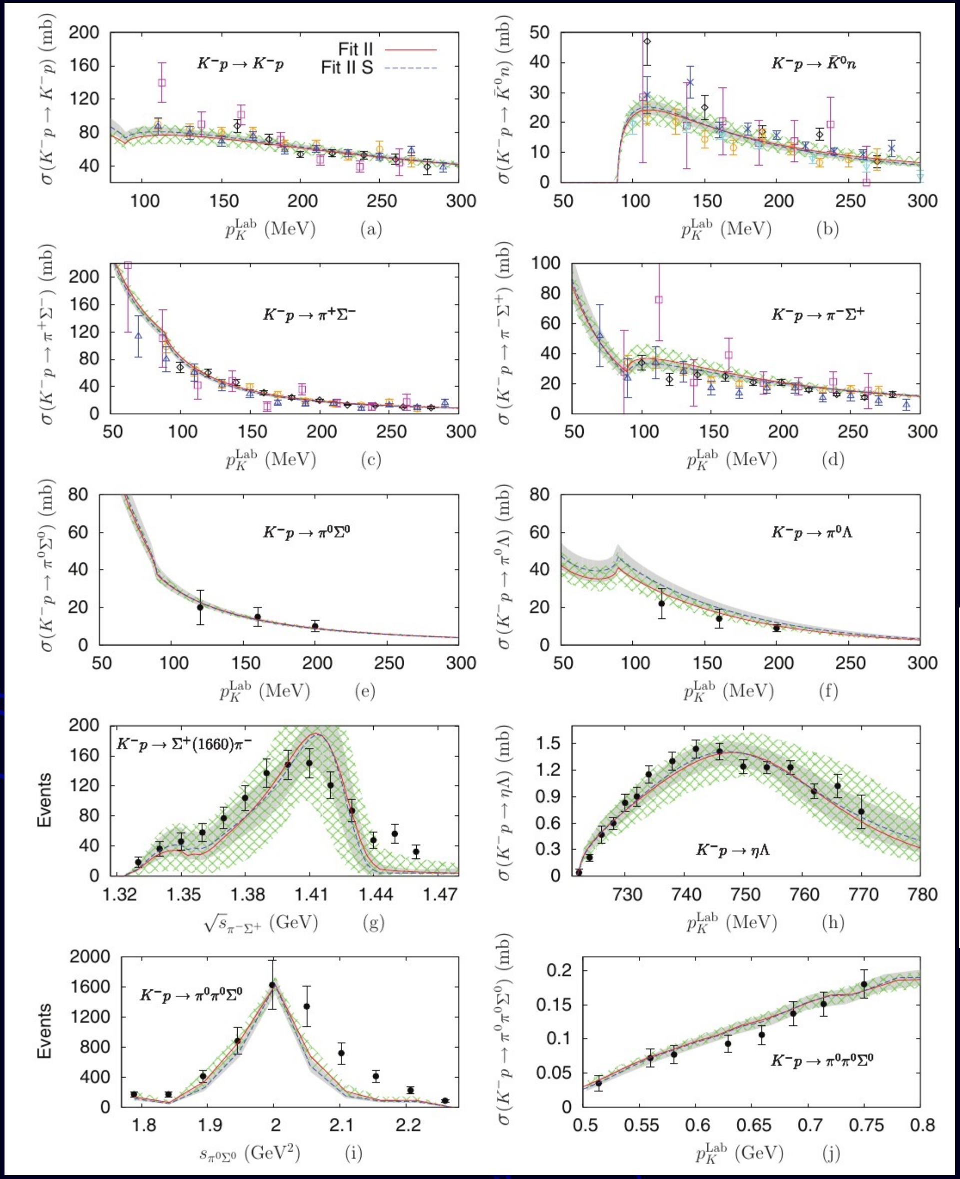
NLO ChPT input:

Little effect in scattering data and $\Lambda$(1405) pole positions
Important to reproduce also amplitude at threshold (SIDDHARTA data for kaonic atoms) and extrapolation to subthreshold

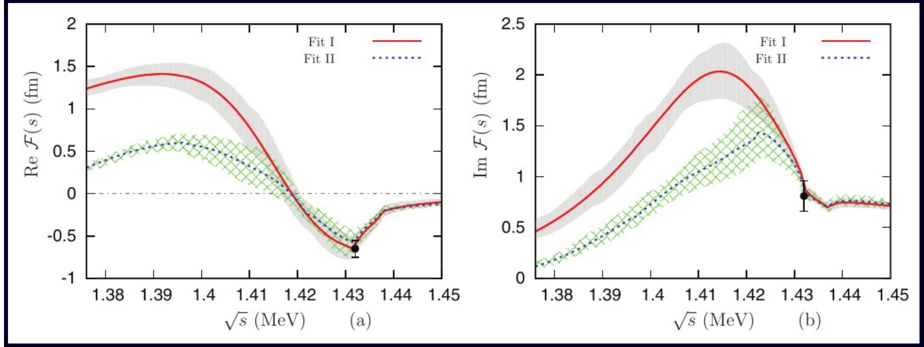



Off-shell effects small:
Mai, Meissner, NPA900,51 (2013)
Dong, Sun, Pang Chinese Phys, C41, (2017)

Similar analysis in **Guo, Oller, PRC87,035202 (2013)**




+ Siddharta datum



In Cieply, Mai, Meissner, Smejkal, Oller, PRC87,035202 (2013) the different models are compared and give different results for subthreshold amplitudes and poles

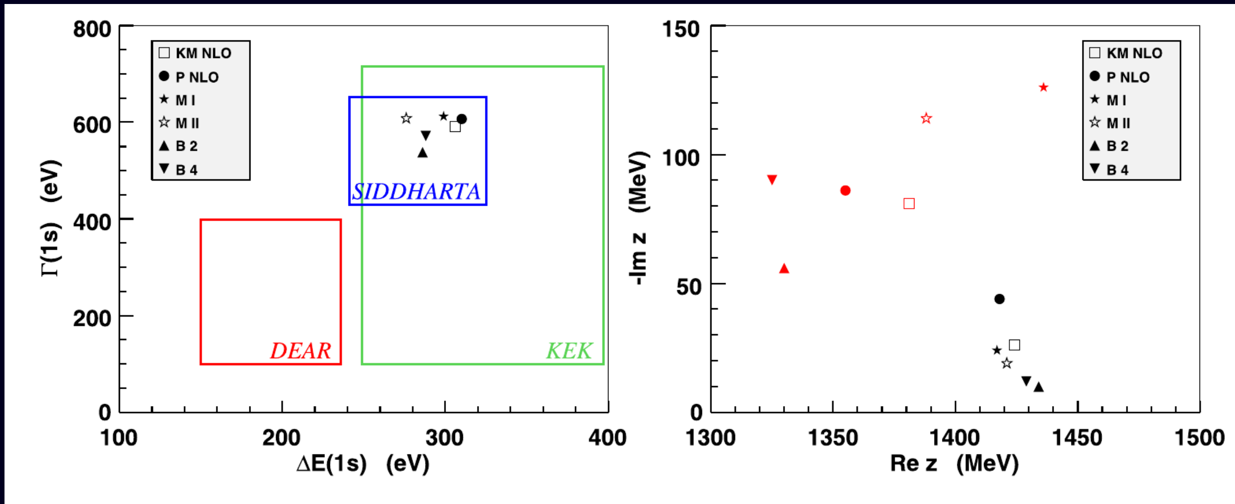



Fig. 1. Kaonic hydrogen characteristics and pole positions for the various approaches.

