Baryon Resonances

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Baryon ground states and excited states

Dynamically generated baryon states and chiral dynamics

Λ(1405) old predictions, recent results

Vector-Baryon molecules

States of two mesons and one baryon

Basic baryons in Nuclear Physics: proton and baryons of its SU(3) octet
(3q in ground state)

Basic mesons .... : pion and mesons of its octet
(q qbar in ground state)

These are ground states hadrons

We consider that the Δ and members of the baryon decuplet or ρ and members of the vector octet are spin realignments of the quarks in their ground state.

What about baryon resonances?

Logical answer: excitations of the quarks. Essence of quark models.

Why not, but ……

Philosophy behind the idea of dynamically generated baryons:

The first excited N* states: N*(1440)($1/2^+$) , N*(1535) ($1/2^-$).
In quark models this tells us the quark excitation requires 500-600 MeV.
It is cheaper to produce one pion, or two (140-280 MeV), if they can be bound.

How do we know if this can occur?
We need dynamics. A potential for the interaction of mesons with ground state baryons and solve the Shroedinger equation (Bethe Salpeter) in coupled channels.
Basic interaction extracted from chiral Lagrangians: the effective theory of QCD at low energies.

Many resonances are generated in this way, like the $1/2^-$ states from meson baryon (N* (1535), two Λ(1405)…) or the $1/2^+$ states from two mesons and a baryon (N*(1710) ….. talk A. Martinez)

From pseudoscalar-baryon octet interaction there are many states generated: one sees them as peaks in the scattering matrices or poles in the complex plane.

Two Λ(1405), Λ(1670), N*(1535)…….

Jido, Ramos, Oller, Meissner,E. O.
Nieves, Garcia Recio, Vicente Vacas
Hyodo, Jido, Hosaka
Borasoy, Niessler, Weise
Oller, Verbeni, Pradres
Borasoy, Niessler, Meissner
…….

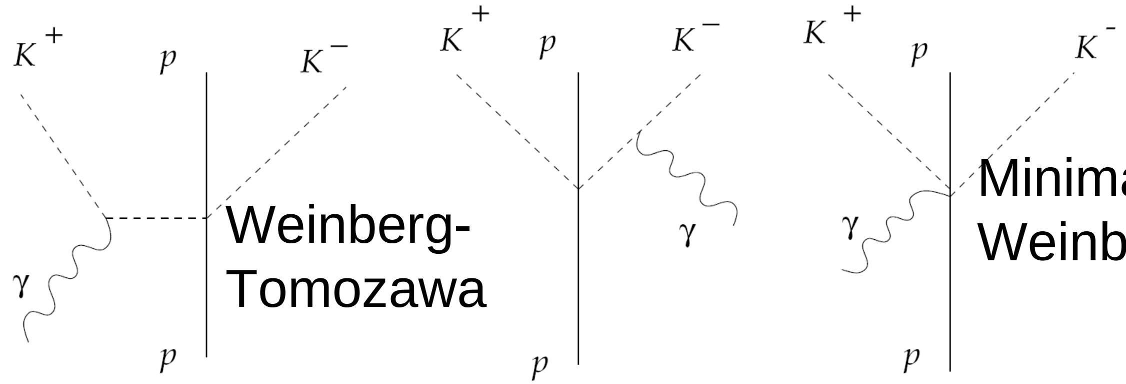
A feature of the chiral unitary approach is its great predictive power

(alternative view: Damocles sward always threatening you because it makes clear predictions that experiment could easily kill).

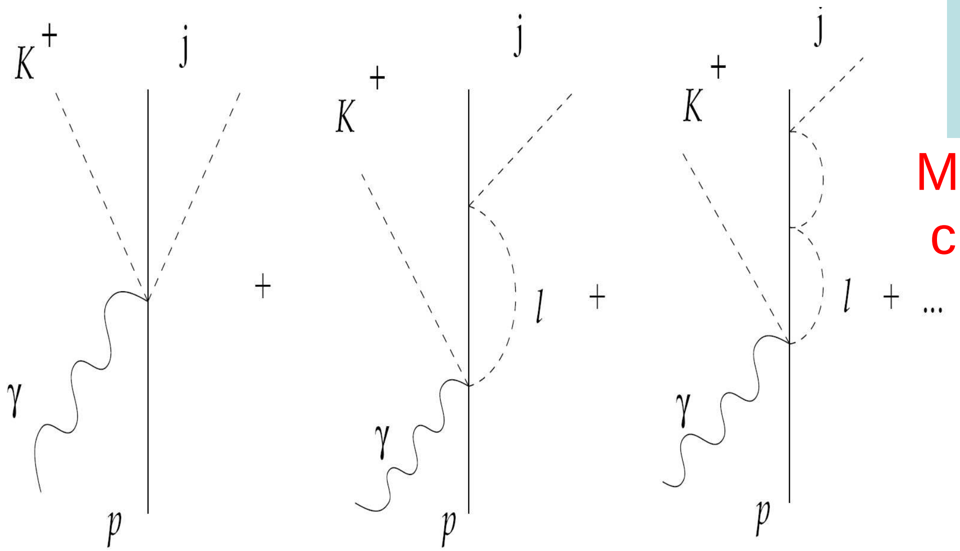
But, so far predictions fulfilled, in production reactions, partial decay rates, meson baryon scattering amplitudes, helicity amplitudes, transition form factors …

Example: Nacher, E. O., Ramos, Toki, PLB 1999
Predictions made for $\gamma\, p \rightarrow k^+\, \Lambda(1405)$, new experiments

