Vector meson-baryon dynamics on meson production reactions around 2 GeV

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Barcelona, November 21, 2013

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Outline

- Introduction
- Vector meson – baryon interaction: why?
- Coupled-channel model (using hidden gauge formalism)
- Manifestations of vector meson-baryon dynamics
  - ✓ role of coupled-channels in $\gamma\, p \rightarrow K^0\, \Sigma^+$, $\gamma\, n \rightarrow K^0\, \Sigma^0$
  - ✓ role of coupled channels in in $\gamma\, p \rightarrow K^{*0}\, \Sigma^+$
  - ✓ K* and ω meson properties in the medium
- Conclusions

Describing the dynamics of hadrons at low energies from the QCD Lagrangian (*quark* and *gluon* d.o.f.) is a highly non-perturbative problem

↓

One may address this problem through the modern perspective of Chiral Perturbation Theory (χPT): effective theory with hadron degrees of freedom which respects the symmetries of QCD, in particular the (spontaneously broken) chiral symmetry.

In ordinary χPT:

→ convergence restricted to low energy physics

→ not adequate close to bound-states (pole in the T-matrix)

↓

Unitarized non-perturbative schemes (UχPT) allow to extend the predictive power of the chiral theories.

↓

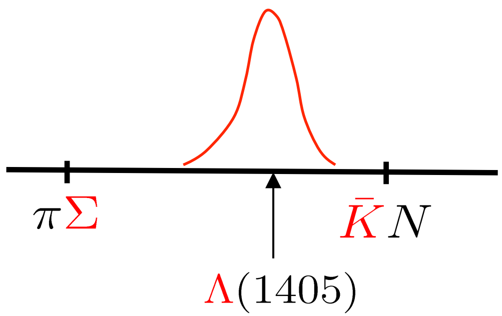
With these non-perturbative methods several known resonances have been generated as poles in the scattering amplitude (quasi-bound states) and many hadron reaction cross sections have been nicely reproduced.

➔ e.g. the $\Lambda(1405)$!

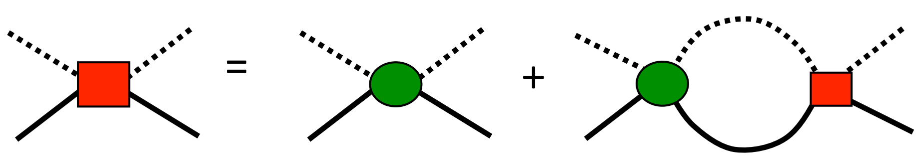
The Λ(1405)

(a nice example of the success of non-perturbative chiral approaches)

Kbar-N scattering in the isospin I=0 channel is dominated by the presence of the Λ(1405), located only 27 MeV below the Kbar-N threshold



It emerges as a quasi-bound state (below the Kbar-N threshold and embedded in the πΣ continuum) of the unitarized pseudoscalar-baryon scattering amplitude employing the chiral Lagrangian to obtain the kernel potential



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

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

Vector Mesons. Why?

- Many new data on meson production reactions around W ~2 GeV and beyond.

- Measurements with vector-mesons in the final state are currently available
  $\gamma N \rightarrow \rho(\pi\pi)N$, ωN, ϕN, $K^* Y$, … ELSA, J-LAB,

→ Theoretical models need to include vector meson – baryon channels .

The introduction of vector mesons as building blocks brings a new perspective into the nature of higher mass mesons and baryons.

SU(6):

C. Garcia-Recio, J. Nieves, L.L. Salcedo, Phys.Rev. D74 (2006) 034025
D. Gamermann, C. Garcia-Recio, J. Nieves, L.L. Salcedo, Phys.Rev. D84 (2011) 056017.

Hidden gauge formalism:

S. Sarkar, B.X. Sun, E. Oset, M.J. Vicente Vacas, Eur.Phys.J. A44 (2010) 431.
E. Oset, A. Ramos, Eur.Phys.J. A44 (2010) 445.
E.J. Garzon, E. Oset, Eur.Phys.J. A48 (2012) 5.
E.J. Garzon, J.J. Xie, E. Oset, arXiv:1302.1295 [hep-ph].
K.P. Khemchandani, H. Kaneko, H. Nagahiro, A. Hosaka, Phys.Rev. D83 (2011) 114041.
K.P. Khemchandani, A. Martinez Torres, H. Kaneko, H. Nagahiro, A. Hosaka, Phys. Rev. D84 (2011) 094018.

Hidden gauge formalism for vector mesons, pseudoscalars and photons

Bando et al. Phys. Rev. Lett. 54, 1215 (85); Phys. Rep. 164, 217 (88)

The hidden-gauge formalism to deal with vector mesons is a useful and internally consistent scheme which:

- Deals simultaneously with vector and pseudoscalar mesons
- Implements chiral symmetry naturally
- Leads to the same lowest order Lagrangian for pseudoscalar mesons
- Reproduces all the empirically successful low-energy relations of the ρ meson (universal coupling, KSFR relation, vector meson dominance,…)

Here, we focus on the interaction of vector mesons

$$V_\mu = \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \Phi \end{pmatrix}_\mu$$