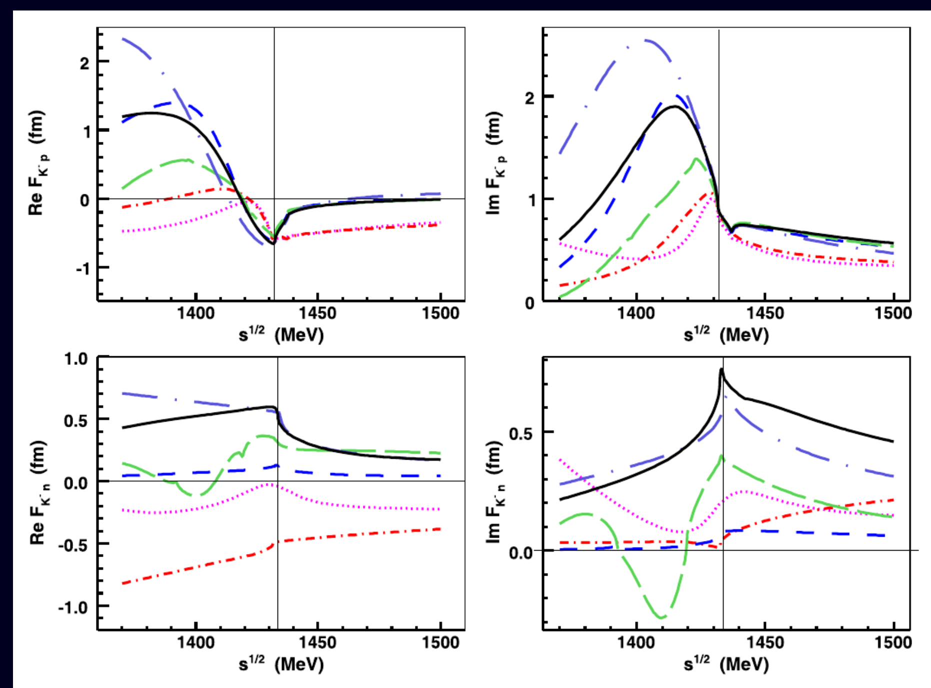



Fig. 2. The $K^-p$ (top panels) and $K^-n$ (bottom panels) elastic scattering amplitudes generated by the NLO approaches

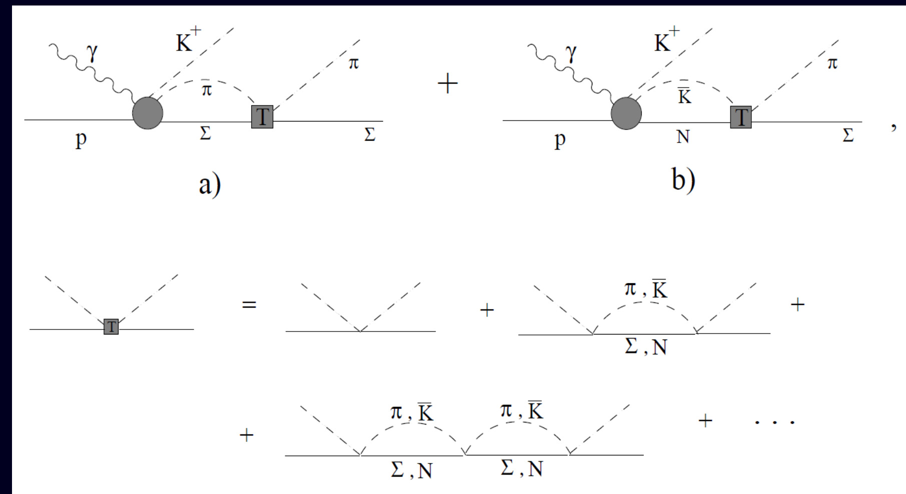
# Fit to photoproduction data

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

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

$\gamma p \to K^+ \pi^\pm \Sigma^\mp$  $\gamma p \to K^+ \pi^0 \Sigma^0$

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

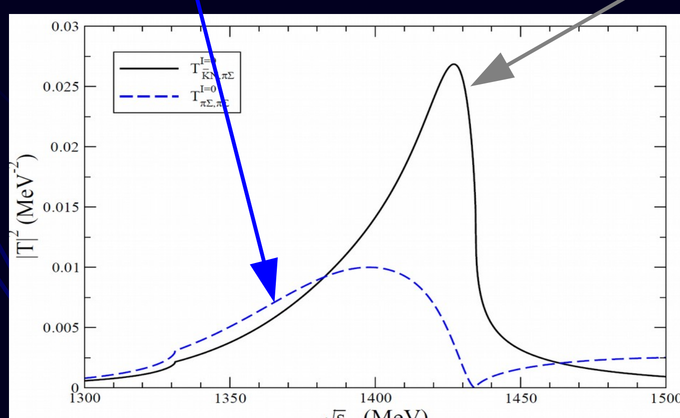



General expression for the photoproduction scattering amplitude:

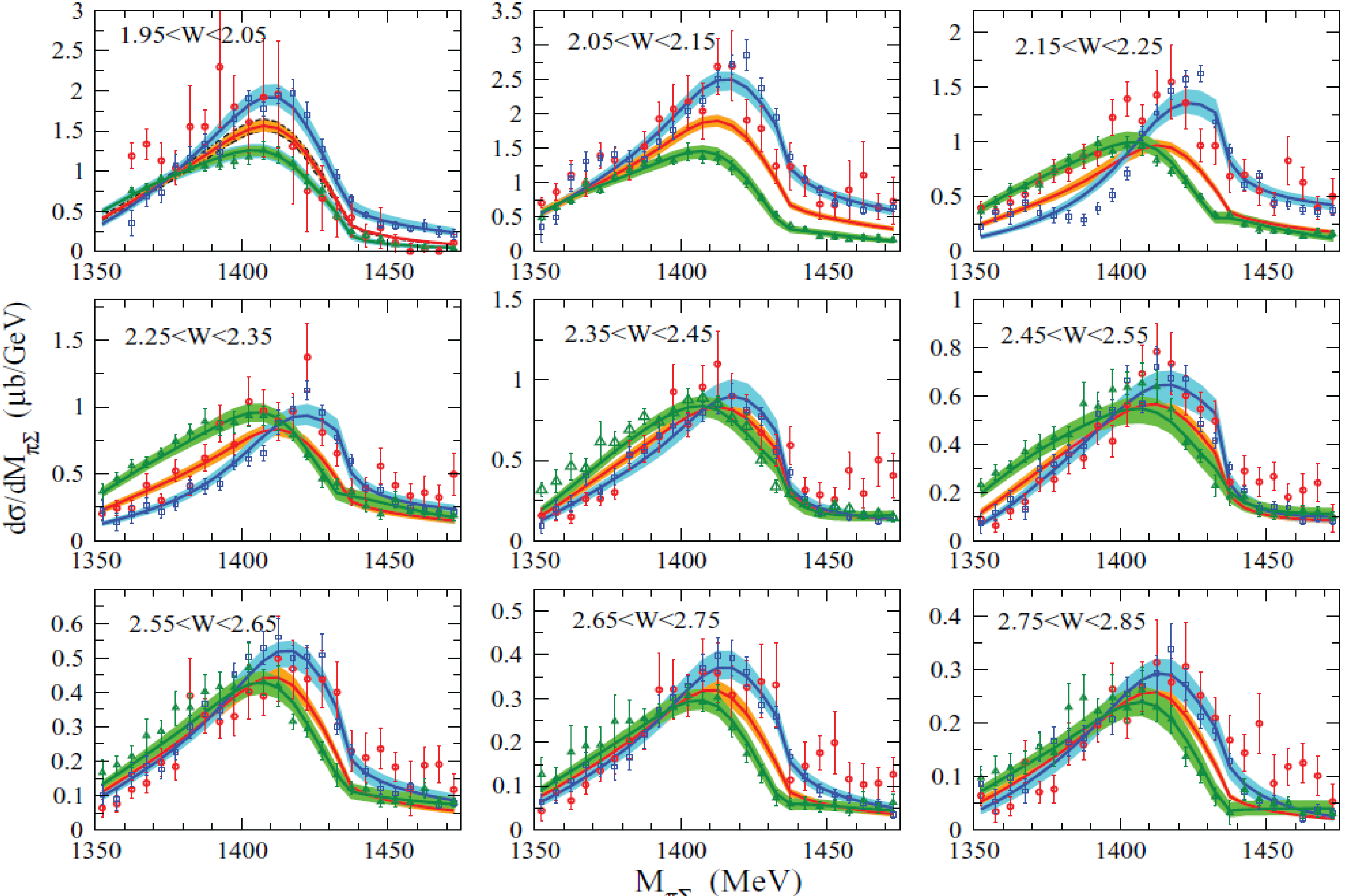
$$t(W) = b(W) G_{\pi\Sigma} T^{I=0}_{\pi\Sigma,\pi\Sigma} + c(W) G_{\bar{K}N} T^{I=0}_{\bar{K}N,\pi\Sigma}$$