Minimal chiral model

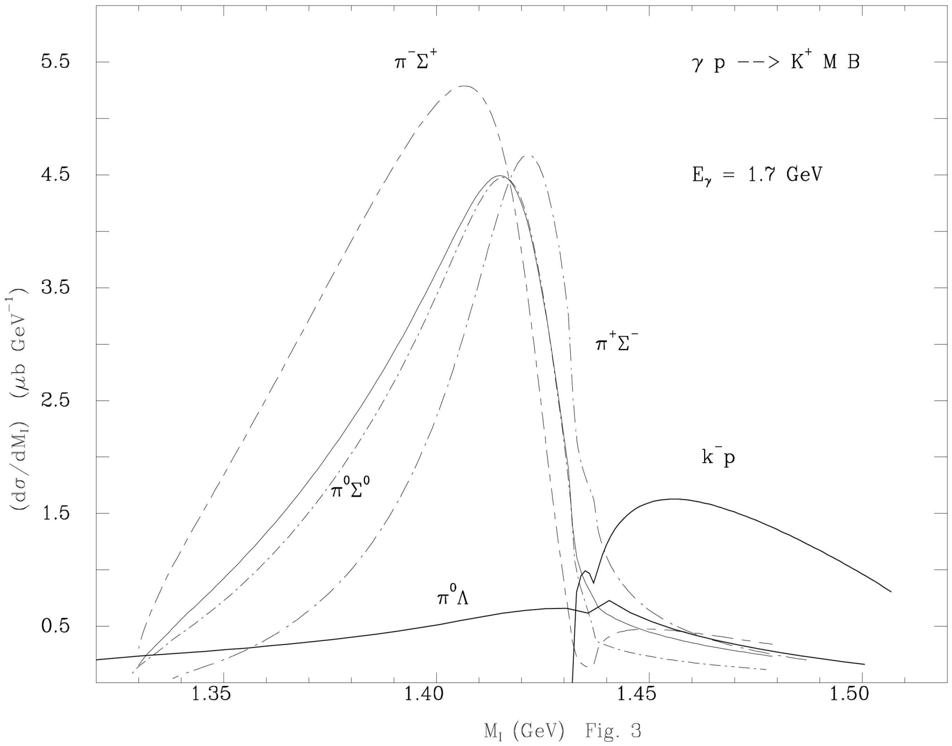


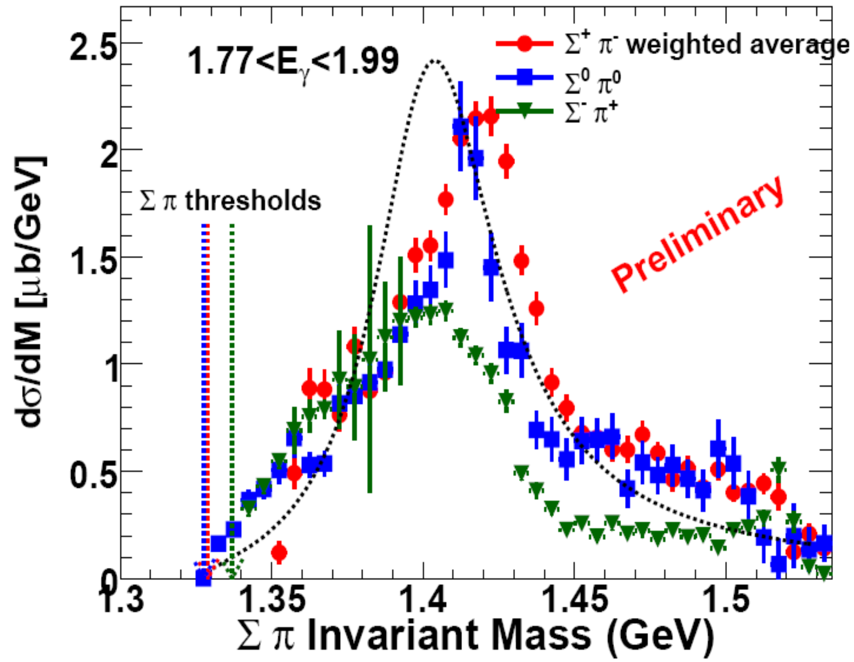
Minimal substitution from Weinberg-Tomozawa



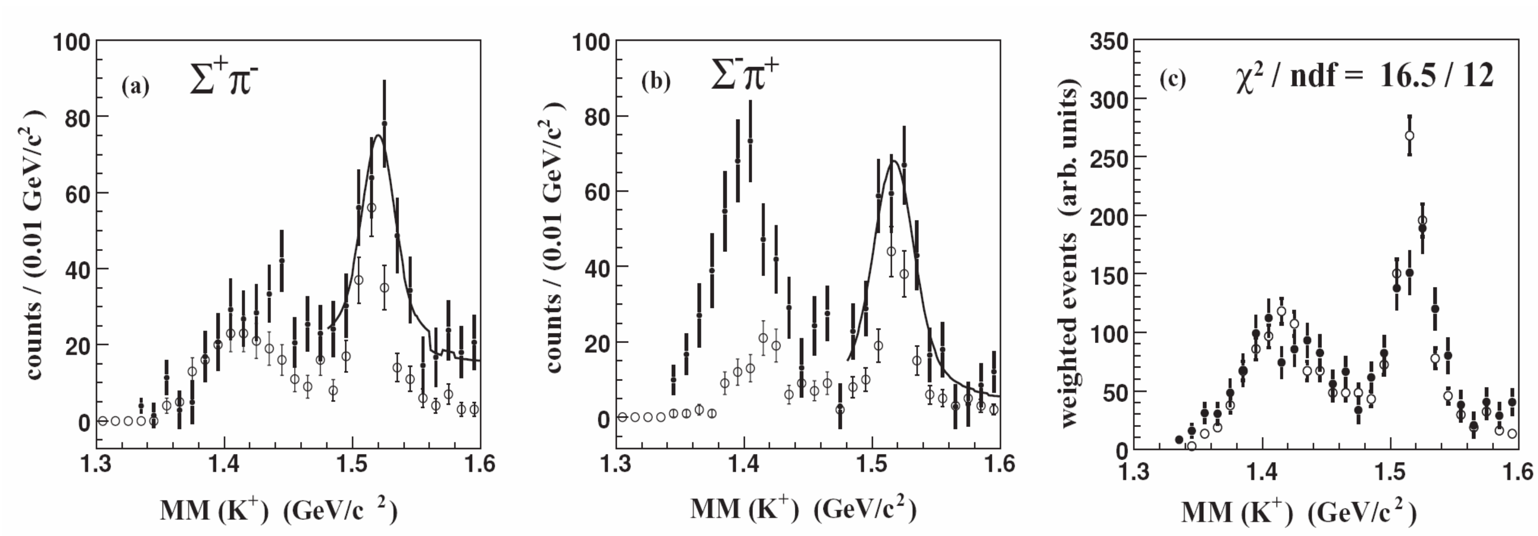
$\pi\Sigma$ in the final state to observe the $\Lambda(1405)$

Meson baryon interaction in coupled channels generate the $\Lambda(1405)$





k. Moriya, Schumacher ….CLASS



M.Niiyama, Ahn, Imai, Nakano, Hicks…LEPS at Spring8/Osaka, PRC 78, 035202,2008

Data are of great value. Contain much information

The minimal model must be improved. Energy dependende, angular dependence, extra terms ….

Care must be payed to $\pi^+\Sigma^-$, $\pi^-\Sigma^+$ asymmetries → information about I=1 background. Sign of a new Σ resonance around 1400 MeV?

Recall Zou talk …

Another nice feature of the chiral approach: the results warn you of limitations of the approach in some cases:

Hyodo, Jido, Hosaka, PRC78,2008

In the case of the N*(1535) the need to use different cut offs (or subtraction constants in dimensional regularization) in different channels is interpreted as need to have further components in the state beyond pseudoscalar-baryon → 3q, ρN …?

→ Time has come to face the problem of vector-baryon interaction !!