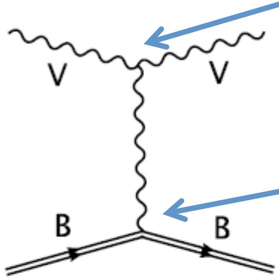
with baryons

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

How to build a vector-baryon scattering amplitude $T_{VB\to V'B'}$

E. Oset, A. Ramos, Eur.Phys.J. A44 (2010) 445-454.

1. Kernel:



$$\mathcal{L}_{III}^{(3V)} = ig\langle(\partial_\mu V_\nu - \partial_\nu V_\mu)V^\mu V^\nu\rangle = ig\langle(V^\mu\partial_\nu V_\mu - \partial_\nu V_\mu V^\mu)V^\nu\rangle$$

$$\mathcal{L}_{BBV} = g\left(\langle\bar{B}\gamma_\mu[V^\mu, B]\rangle + \langle\bar{B}\gamma_\mu B\rangle\langle V^\mu\rangle\right)$$

$$g = \frac{M_V}{2f}$$

In the limit $q^2/M_V^2 \to 0$ we obtain for the VB→VB amplitude:

$$V_{ij} = -C_{ij}\,\frac{1}{4f^2}\,(k^0 + k'^{\,0})\;\vec{\epsilon}\,\vec{\epsilon}\,'$$

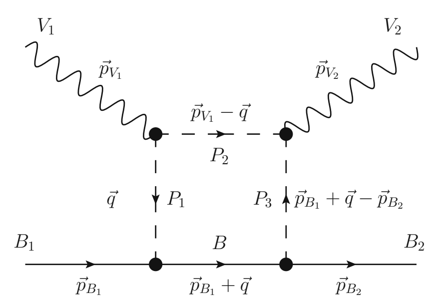
vector meson energies

→ the same S-wave vector-baryon amplitude as in the pseudoscalar-baryon case!
(spin independent: degenerate 1/2- and 3/2- baryons)

Including also Pseudoscalars:

E.J. Garzon, E. Oset, Eur.Phys.J. A48 (2012) 5.

(degeneracy removed)



2. Unitarization: We solve the Bethe-Salpeter equation in coupled channels (s-wave)

T = V + V G T

Coupled channels in the N* (I=1/2,S=0) sector:

ρN(1710) *ωN(1721)* *ϕN(1958)* *K*Λ(2010)* *K*Σ(2087)*

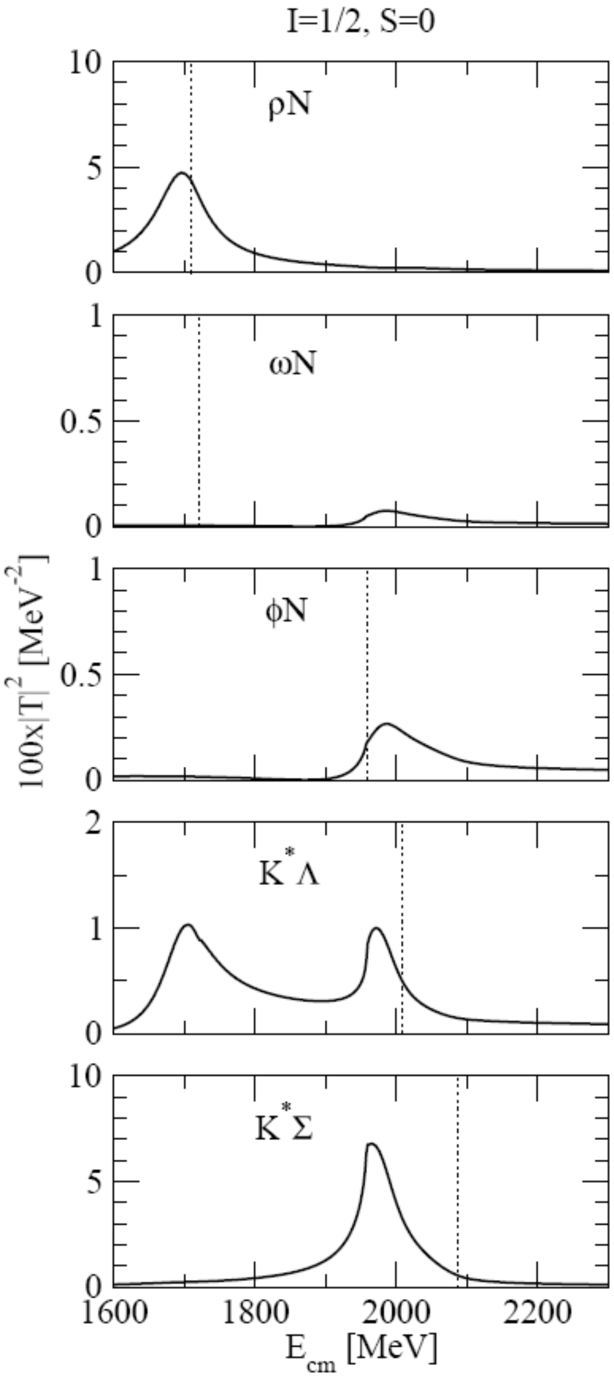
3. Regularization of loop function: $G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$

$$
\begin{aligned}
G_l \;=\; & \frac{2M_l}{16\pi^2}\Big\{a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} + \\
& + \frac{\bar{q}_l}{\sqrt{s}}\Big[\ln(s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \\
& - \ln(-s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s})\Big]\Big\}
\end{aligned}
$$

$a_l(\mu) \simeq -2$ “natural size (μ~700 MeV)