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

only I=0



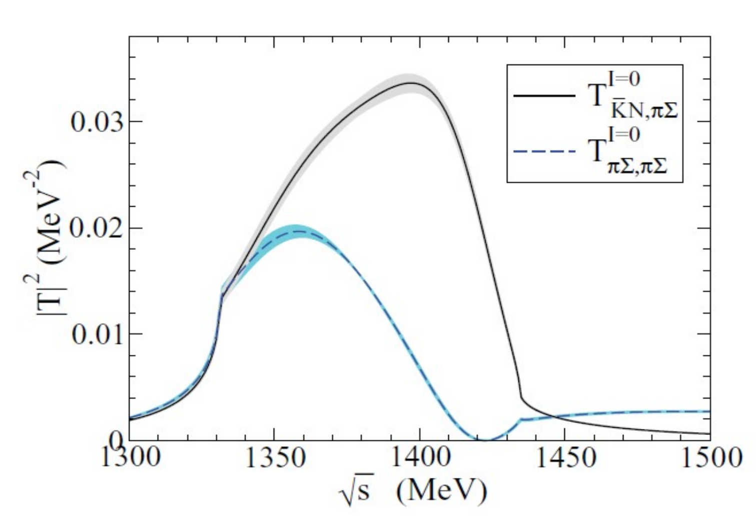

*b* and *c* (complex) coefficients fitted for each energy!



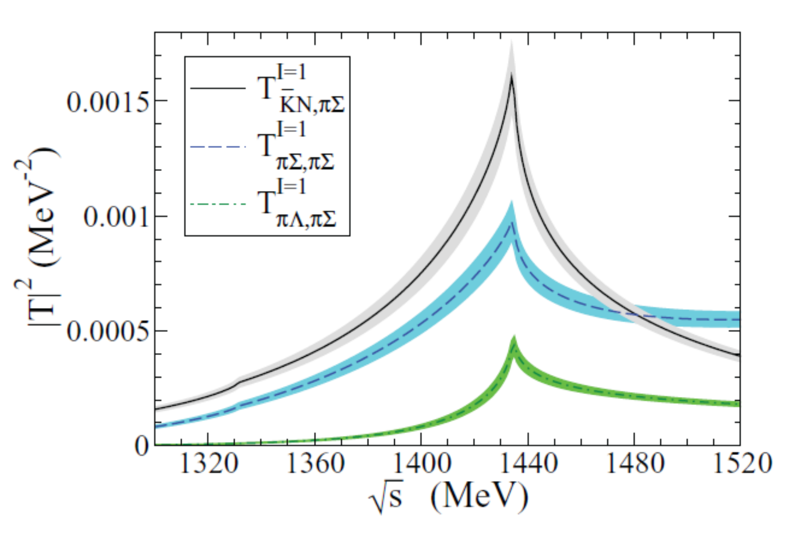

Red: $\pi^0\Sigma^0$; blue: $\pi^-\Sigma^+$, green: $\pi^+\Sigma^-$

Results of the global fit:

| | $I=0$ | | $I=1$ |
|---|---|---|---|
| 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".



Other analysis similar to ours:

Mai, Meissner, EPJA51,30 (2015)

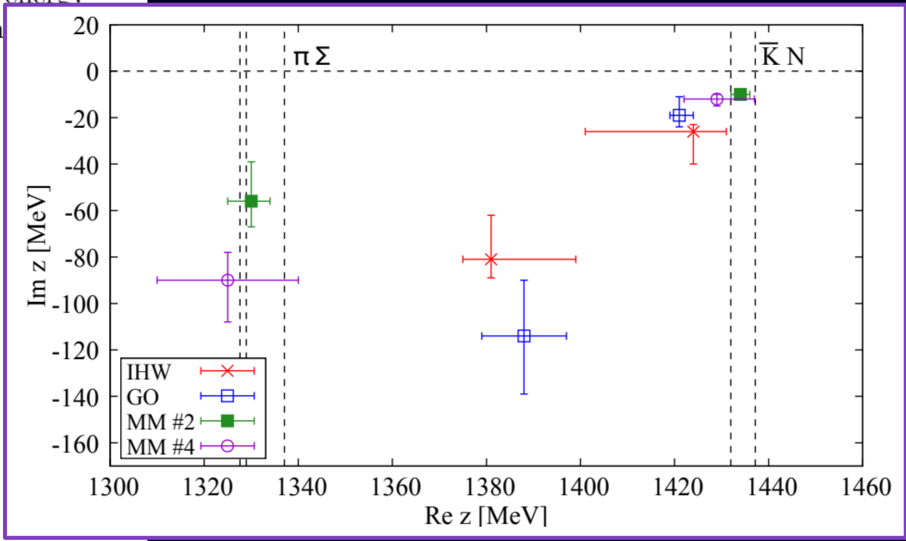
Global fit including: NLO + fit to (scattering + photoproduction + SIDDHARTA)

| solution | pole 1 | pole 2 |
|---|---|---|
| #2 | $1434^{+2}_{-2} - i\,10^{+2}_{-1}$ | $1330^{+4}_{-5} - i\,56^{+17}_{-11}$ |
| #4 | $1429^{+8}_{-7} - i\,12^{+2}_{-3}$ | $1325^{+15}_{-15} - i\,90^{+12}_{-18}$ |

# PDG 2018 review by Hyodo and Meissner

**Table 100.1:** Comparison of the pole positions of $\Lambda(1405)$ in the complex energy plane from next-to-leading order chiral unitary coupled-channel approaches including the SIDDHARTA constraint.

| | approach | pole 1 [MeV] | pole 2 [MeV] |
|---|---|---|---|
| Ikeda et al. | Refs. 11,12, NLO | $1424^{+7}_{-23} - i\,26^{+3}_{-14}$ | $1381^{+18}_{-6} - i\,81^{+19}_{-8}$ |
| Guo, Oller | Ref. 14, Fit II | $1421^{+3}_{-2} - i\,19^{+8}_{-5}$ | $1388^{+9}_{-9} - i\,114^{+24}_{-25}$ |
| Mai, Meissner | Ref. 15, solution #2 | $1434^{+2}_{-2} - i\,10^{+2}_{-1}$ | $1330^{+4}_{-5} - i\,56^{+17}_{-11}$ |
| | Ref. 15, solution #4 | $1429^{+8}_{-7} - i\,12^{+2}_{-3}$ | $1325^{+15}_{-15} - i\,90^{+12}_{-18}$ |