Hidden gauge formalism for vector mesons, pseudoscalars and photons

Bando et al. PRL, 112 (85); Phys. Rep. 164, 217 (88)

$$\mathcal{L} = \mathcal{L}^{(2)} + \mathcal{L}_{III} \tag{1}$$

with

$$\mathcal{L}^{(2)} = \frac{1}{4} f^2 \langle D_\mu U D^\mu U^\dagger + \chi U^\dagger + \chi^\dagger U \rangle \tag{2}$$

$$\mathcal{L}_{III} = -\frac{1}{4} \langle V_{\mu\nu} V^{\mu\nu} \rangle + \frac{1}{2} M_V^2 \langle [V_\mu - \frac{i}{g} \Gamma_\mu]^2 \rangle, \tag{3}$$

where $\langle ... \rangle$ represents a trace over $SU(3)$ matrices. The covariant derivative is defined by

$$D_\mu U = \partial_\mu U - ieQA_\mu U + ieUQA_\mu, \tag{4}$$

with $Q = diag(2, -1, -1)/3$, $e = -|e|$ the electron charge, and A_μ the photon field. The chiral matrix U is given by

$$U = e^{i\sqrt{2}\phi/f} \tag{5}$$

$$\phi \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}, \quad V_\mu \equiv \begin{pmatrix} \frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & \rho^+ & K^{*+} \\ \rho^- & -\frac{1}{\sqrt{2}}\rho^0 + \frac{1}{\sqrt{2}}\omega & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \phi \end{pmatrix}_\mu . \tag{6}$$

In $\mathcal{L}_{III}$, $V_{\mu\nu}$ is defined as

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu - ig[V_\mu, V_\nu] \tag{9}$$

and

$$\Gamma_\mu = \frac{1}{2}[u^\dagger(\partial_\mu - ieQA_\mu)u + u(\partial_\mu - ieQA_\mu)u^\dagger] \tag{10}$$

with $u^2 = U$. The hidden gauge coupling constant g is related to f and the vector meson mass (M_V) through

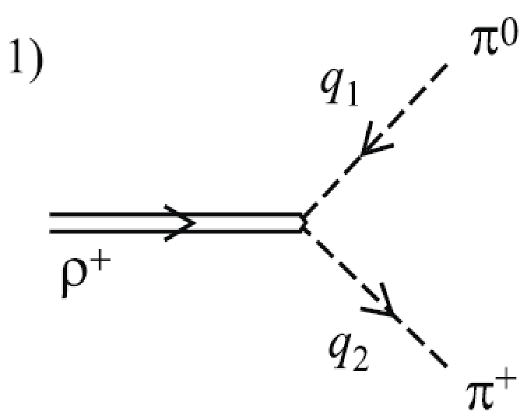
$$g = \frac{M_V}{2f}, \tag{11}$$

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

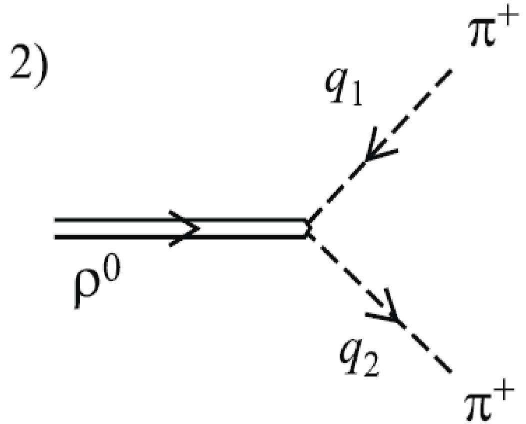
$$\mathcal{L}_{V\gamma PP} = e\frac{M_V^2}{4gf^2} A_\mu \langle V^\mu (Q\phi^2 + \phi^2 Q - 2\phi Q \phi) \rangle$$

$$\mathcal{L}_{VPP} = -i\frac{M_V^2}{4gf^2} \langle V^\mu [\phi, \partial_\mu \phi] \rangle$$

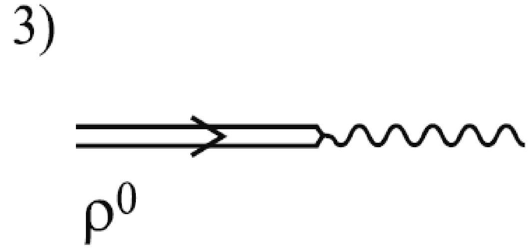
$$\mathcal{L}_{III}^{(c)} = \frac{g^2}{2} \langle V_\mu V_\nu V^\mu V^\nu - V_\nu V_\mu V^\mu V^\nu \rangle \; , \qquad \mathcal{L}_{III}^{(3V)} = ig \langle (\partial_\mu V_\nu - \partial_\nu V_\mu) V^\mu V^\nu \rangle \; ,$$


1)
π^0
q_1
ρ^+
q_2
π^+

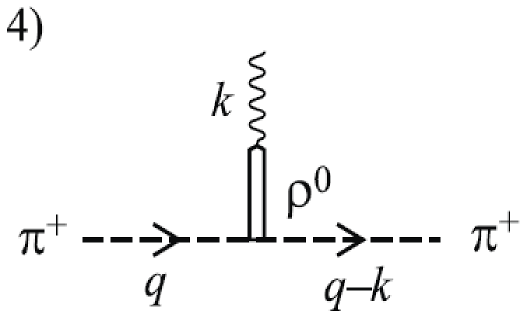
(a)

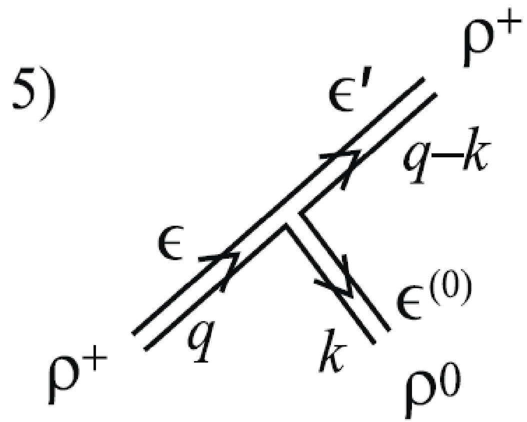

2)
π^+
q_1
ρ^0
q_2
π^+

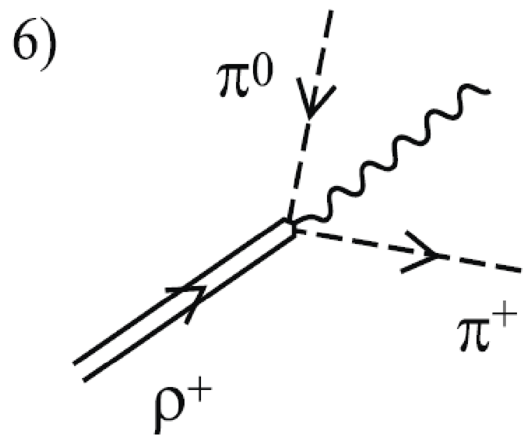
(b)

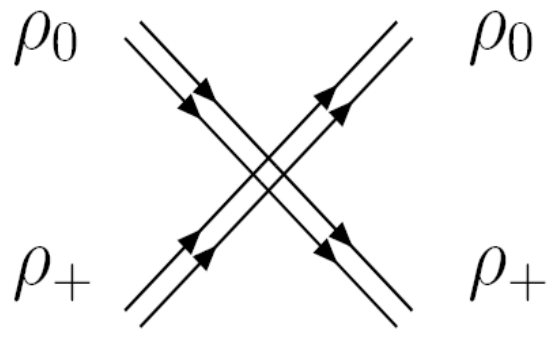

3)
ρ^0

(c)