J.A. Oller and U.G. Meissner, Phys. Lett. B500 (2001) 263

[the G function takes into account the mass distribution (width) of the vectors ρ and K*]



N* $J^P = 1/2^-, 3/2^-$ (degenerate)

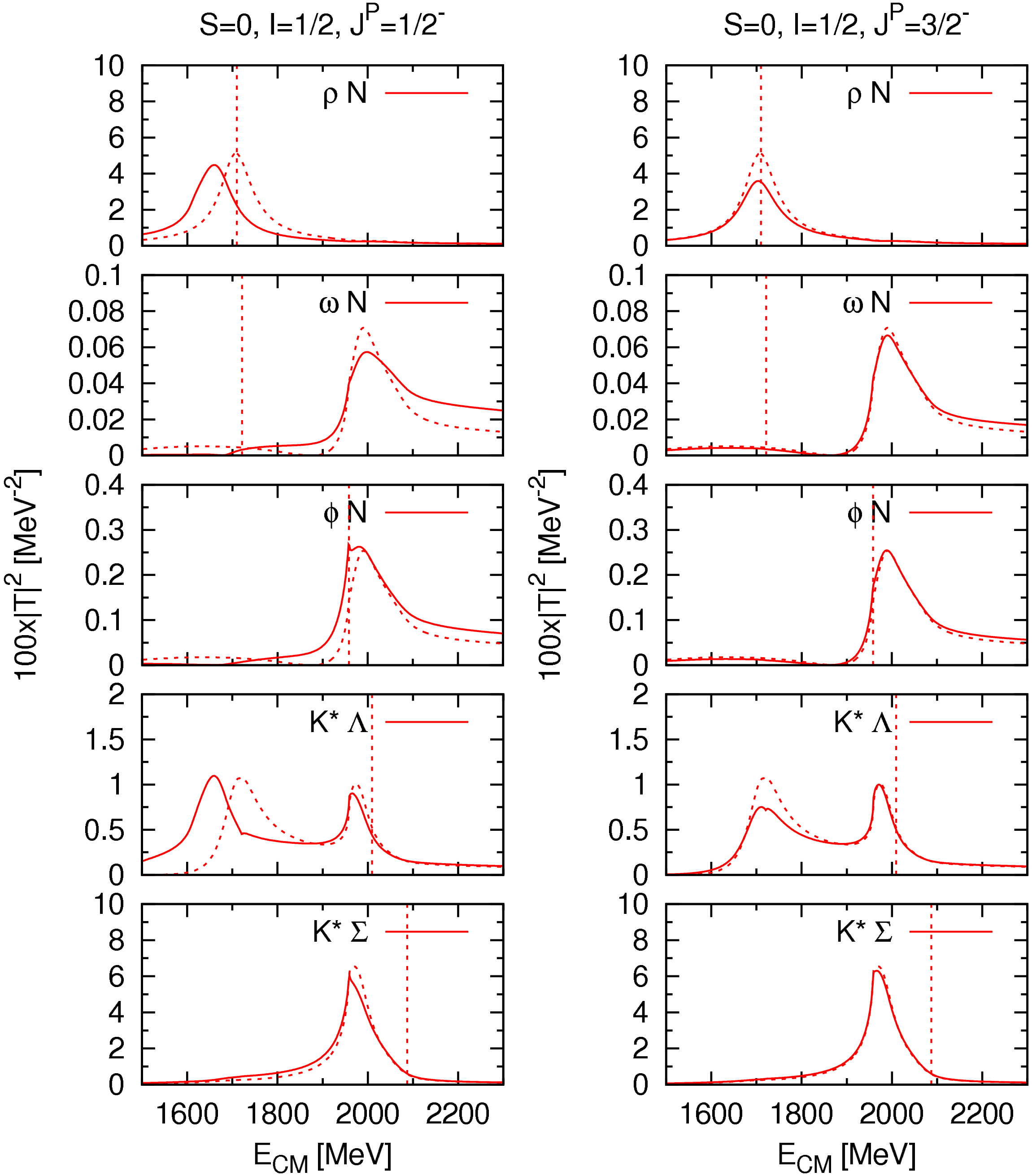
z_R	$1696^{(*)}$		$1977 + i53$	
	g_i	$\|g_i\|$	g_i	$\|g_i\|$
$\rho N(1710)$	$3.2 + i0$	3.2	$-0.3 - i0.5$	0.6
$\omega N(1721)$	$0.1 + i0$	0.1	$-1.1 - i0.4$	1.2
$\phi N(1958)$	$-0.2 + i0$	0.2	$1.5 + i0.6$	1.7
$K^*\Lambda(2010)$	$2.3 + i0$	2.3	$2.2 - i0.9$	2.3
$K^*\Sigma(2087)$	$-0.6 + i0$	0.6	$3.9 + i0.2$	3.9

We obtain a N* resonance at
1700 MeV coupling mostly to ρN
and another at
1977 MeV coupling mostly to $K^*\Sigma$ and $K^*\Lambda$

N*

$J^P = 1/2^-$ | $J^P = 3/2^-$

E.J. Garzon, E. Oset, Eur.Phys.J. A48 (2012) 5



The inclusion of pseudoscalar-baryon channels in s-wave does not change the picture appreciably, but…

… coupling to pseudoscalars in d-wave and including decuplet baryons, e.g.
ρN(s), πN(d), $\pi\Delta$(s), $\pi\Delta$(d)
leads to new resonances
➔ N*(1520) coupling to ρN