Lower dispersion for higher pole

**References:**


1. R.H. Dalitz, S.F. Tuan Phys. Rev. Lett. **2**, 425 (1959).
2. V. Bernard *et al.*, Int. J. Mod. Phys. **E4**, 193 (1995).
3. N. Kaiser *et al.*, Nucl. Phys. **A594**, 325 (1995).
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5. J.A. Oller, U.-G. Meißner, Phys. Lett. **B500**, 263 (2001).
6. D. Jido *et al.*, Nucl. Phys. **A725**, 181 (2003).
7. T. Hyodo, W. Weise, Phys. Rev. **C77**, 035204 (2008).
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9. M. Bazzi *et al.*, Nucl. Phys. **A881**, 88 (2012).
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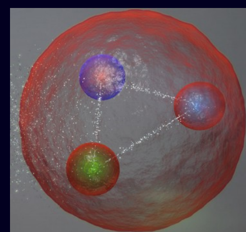
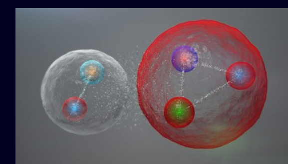
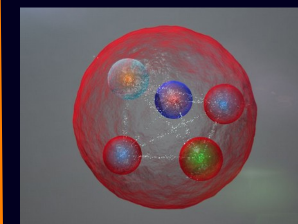
11. Y. Ikeda *et al.*, Phys. Lett. **B706**, 63 (2011).
12. Y. Ikeda *et al.*, Nucl. Phys. **A881**, 98 (2012).
13. M. Mai, U.-G. Meißner, Nucl. Phys. **A900**, 51 (2013).
14. Z.-H. Guo, J. Oller, Phys. Rev. **C87**, 035202 (2013).
15. M. Mai, U.-G. Meißner, Eur. Phys. J. **A51**, 30 (2015).
16. M. Niiyama *et al.*, Phys. Rev. **C78**, 035202 (2098).
17. K. Moriya *et al.*, Phys. Rev. **C87**, 035206 (2013).
18. K. Moriya *et al.*, Phys. Rev. Lett. **112**, 082004 (2014).
19. H.Y. Lu *et al.*, Phys. Rev. **C88**, 045202 (2013).
20. I. Zychor *et al.*, Phys. Lett. **B660**, 167 (2008).
21. G. Agakishiev *et al.*, Phys. Rev. **C87**, 025201 (2013).
22. L. Roca, E. Oset, Phys. Rev. **C87**, 055201 (2013).
23. M. Hassanvand *et al.*, Phys. Rev. **C87**, 055202 (2013).

## More on the compositeness of the $\Lambda(1405)$

Recall:

$|\Lambda(1405)\rangle = \alpha_1 |$  $\rangle + \alpha_2 |$  $\rangle + \alpha_3 |$  $\rangle$

$+ \sum_i \alpha_i \, |\text{anything with same quantum numbers}\rangle$

What is the weight $\alpha_i$ of the different contributions?

# More on the compositeness of the $\Lambda(1405)$

We have already seen that qqq fails and Lattice obtains KN molecule

**More reasons** why we consider it a **molecule**:

✓ Large $N_c$ behaviour not compatible with qqq

**Hyodo, Jido, L.R., PRD77,056010 (2008)**
**Hyodo, Jido, L.R., NPA809,65 (2008)**

✓ Weinberg compositeness condition applied to coupled channels:

**S. Weinberg, Phys. Rev. 137 (1965)**

**Gamermann, Nieves, Oset, Ruiz-Arriola, PRD81,014028 (2010)**
**Molina, Döring, PRD94 (2016)**
**Hyodo, Jido,Hosaka, PRC85, 015201 (2012)**
**Hyodo, JMP A, 28, 1330045. (2013)**

$$Z \equiv |\langle B_0 | B \rangle|^2$$

Elementariness: Z=1, pure bare state
Z=0, pure MB molecule

Bare component (qqq)

$$X \equiv \int d\boldsymbol{p} |\langle \boldsymbol{p} | B \rangle|^2 = -\sum_i \left( g_i^2 \left[ \frac{dG_i}{dE} \right]_{E=E_R} \right) = 1 - Z$$

**Compositeness**: X=1, pure MB molecule
X=0, pure bare state

(overlap with scattering states (MB) )

| | $1-\mathcal{Z}$ | $\mathcal{Z}$ |
|---|---|---|
| Lowest pole | $0.28 + 0.47i$ | $0.72 - 0.47i$ |
| Highest pole | $0.82 - 0.16i$ | $0.18 + 0.16i$ |

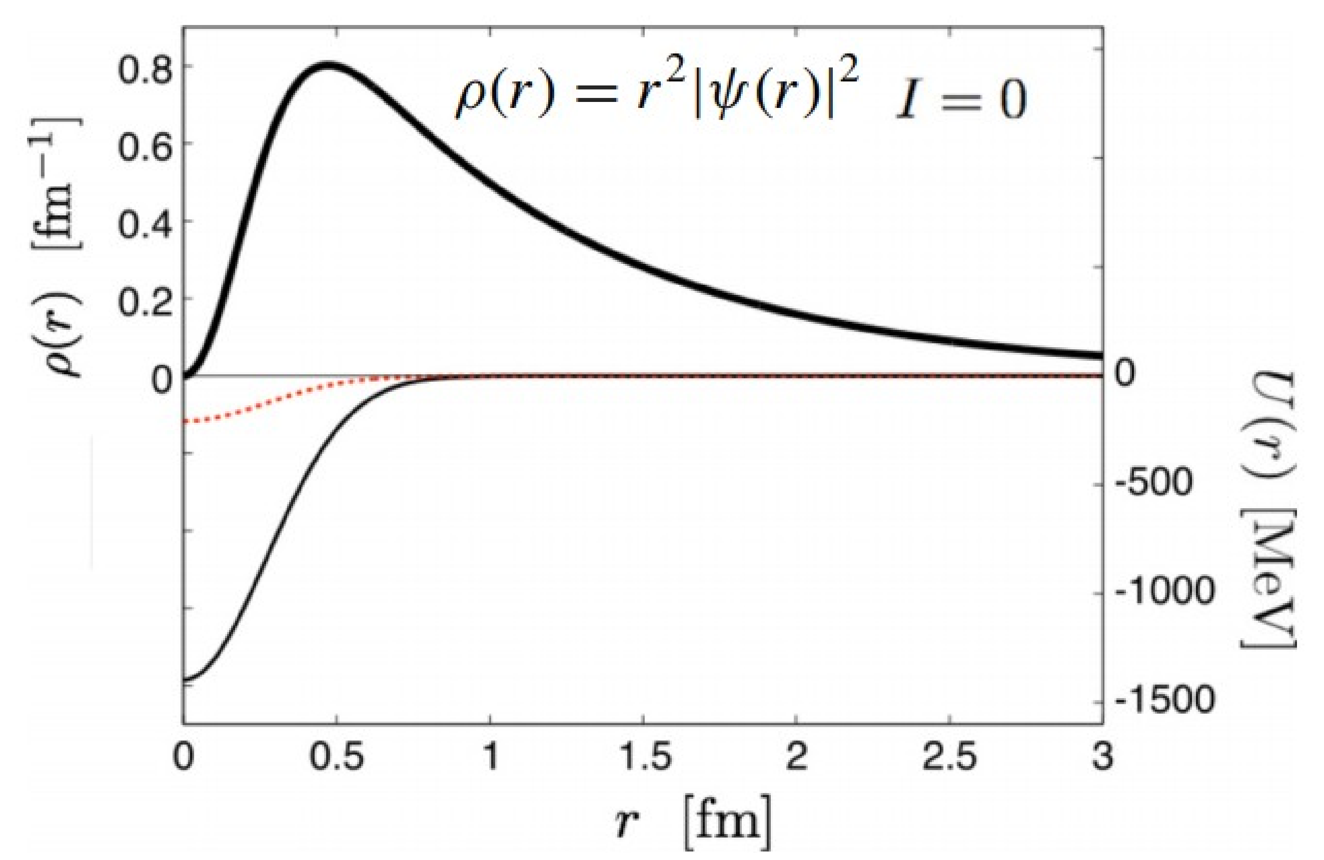
**Molina, Döring, PRD94 (2016)**
**(similar to other UchPT results)**

| | | |
|---|---|---|
| Lowest pole | $0.73^{+0.15}_{-0.10}$ | $0.27^{+0.15}_{-0.10}$ |
| Highest pole | $1.00^{+0.49}_{-0.25}$ | $0.00^{+0.49}_{-0.25}$ |