4)
k
ρ^0
π^+
π^+
q
$q-k$


5)
ρ^+
ϵ'
$q-k$
ϵ
$\epsilon^{(0)}$
ρ^+
q
k
ρ^0


6)
π^0
π^+
ρ^+


ρ_0
ρ_0
ρ_+
ρ_+

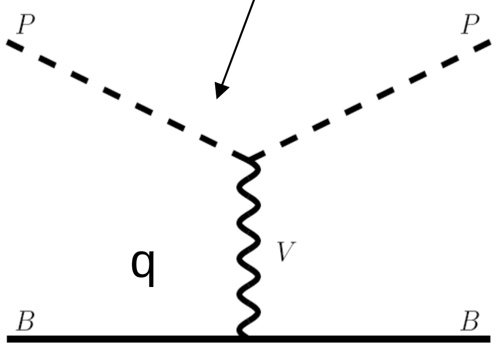
Extension to the baryon sector

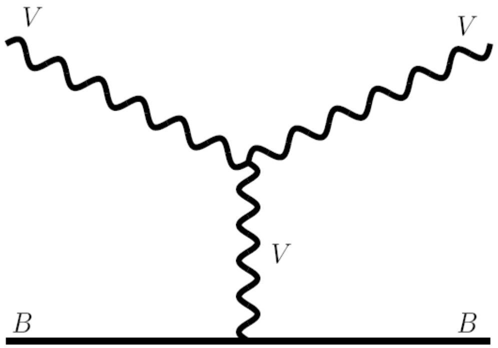
$$\mathcal{L}_{BBV} = -\frac{g}{2\sqrt{2}}\left(tr(\bar{B}\gamma_\mu[V^\mu, B] + tr(\bar{B}\gamma_\mu B)tr(V^\mu)\right)$$

Vector propagator $1/(q^2-M_V^2)$

In the approximation $q^2/M_V^2 = 0$ one recovers the chiral Lagrangians Weinberg-Tomozawa term. For consistency, for vectors we take $\vec{q}/M_V=0$

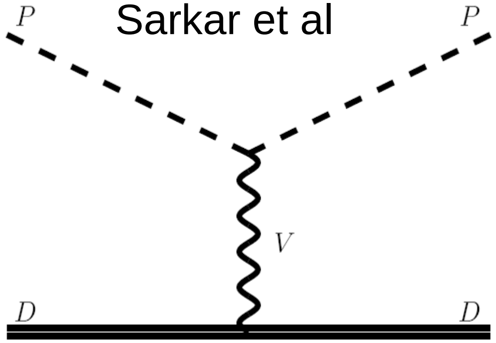
> 200 works

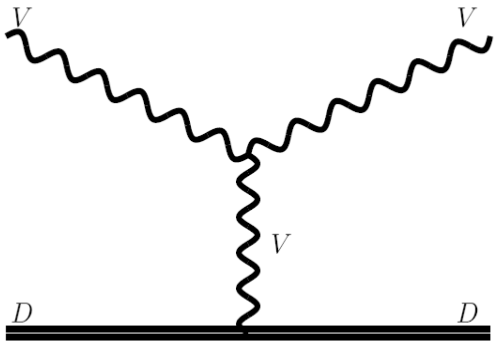




New: A. Ramos, E. O.

Kolomeitsev et al
Sarkar et al





New: J. Vijande, P. Gonzalez. E.O
PRC,2009
Sarkar, Vicente Vacas, B.X.Sun, E.O

Vector octet – baryon octet interaction

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

$$\mathcal{L}_{VPP} = -ig\ tr\left([P, \partial_\mu P] V^\mu\right)$$

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

V^ν cannot correspond to an external vector.
Indeed, external vectors have only spatial components in the approximation of neglecting three momenta, ε^0= k/M for longitudinal vectors, ε^0=0 for transverse vectors. Then ∂_ν becomes three momentum which is neglected. →
V^ν corresponds to the exchanged vector. → complete analogy to VPP
Extra $\varepsilon_\mu \varepsilon^\mu = -\varepsilon_i \varepsilon_i$ but the interaction is formally identical to the case of PB→PB
In the same approximation only γ^0 is kept for the baryons → the spin dependence is only $\varepsilon_i \varepsilon_i$ and the states are degenerate in spin 1/2 and 3/2

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

K^0 energy of vector mesons

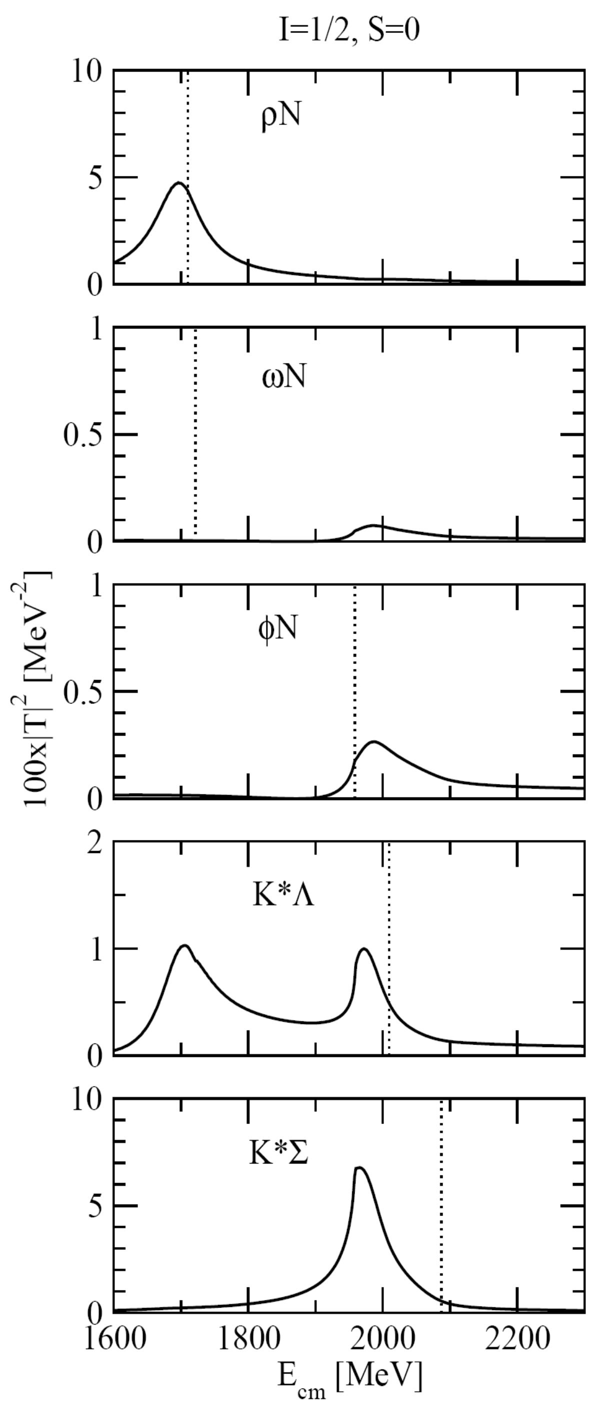
We solve the Bethe Salpeter equation in coupled channels Vector-Baryon octet.