	$N^*(1520)D_{13}$		$N^*(1700)D_{13}$	
Pole	1467+i83		1665+i78	
Channel	g_i	$\lvert g_i\rvert$	g_i	$\lvert g_i\rvert$
$\rho N(s)$	6.18-1.63i	6.39	1.49+0.42i	1.55
$\pi\Delta(s)$	0.88+0.76i	1.14	-0.39+0.12i	0.41
$\pi\Delta(d)$	-0.75-0.14i	0.77	0.50-0.50i	0.70
$\pi N(d)$	-1.51-0.51i	1.60	-0.09-0.94i	0.94

E.J. Garzon, J.J. Xie, E. Oset, Phys.Rev. C87 (2013) 055204

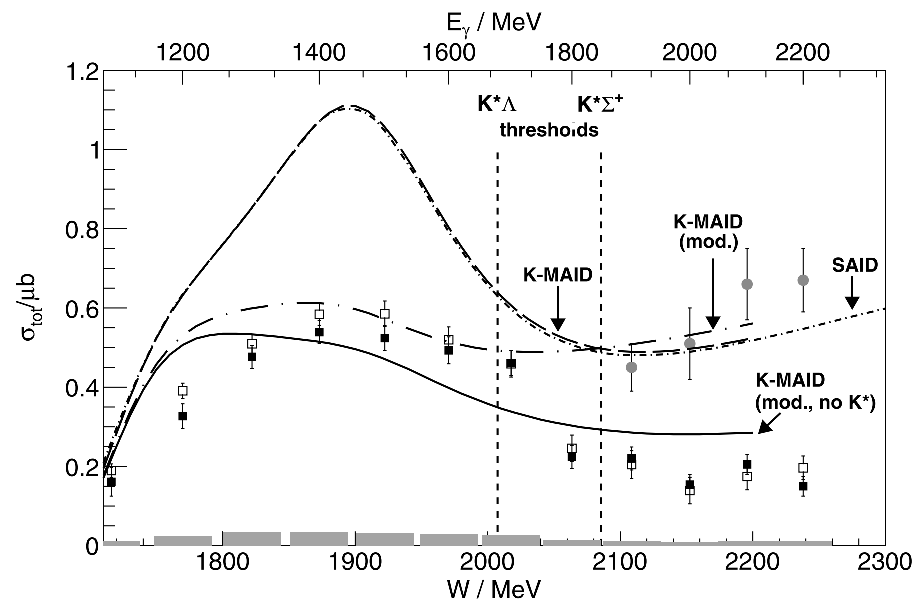
Manifestations of vector-meson dynamics in the $\gamma\, p \rightarrow K^0\, \Sigma^+$, $\gamma\, n \rightarrow K^0\, \Sigma^0$ reactions

R. Ewald et al. (CBELSA/TAPS Collaboration)
Phys. Lett. B713 (2012) 180-185.

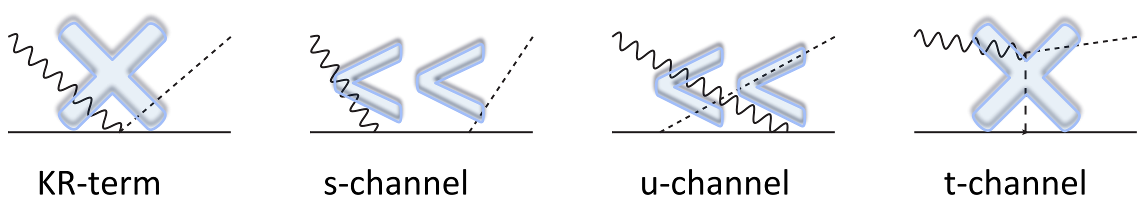
A sharp downfall occurs in between the $K^*\Lambda$ and $K^*\Sigma$ thresholds

Partial wave analyses and models (including πN, ηN, $\rho(\pi\pi)$N, KΛ, KΣ, ωN but not $K^*\Lambda$ and $K^*\Sigma$) do not reproduce the observed behavior.

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



Neutral meson K^0 is measured → tree level diagrams either zero or not too important



→ This process enhances the relevance of loops. The consideration of coupled $K^*\Lambda$ and $K^*\Sigma$ channels in these loops may provide an explanation!