**Guo, Oller, PRD93,096001 (2016)**

✓ Spatial distribution of the higher mass pole

Miyahara, Hyodo, PRC93, 015201 (2016)



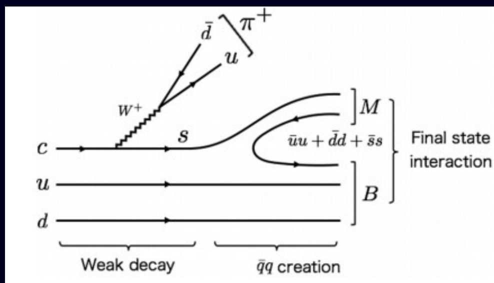

KN potential

$$\sqrt{\langle r^2 \rangle} = 1.44 \text{ fm}$$

significantly out of the potential range

# Other production reactions

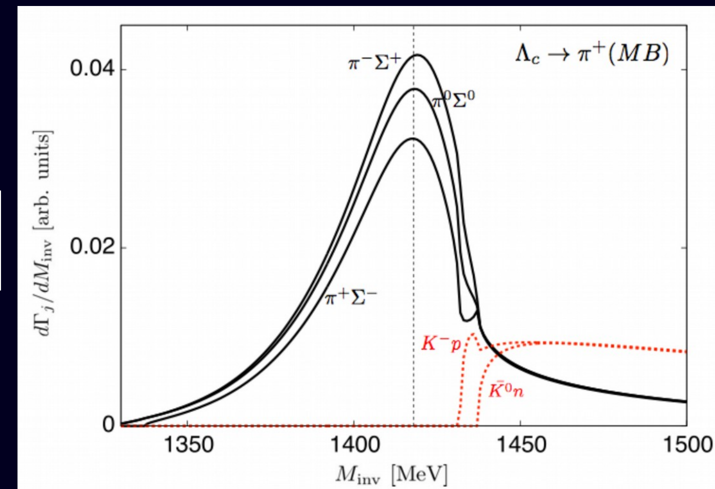
$\Lambda_c \to \pi^+ MB$ Miyahara, Hyodo, Oset, Phys. Rev. C 92 (5) (2015) 055204.




Dominated by I=0

$$|MB\rangle = \underbrace{|K^- p\rangle + |\bar{K}^0 n\rangle}_{} - \frac{\sqrt{2}}{3}|\eta\Lambda\rangle$$

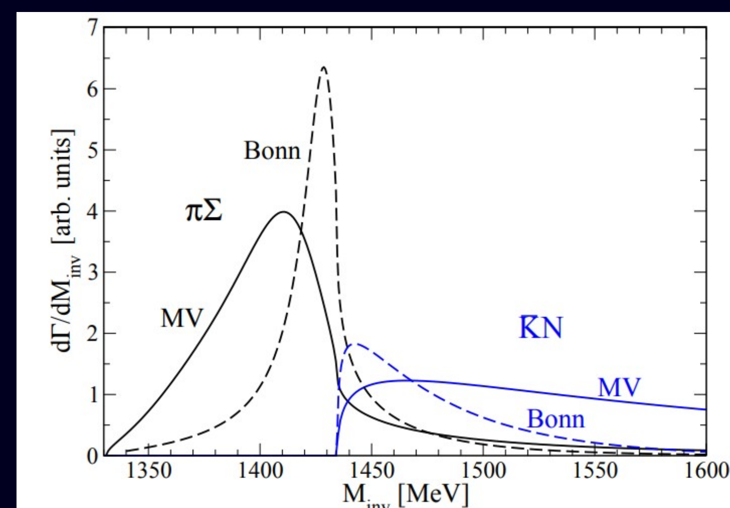
Weighs the highest mass pole




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

Roca, Mai, Oset, Meissner Eur.Phys.J. C75 (2015) no.5, 218

Also weighs more the highest mass pole

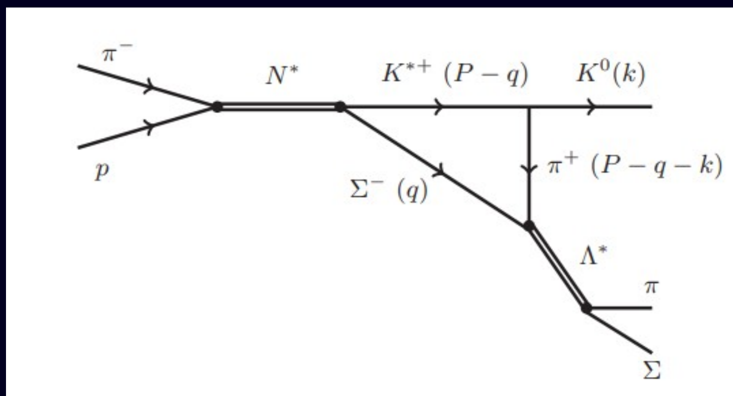


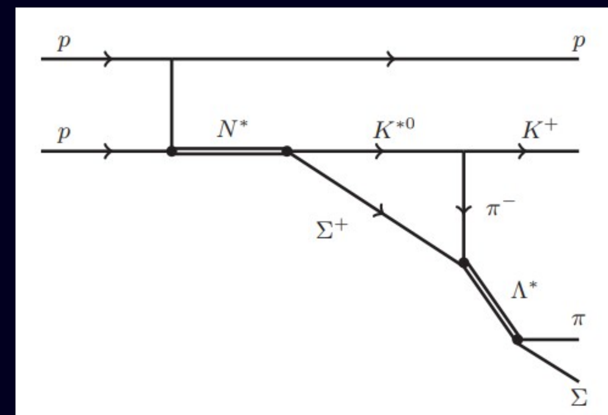
PHYSICAL REVIEW C **97**, 035203 (2018)

# Role of the triangle singularity in Λ(1405) production in the $\pi^- p \to K^0 \pi \Sigma$ and $pp \to pK^+ \pi \Sigma$ processes

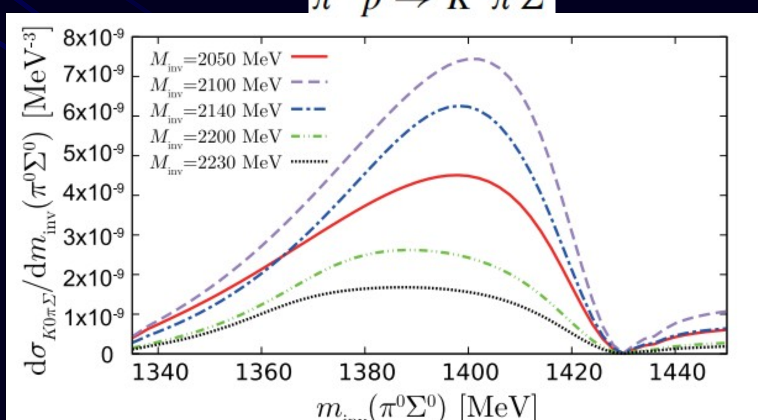
M. Bayar,[1,2,*] R. Pavao,[2] S. Sakai,[2] and E. Oset[2]