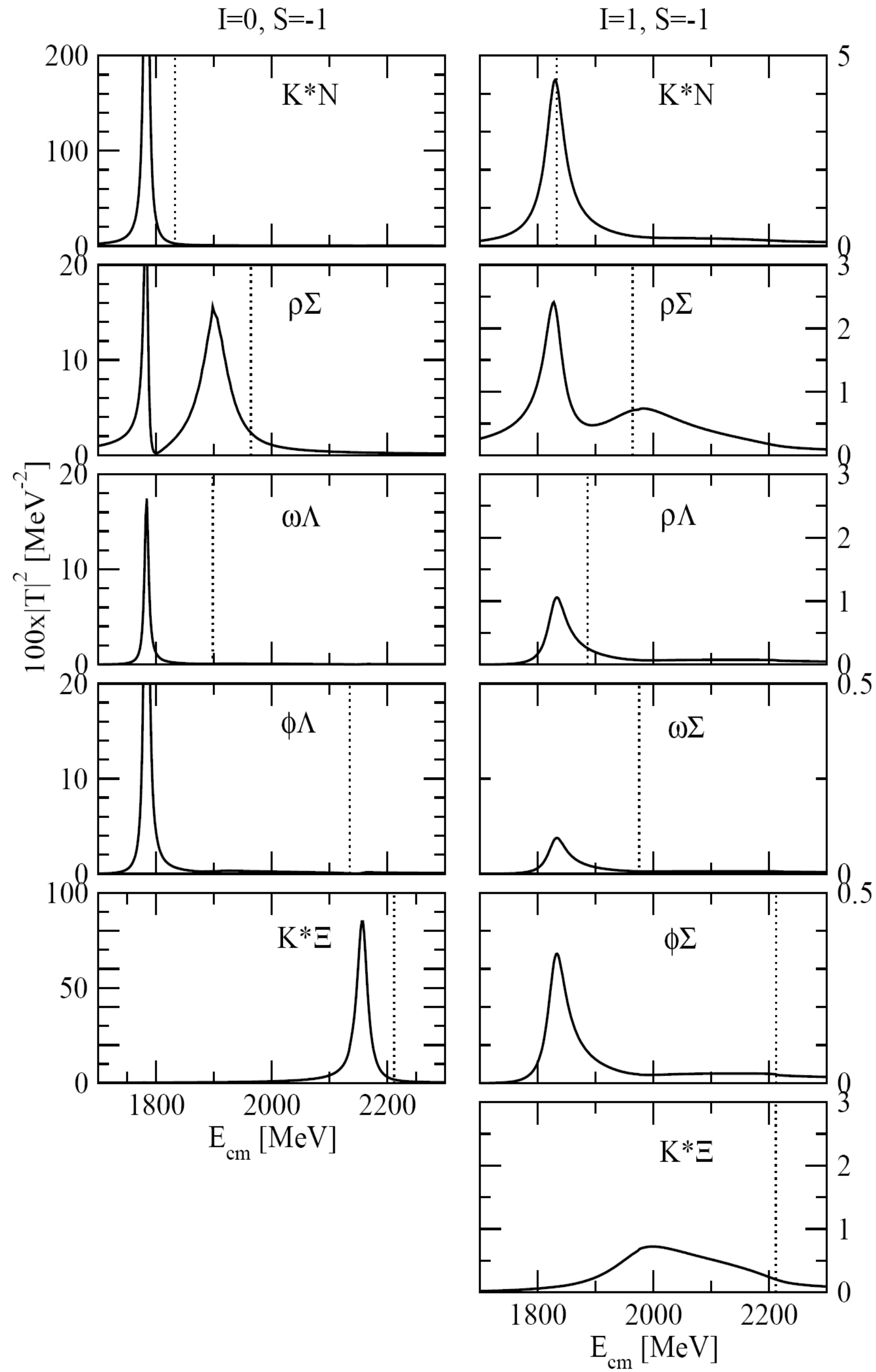
$T = (1-GV)^{-1} V$

with G the loop function of vector-baryon

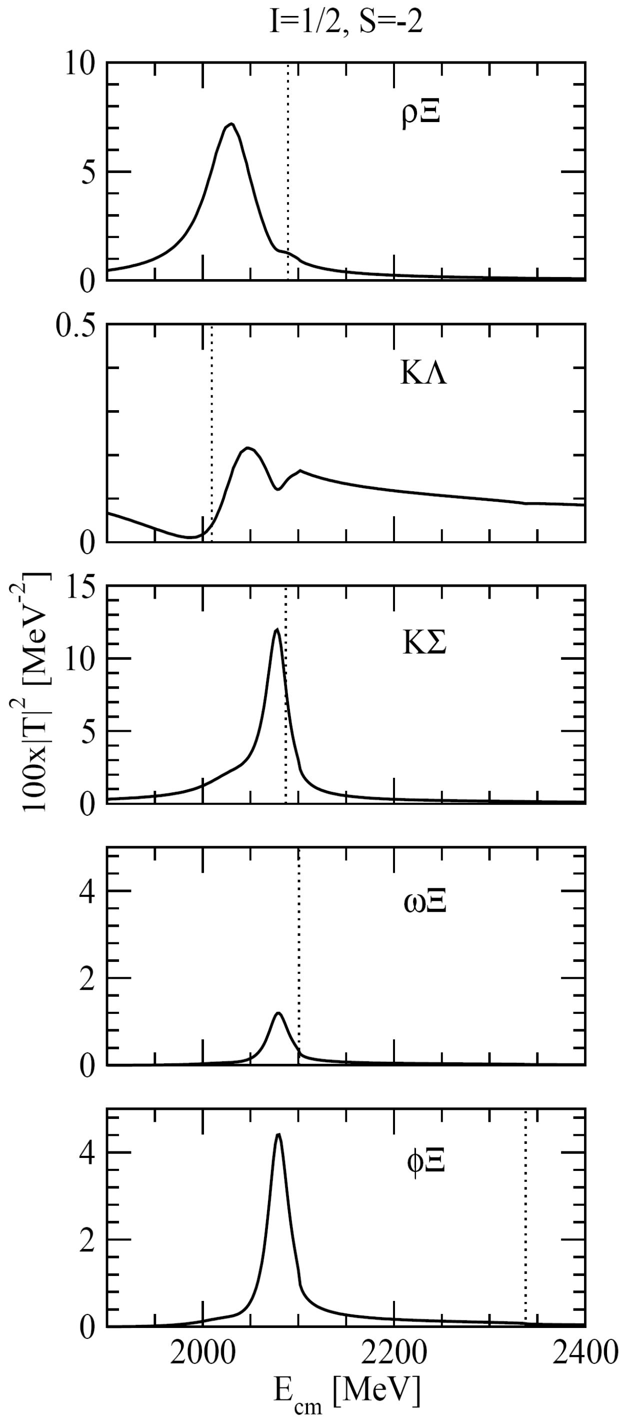
Apart from the peaks, poles are searched In the second Riemann sheet and pole positions and residues are determined.