On the cross section ratio σ_n/σ_p in η photoproduction

M. Döring, K. Nakayama, Phys.Lett.B683 (2010) 145

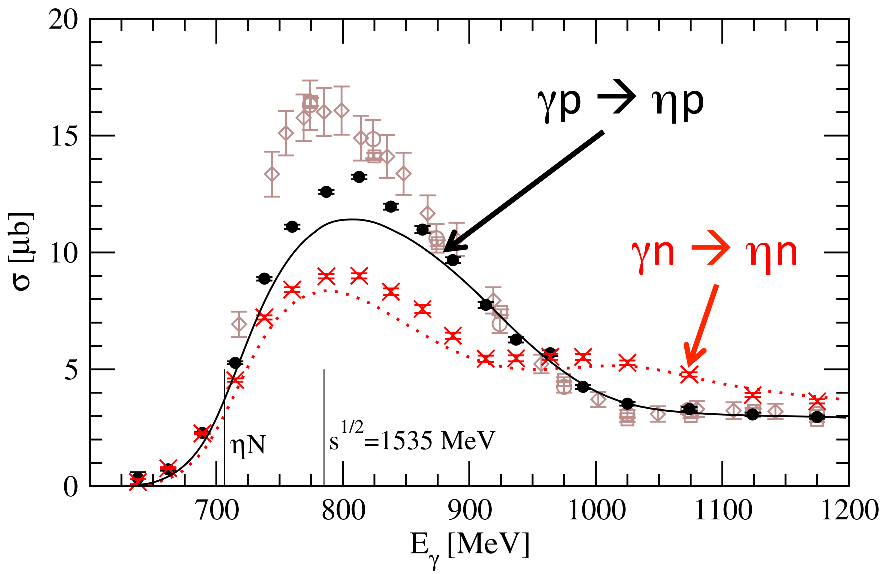
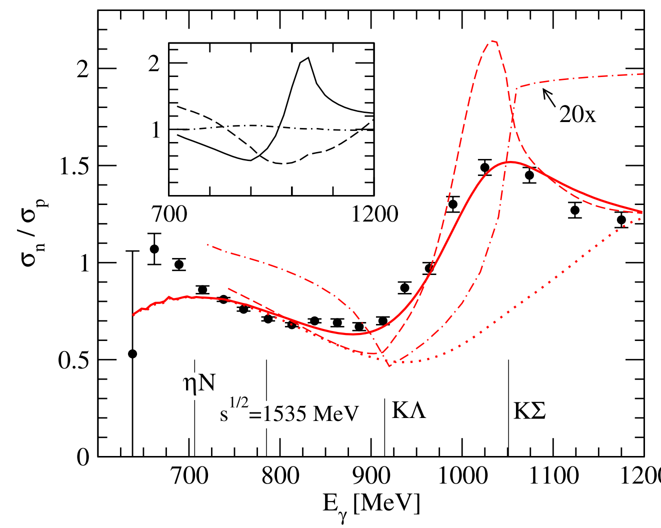
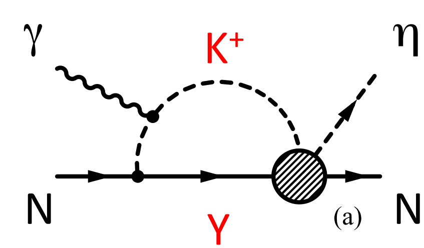


Fig. 2. Present result (Fermi folded) for the photoproduction on the quasi-free proton (solid line) and neutron (dotted line). The data are from Ref. [19] for the photoproduction on the quasi-free proton (solid circles) and neutron (crosses). The data for the free proton are also shown (open symbols, same as in Fig. 1). The vertical lines indicate the threshold energy of $\sqrt{s} = m_\eta + M_N$ for the free process and the nominal position of the $N^*(1535)$.



Destructive interference between $K^+\Sigma^0$ and $K^+\Lambda$ in γp → ηp

No interference (only $K^+\Sigma^-$) in γn → ηn



Model for the γ N → K^0 Σ reaction

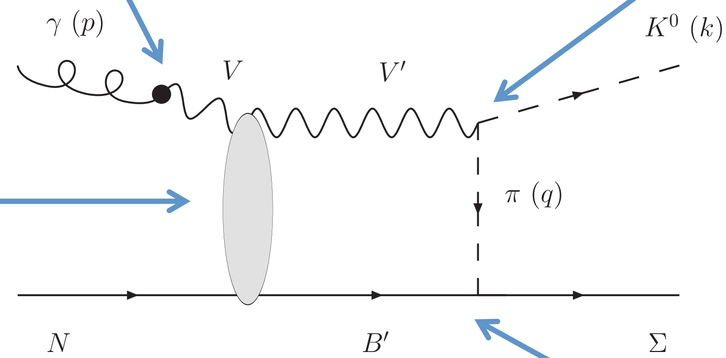
A. Ramos, E. Oset, Phys. Lett. B (2013) 287

Since tree-level diagrams are not contributing, we can obtain the γ N → K^0 Σ process from:

$$\mathcal{L}_{\gamma V} = -M_V^2 \frac{e}{g} A_\mu \langle V^\mu Q \rangle$$

$$\mathcal{L}_{VPP} = -ig\langle [P, \partial_\mu P] V^\mu \rangle$$

$$t_{VN \to V'B'}$$



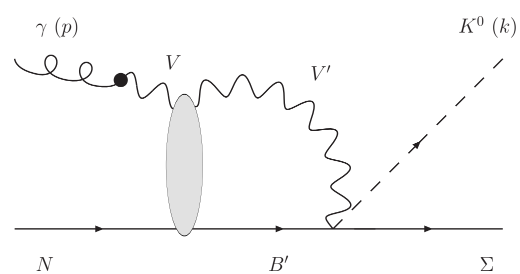
*V'B'=K*Y*

$$\mathcal{L}_{PBB} = \frac{1}{2}(D+F)\langle \bar{B}\gamma^\mu\gamma^5 u_\mu B\rangle + \frac{1}{2}(D-F)\langle \bar{B}\gamma^\mu\gamma^5 B u_\mu\rangle$$