Weighs more lower pole ($\pi\Sigma$)

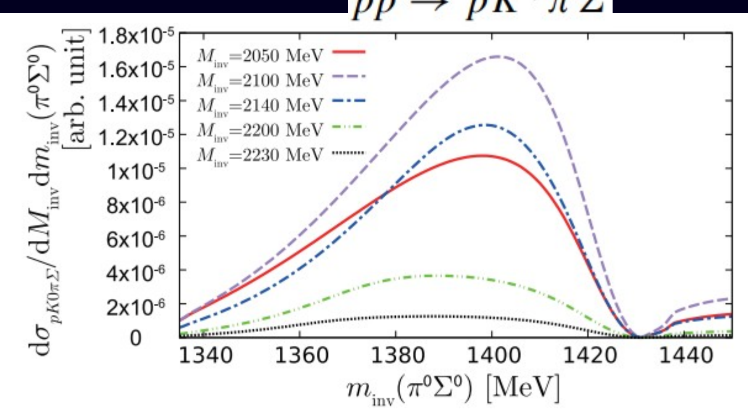



$\pi^- p \to K^0 \pi \Sigma$

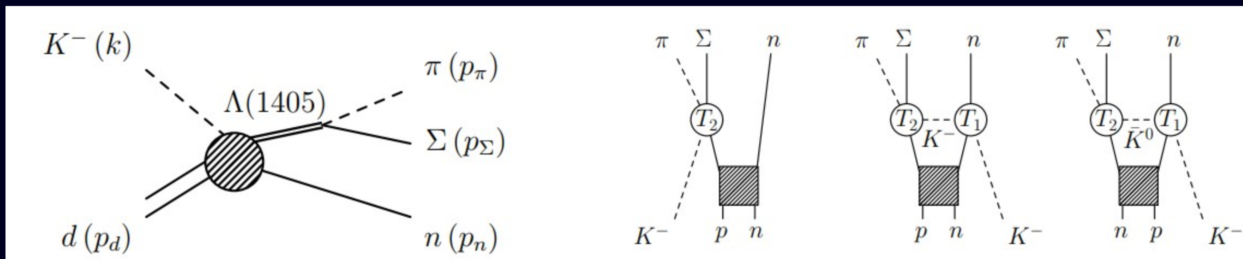


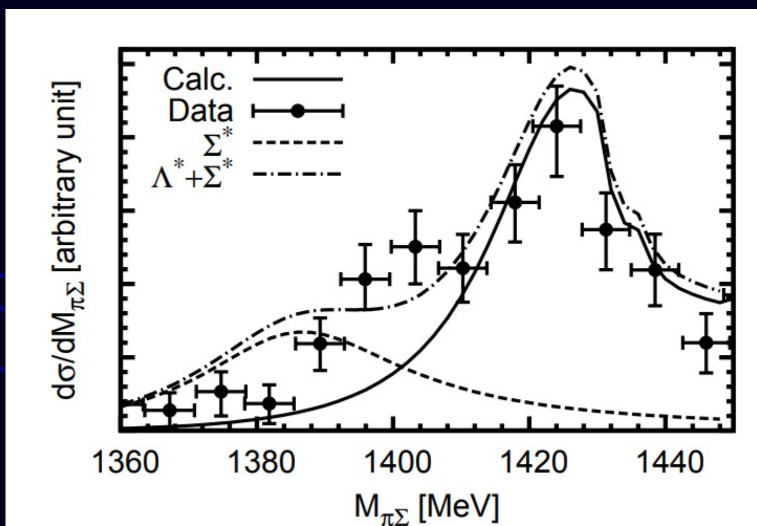

$pp \to pK^+ \pi \Sigma$



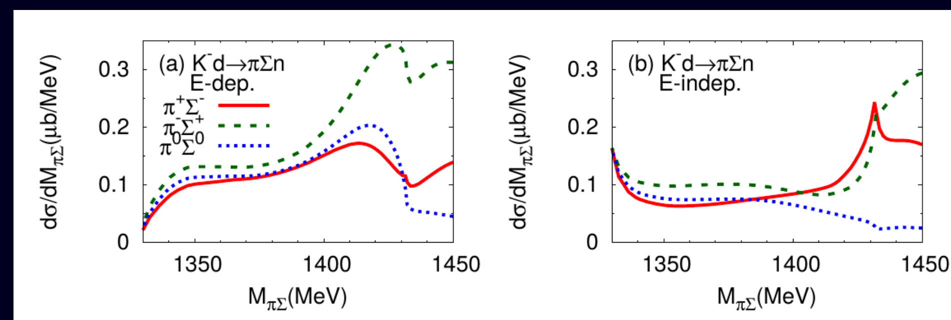
$$K^- d \rightarrow \pi \Sigma n$$

Jido, Oset, Sekihara, Eur.Phys.J. A42 (2009) 257-268
Jido, Oset, Sekihara, Eur.Phys.J. A49 (2013) 95




Exp. data from Braun et al., Nucl. Phys. B 129, 1 (1977)




Ohnishi, Ikeda, Hyodo, Weise PRC93 (2016)

# Summary

✓ $\Lambda(1405)$ well established but until recently poorly understood in quark models

✓ SU(3) chiral dynamics and unitarity produce a **double pole** structure, dynamically generated from $\pi\Sigma$ and $\bar{K}N$ (basically)

- Higher mass pole position (closer to $\bar{K}N$ threshold) better detemined

(for this it is important the datum on $K^-p$ scattering length, SIDDHARTA)

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

✓Different reactions can weigh differently the different MB 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

- WARNING for experimentalists: two poles are not always necessary to fit the data: depending on the reaction it might weigh much more one of the two poles

✓ Wide evidence for the **molecular picture**, (specially for the highest mass pole)

# BACKUP SLIDES

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)