The G function takes into account the mass distribution of the vectors (width). Decay into pseudoscalar-baryon not yet considered.





I=0, S=-1
I=1, S=-1
K*N
ρΣ
ωΛ
ρΛ
φΛ
ωΣ
K*Ξ
φΣ
100x|T|^2 [MeV^-2]
E_cm [MeV]
1800
2000
2200
200
100
20
10
50
0
5
3
2
1
0.5

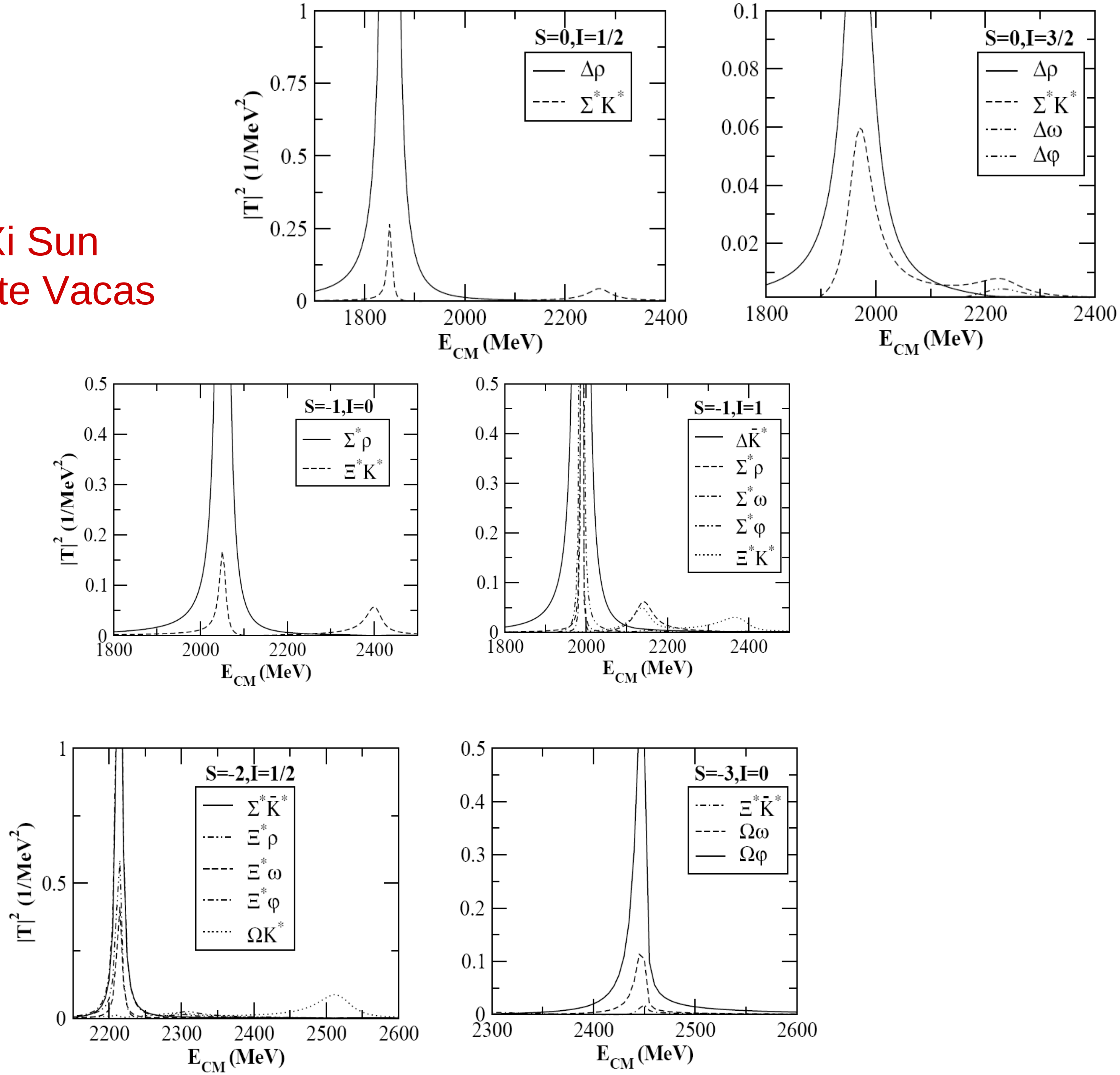

I=1/2, S=-2
ρΞ
KΛ
KΣ
ωΞ
φΞ
100x|T|^2 [MeV^-2]
E_cm [MeV]
10
5
0
0.5
0
15
10
5
0
4
2
0
4
2
0
2000
2200
2400

$S,\ I$	Theory		PDG data				
	(real axis)		name	J^P	status	mass	width
	mass	width					
$0, 1/2$	1699	84	$N(1650)$	$1/2^-$	$\star\star\star\star$	1645-1670	145-185
			$N(1700)$	$3/2^-$	$\star\star\star$	1650-1750	50-150
	1967	82	$N(2080)$	$3/2^-$	$\star\star$	≈ 2080	180-450
			$N(2090)$	$1/2^-$	$\star$	≈ 2090	100-400
$-1, 0$	1783	8	$\Lambda(1690)$	$3/2^-$	$\star\star\star\star$	1685-1695	50-70
			$\Lambda(1800)$	$3/2^-$	$\star\star\star$	1720-1850	200-400
	1900	54	$\Lambda(2000)$	$?^?$	$\star$	≈ 2000	73-240
	2158	20					
$-1, 1$	1830	44	$\Sigma(1750)$	$1/2^-$	$\star\star\star$	1730-1800	60-160
	1985	244	$\Sigma(1940)$	$3/2^-$	$\star\star\star$	1900-1950	150-300
			$\Sigma(2000)$	$1/2^-$	$\star$	≈ 2000	100-450
$-2, 1/2$	2030	52	$\Xi(2030)$	$?^?$	$\star\star\star$	2025 ± 5	21 ± 6
	2080	24	$\Xi(2120)$	$?^?$	$\star$	≈ 2120	25

Table 1: The properties of the 9 dynamically generated resonances and their possible PDG counterparts.