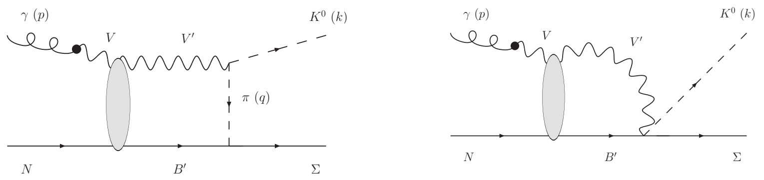
$$D = 0.795,\ F = 0.465$$

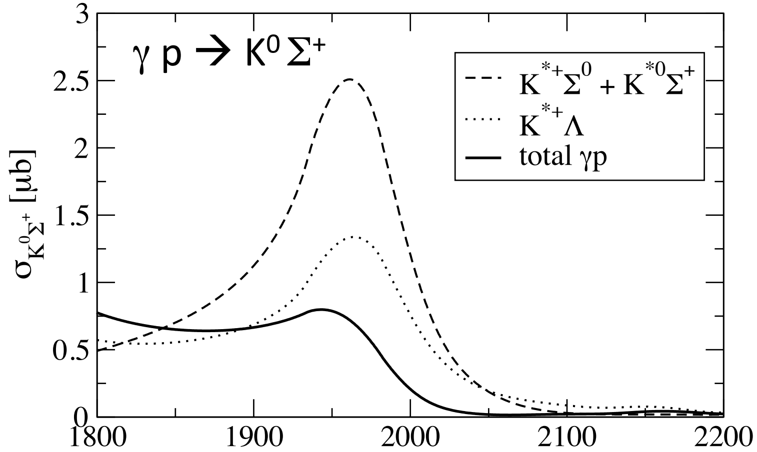
+ Form factor at the Yukawa-type vertex

Also:



Effect of coupled channels: V'B'= K*Λ, K*Σ

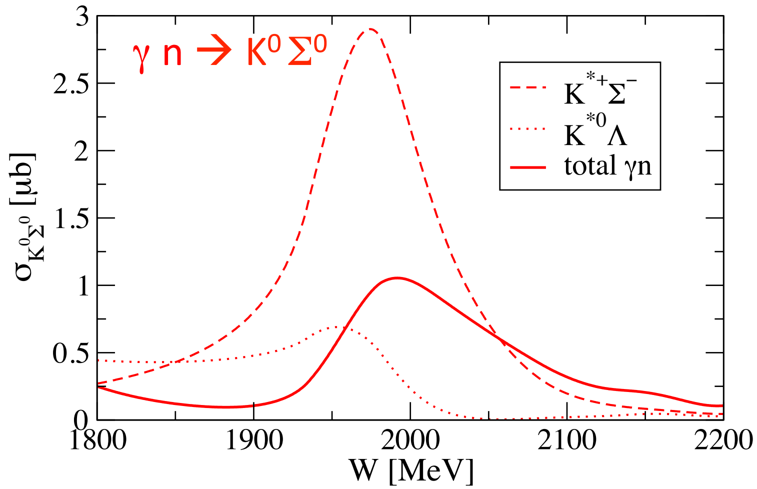




$\gamma\, p \to K^0\, \Sigma^+$

Destructive interference between $K^*\Sigma$ and $K^*\Lambda$ amplitudes, of similar size and shape.

→ Abrupt downfall of the charged cross section.



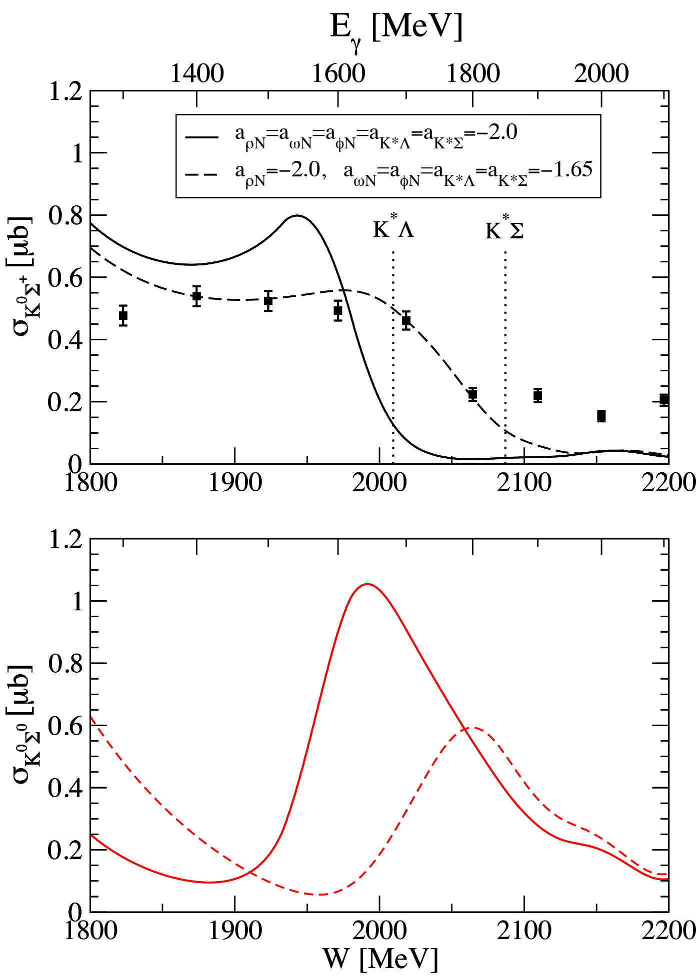
$\gamma\, n \to K^0\, \Sigma^0$

$K^*\Sigma$ and $K^*\Lambda$ amplitudes have a different size.

→ Neutral cross section retains the peak of the resonance.