$\alpha_i$ coefficients are fitted

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

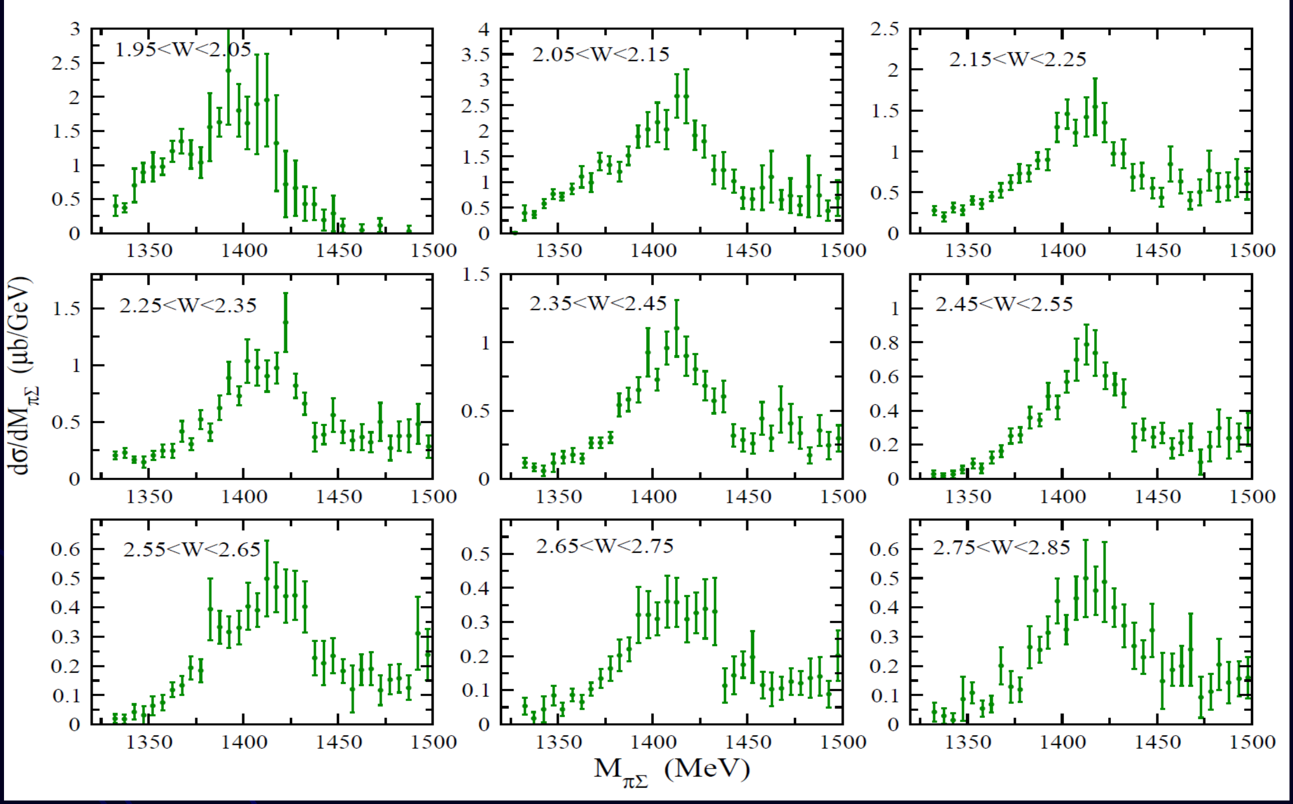
# Fit to photoproduction data

$\gamma p \to K^+ \pi^\pm \Sigma^\mp$ $\gamma p \to K^+ \pi^0 \Sigma^0$

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

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

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

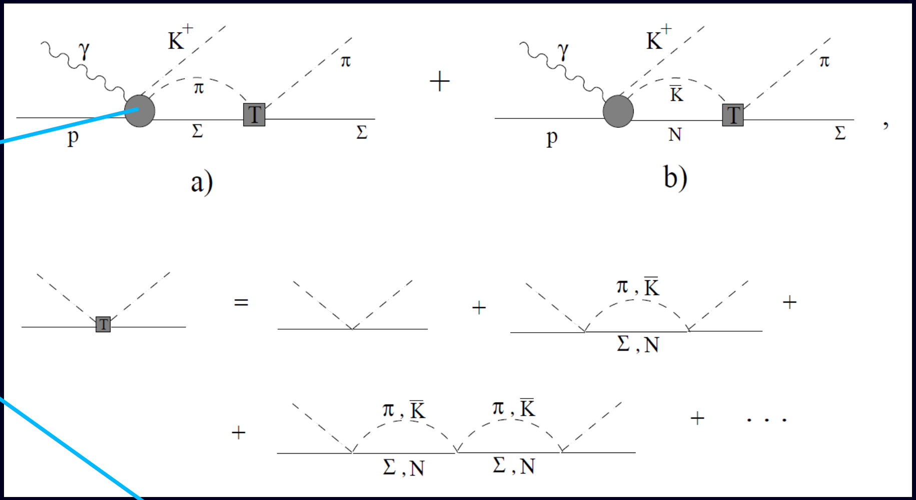



Clear $\Lambda(1405)$ shape, but how to extract its physical properties given its double pole structure?

# Our analysis:

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

Production mechanism
**(whatever)**



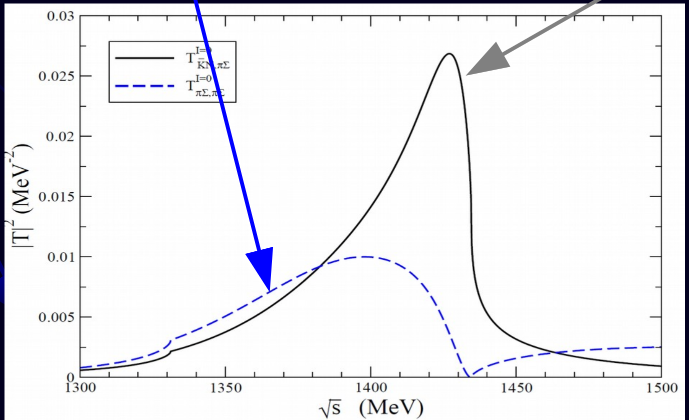

General expression for the photoproduction scattering amplitude:

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

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

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)

$\alpha_i$ coefficients are fitted

Results of the global fit:

| $\alpha^0_{11}$ | $\alpha^0_{12}$ | $\alpha^0_{22}$ | $\alpha^1_{11}$ | $\alpha^1_{12}$ | $\alpha^1_{13}$ | $\alpha^1_{22}$ | $\beta_1$ | $\beta_2$ | $\beta_3$ |
|---|---|---|---|---|---|---|---|---|---|
| 1.037 | 1.466 | 1.668 | 0.85 | 0.93 | 1.056 | 0.77 | 1.187 | 0.722 | 1.119 |

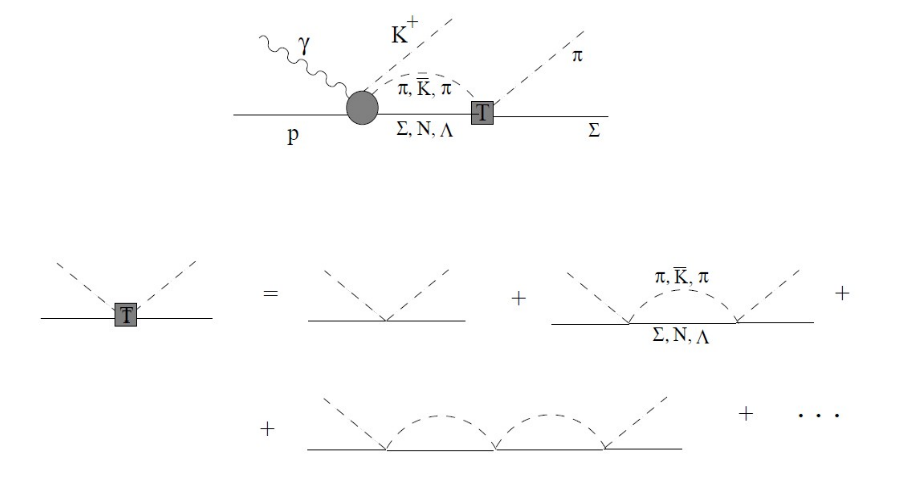
(order 1)