Extension to the octet of vectors and decuplet of Baryons

S. Sarkar, Bao Xi Sun
E. O, M.J. Vicente Vacas
09



$S,\ I$	Theory			PDG data				
	pole position	real axis		name	J^P	status	mass	width
		mass	width					
$0, 1/2$	$1850 + i5$	1850	11	$N(2090)$	$1/2^-$	$\star$	1880-2180	95-414
				$N(2080)$	$3/2^-$	$\star\star$	1804-2081	180-450
		2270(*bump*)		$N(2200)$	$5/2^-$	$\star\star$	1900-2228	130-400
$0, 3/2$	$1972 + i49$	1971	52	$\Delta(1900)$	$1/2^-$	$\star\star$	1850-1950	140-240
				$\Delta(1940)$	$3/2^-$	$\star$	1940-2057	198-460
				$\Delta(1930)$	$5/2^-$	$\star\star\star$	1900-2020	220-500
		2200(*bump*)		$\Delta(2150)$	$1/2^-$	$\star$	2050-2200	120-200
$-1, 0$	$2052 + i10$	2050	19	$\Lambda(2000)$	$?^?$	$\star$	1935-2030	73-180
$-1, 1$	$1987 + i1$	1985	10	$\Sigma(1940)$	$3/2^-$	$\star\star\star$	1900-1950	150-300
	$2145 + i58$	2144	57	$\Sigma(2000)$	$1/2^-$	$\star$	1944-2004	116-413
	$2383 + i73$	2370	99	$\Sigma(2250)$	$?^?$	$\star\star\star$	2210-2280	60-150
				$\Sigma(2455)$	$?^?$	$\star\star$	2455±10	100-140
$-2, 1/2$	$2214 + i4$	2215	9	$\Xi(2250)$	$?^?$	$\star\star$	2189-2295	30-130
	$2305 + i66$	2308	66	$\Xi(2370)$	$?^?$	$\star\star$	2356-2392	75-80
	$2522 + i38$	2512	60	$\Xi(2500)$	$?^?$	$\star$	2430-2505	59-150
$-3, 0$	$2449 + i7$	2445	13	$\Omega(2470)$	$?^?$	$\star\star$	2474±12	72±33

Novel approach to three body systems with chiral dynamics

A. Martinez, K. Khemchandani …..PRC2008, 2009, EPJA 2008, PLB2009

Uses meson-baryon or meson-meson amplitudes evaluated within the chiral unitary approach with coupled channels.

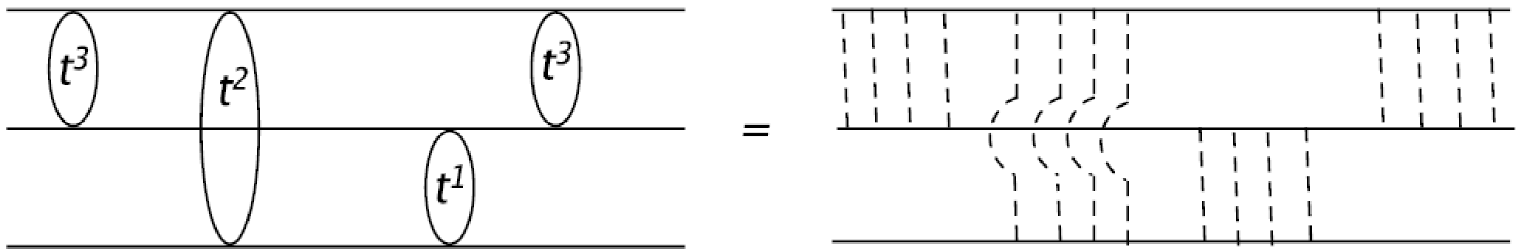
Show that only the on shell part of the amplitudes is needed →

Find a suitable approximation that converts Faddeev equations into algebraic equations.

→Only experimental amplitudes are needed as input in this approach (sometimes extrapolated below threshold with $q^2=m^2$)

Three body Faddeev equations

One starts from a two nucleon potential and draws all possible diagrams with any amount of interactions between two particles



The iterative potential exchanges between two same lines sum up to give the two nucleon t-matrix

The $\pi K\bar{N}$ system
and
its coupled channels

- We study the $\pi\bar{K}N$ system by solving the Faddeev equations in the coupled channel approach.

- The $\bar{K}N$ system couples strongly to the $\Lambda(1405)$

↓

correlation of the $\bar{K}N$ and its coupled channels should be largely kept during the three body scattering

↓

We begin with a given invariant mass for the $\bar{K}N$ system, s_{23}, for a fixed total energy. Later we vary these two variables.

- The three pairs (πN, $K\bar{N}$, $K\bar{\pi}$) couple strongly to many other channels.

⇒ **We need to solve the Faddeev equations taking coupled channels into account.**

π + { pseudoscalar meson of the SU(3) octet + baryon of the $1/2^+$ octet } S = -1 ➡ 22 coupled channels

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

$$\pi^+ K^- n,\ \pi^+ \pi^0 \Sigma^-,\ \pi^+ \pi^- \Sigma^0,\ \pi^+ \pi^- \Lambda,\ \pi^+ \eta \Sigma^-,\ \pi^+ K^0 \Xi^-$$

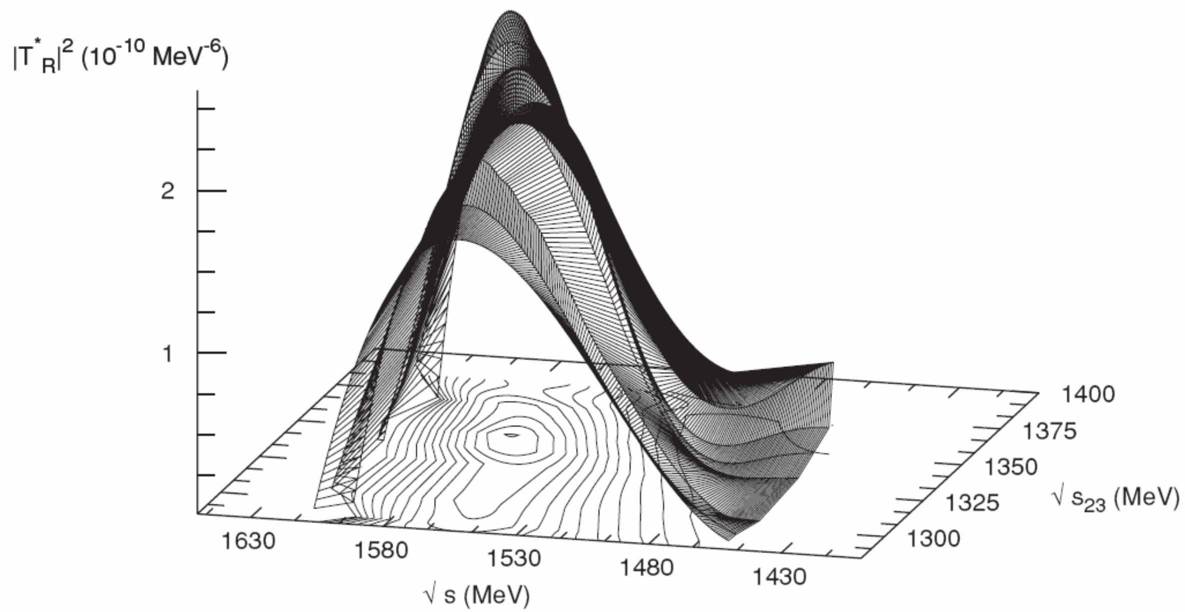
$$\pi^- \bar{K}^0 p,\ \pi^- \pi^0 \Sigma^+,\ \pi^- \pi^+ \Sigma^0,\ \pi^- \pi^+ \Lambda,\ \pi^- \eta \Sigma^+,\ \pi^- K^+ \Xi^0$$

$\Lambda(1600)\ P_{01}$

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

There are quite possibly two P_{01} states in this region

$I = 0,\ I_{\pi\bar{K}} = 1/2$



- We find two peaks at 1568 MeV (width 70 MeV) and 1700 MeV (width 136 MeV) in the $\pi\bar{K}N$ amplitude .