Comparison to cross section data

R. Ewald et al. (CBELSA/TAPS Collaboration)
Phys. Lett. B713 (2012) 180-185



$J^P = 1/2^-, 3/2^-$

——— M_R = 1977 MeV Γ_R = 64 MeV

VB model adjusted to reproduce downfall:

- - - - M_R = 2035 MeV Γ_R = 125 MeV

✓ N*(2080) (3/2-) and N*(2090) (1/2-) were in earlier PDG versions…

✓ N*(2080) (3/2-) leads to good description of LEPS data for γ p ➔ K^+ Λ(1520)

J.J. Xie and J. Nieves, Phys. Rev. C82 (2010) 045205

✓ it appears in other VM models too:

D. Gamermann, C. Garcia-Recio, J. Nieves, L.L. Salcedo, Phys.Rev. D84 (2011) 056017

K.P. Khemchandani, H. Kaneko, H. Nagahiro, A. Hosaka, Phys.Rev. D83 (2011) 114041

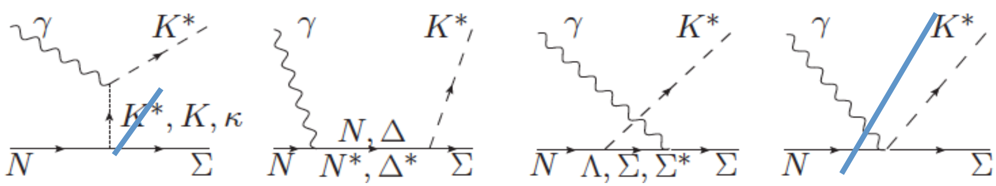
Another reaction: $\gamma\, p \rightarrow K^{*0}\, \Sigma^{+}$

- Data from CLAS and CBELS/TAPS (discrepancies)

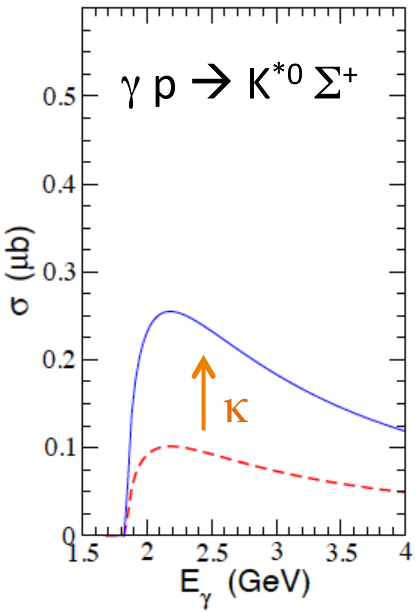
  I. Hleiqawi et al, Phys.Rev.C75 (2007) 042201 (R); 76 (2007) 039905 (E)

  M. Nanova et al, Eur.Phys.J. A 35 (2008) 333

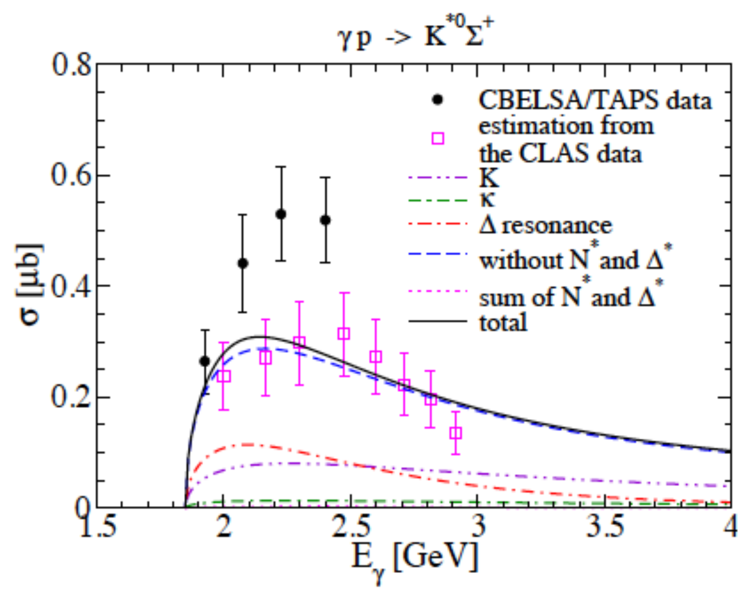
- A few theoretical models exist, based on tree-level Born approximation



Y. Oh, and H. Kim. Phys.Rev.C74 (2006) 015208



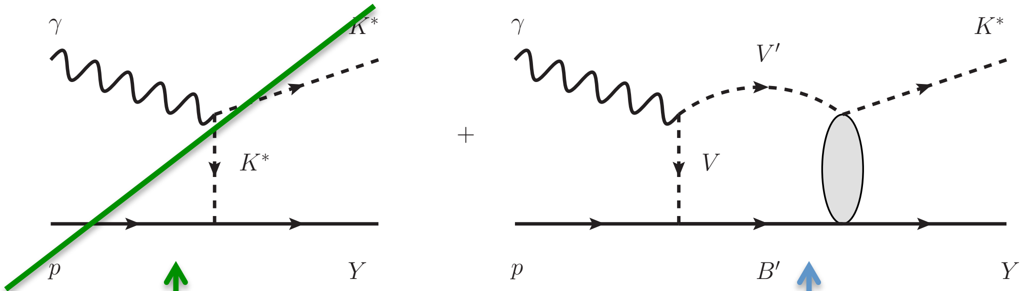
S-H. Kim, A. Hosaka, S-i. Nam, H-C. Kim, arXiv:1310.6551 [hep-ph]



The γ p → K^{*0} Σ^+ reaction from VB dynamics

A. Ramos, E. Oset, in preparation

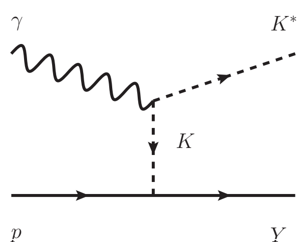
(t-channel mechanism)



No t-channel tree-level term (K* has zero charge!)