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

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

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

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




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

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

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

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

## Prediction. Not fitted!

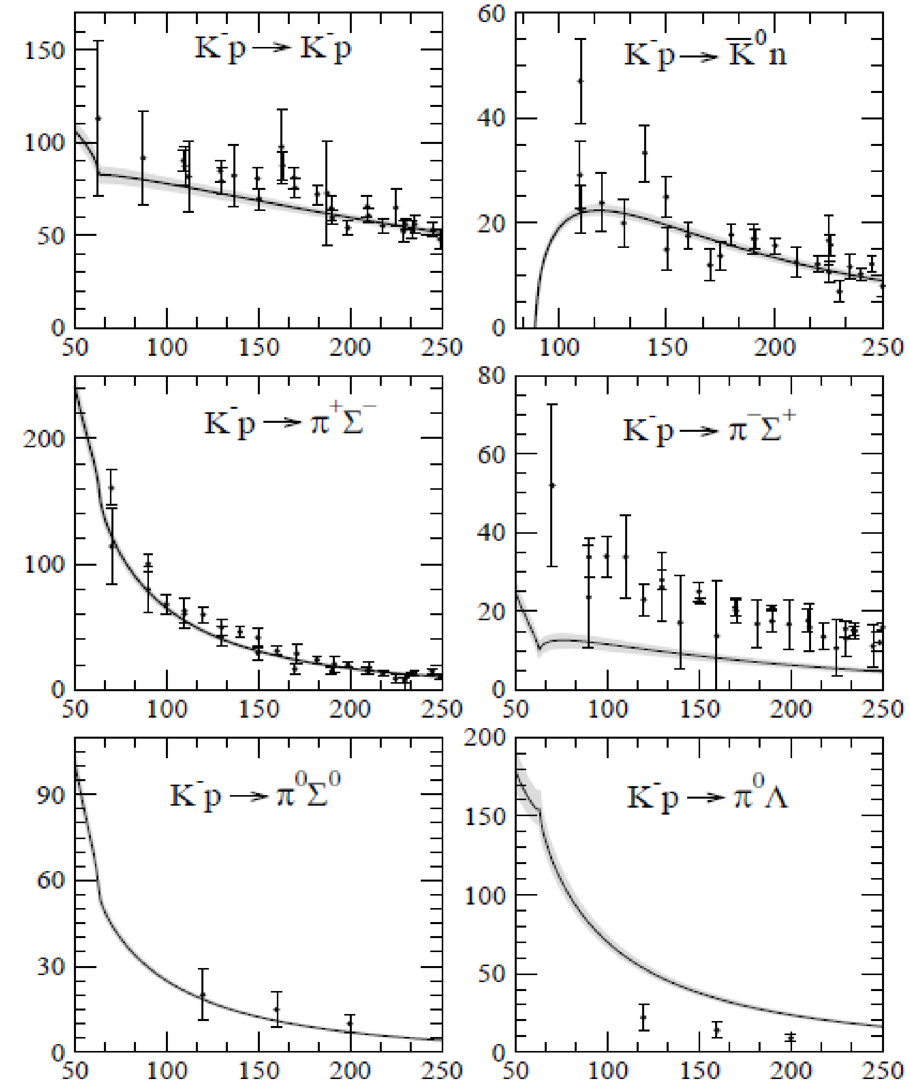



FIG. 10. Predicted $K^- p$ cross sections (in mb). Experimental data from ref. [53].

1s kaonic hydrogen energy shift:

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

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

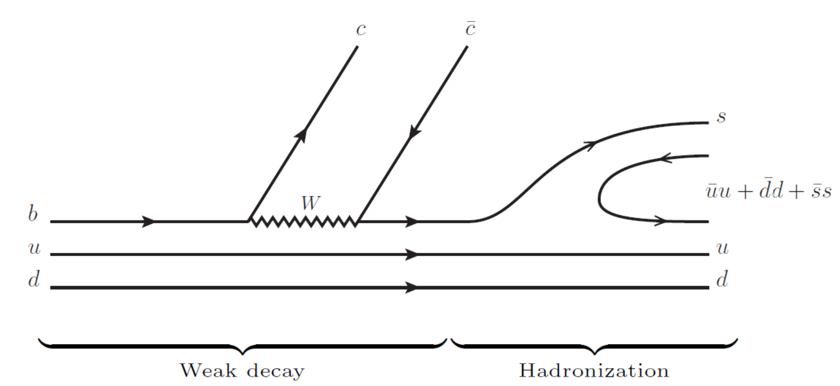
Exp.: SIDDHARTA exp. @ Daphne, PLB704, 113 (2011)

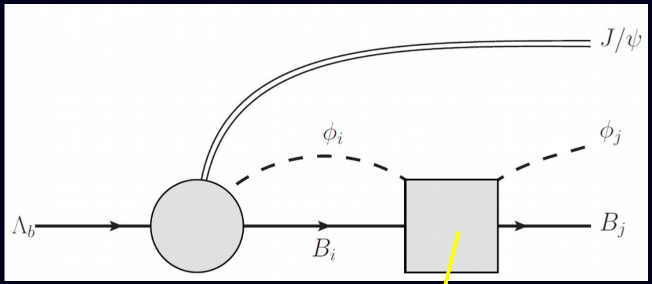
$$(283 \pm 42) - i(271 \pm 55) \text{ eV.}$$

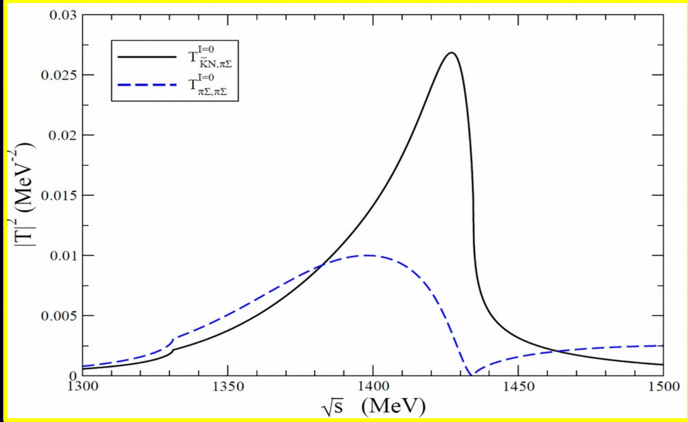
# The $\Lambda(1405)$ in $\Lambda_b \to J/\psi\ \Lambda(1405)$

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

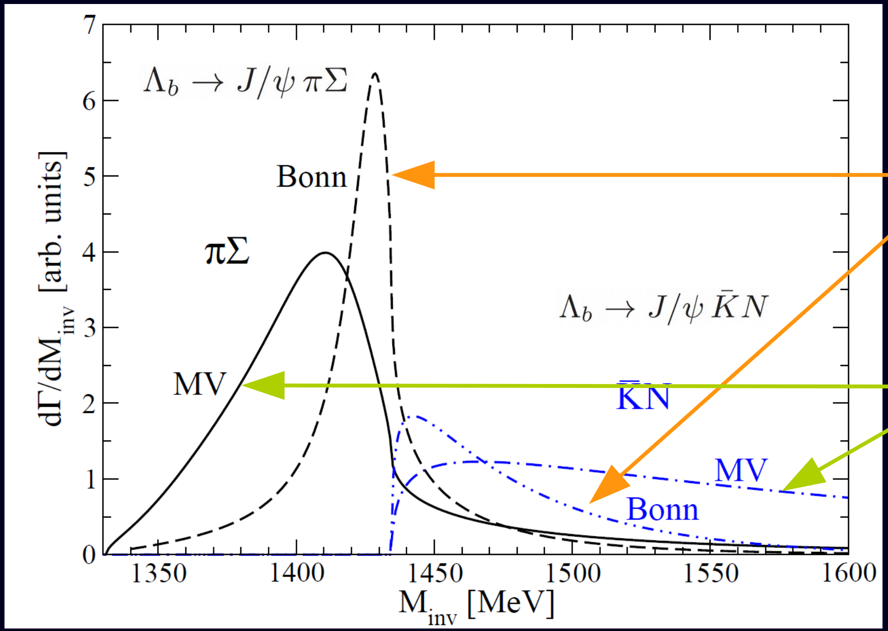
$\Lambda_b \to J/\psi\,\pi\Sigma$ $\Lambda_b \to J/\psi\,\bar{K}N$



## 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**