→ the coupled-channel loop acquires a dominant role!

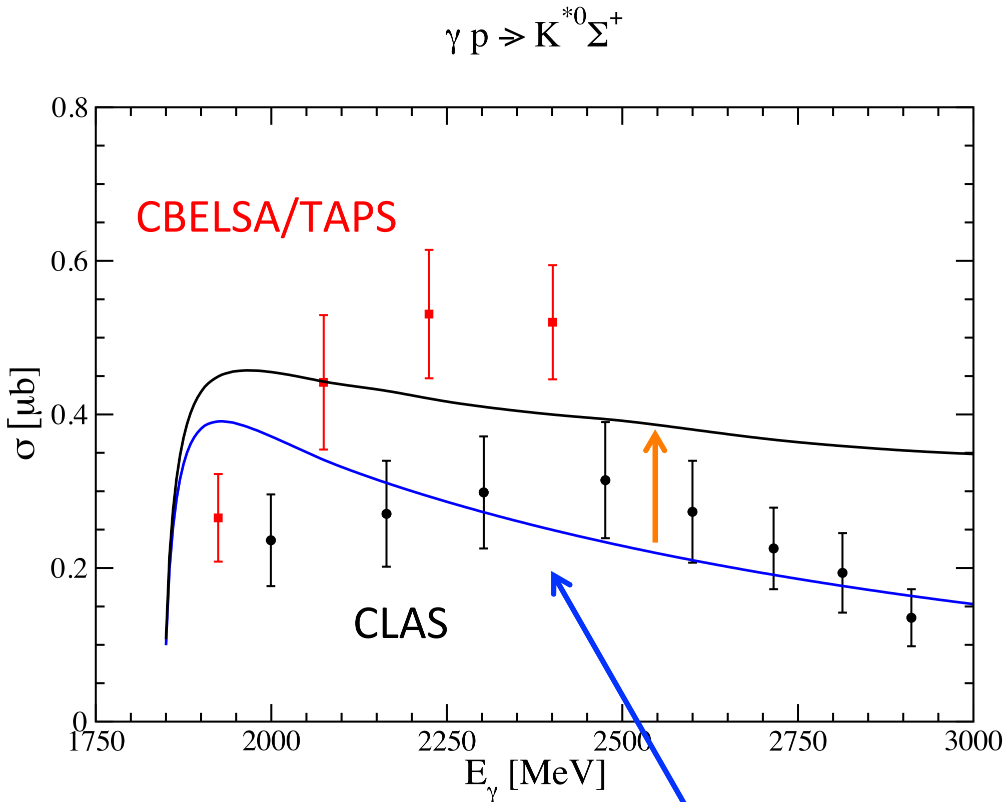
A tree-level term of the type γKK* (anomalous) also contributes (unitarization of this contribution is negligible)

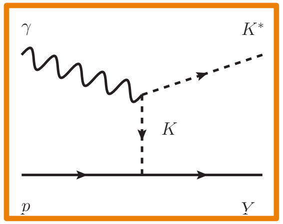


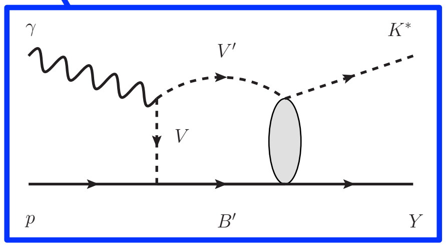
→ smooth background contribution free from coupled-channel interference effects

Results for $\gamma\, p \rightarrow K^{*0}\, \Sigma^{+}$

(preliminary!)







Missing mechanism in previous works!

Conclusions

- The combination of Chiral dynamics with non-perturbative unitary techniques has revealed as a powerful method to investigate the nature of hadrons.

→ Poles in the amplitudes correspond to dynamically generated resonances. (many of the known baryon resonances can be interpreted this way)

- Vector mesons should enter the scheme in order to interpret the resonances and reactions for $W \geq 2$ GeV.

- The reaction $\gamma\, p \rightarrow K^0 \Sigma^+$ around 2 GeV is a nice example that demonstrate the important role of vector mesons in coupled channels.

→ Our model for the VB interaction reproduces the rapid downfall of the $\gamma\, p \rightarrow K^0 \Sigma^+$ reaction, from an interference between amplitudes containing intermediate $K^* \Sigma$ and $K^* \Lambda$

→ A fit to the CBELSA/TAPS data allows to predict the position of a resonance at 2030 MeV

→ Predictions are given for $\gamma\, n \rightarrow K^0 \Sigma^0$

- The coupled-channel vector-baryon interaction has also revealed important in the study of the reaction $\gamma\, p \rightarrow K^{*0} \Sigma^+$

→ More work is needed…