- Solving these equations for the $\pi \bar{K} N$ system and its coupled channels, we find four Σ's and two Λ's as dynamically generated resonances in this system.

	Γ (*PDG*) (MeV)	Peak position (this work) (MeV)	Γ (this work) (MeV)
Isospin = 1			
Σ(1560)	10 - 100	1590	70
Σ(1620)	10 - 100	1630	39
Σ(1660)	40 - 200	1656	30
Σ(1770)	60 - 100	1790	24
Isospin = 0			
Λ(1600)	50 - 250	1568, 1700	60, 136
Λ(1810)	50 - 250	1740	20

- It is rewarding that the widths for all these resonances are smaller than the total ones listed by the PDG.

It should be emphasized that all the Σ's and all the Λ's $1/2^+$ up to 1810 MeV get dynamically generated as three body resonances.

Other states obtained with π π N and coupled channels:
The π N amplitudes at energies bigger than 1600 MeV have been taken from experiment

$\mathbf{I(J^P)}$	**Theory**			**PDG data**		
	channels	mass (MeV)	width (MeV)	name	mass (MeV)	width (MeV)
$1/2\,(1/2^+)$	only $\pi\pi N$	1704	375	$N^*(1710)$	1680-1740	90-500
	$\pi\pi N$, $\pi K\Sigma$, $\pi K\Lambda$, $\pi\eta N$	$\sim$ no change	$\sim$ no change			
$1/2\,(1/2^+)$	only $\pi\pi N$	2100	250	$N^*(2100)$	1885-2270	80-400
	$\pi\pi N$, $\pi K\Sigma$, $\pi K\Lambda$, $\pi\eta N$	2080	54			
$3/2\,(1/2^+)$	$\pi\pi N$, $\pi K\Sigma$, $\pi K\Lambda$, $\pi\eta N$	2126	42	$\Delta(1910)$	1870-2152	190-270
$1/2\,(1/2^+)$	$N\pi\pi$, $N\pi\eta$, NKK	1924	20	$N^*(?)$	?	?

Mostly N $f_0(980)$, N $a_0(980)$

First predicted by Jido and Eny'o, PRC78, 2008

Martinez Torres, Khemchandani, Meissner, Oset, EPJA 2009, claim this state is responsible for peak of γ p → K+ Λ around 1920 MeV

Mart and Bennhold PRC 2000

1925 MeV

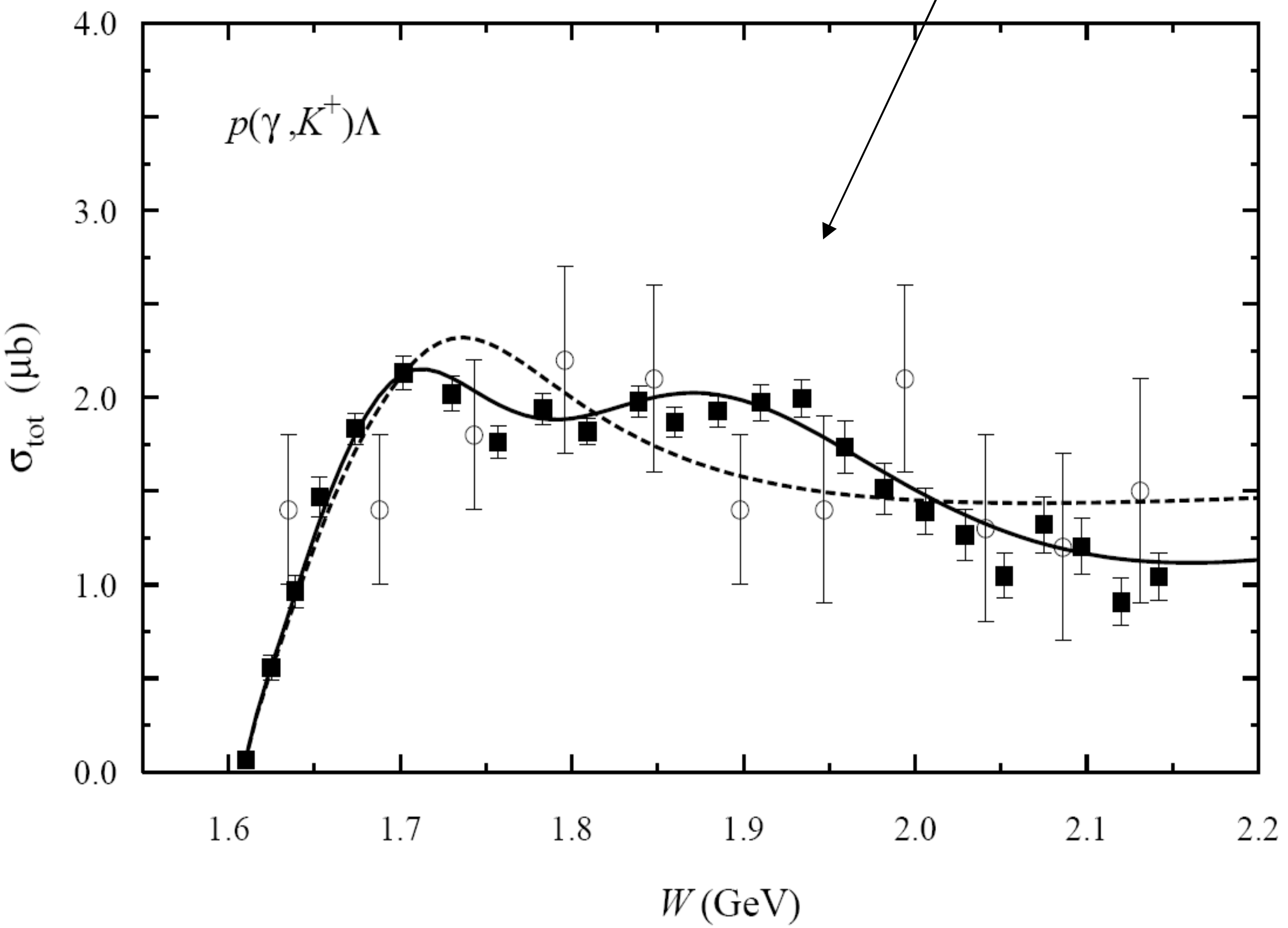


FIG. 1. Total cross section for $K^+\Lambda$ photoproduction on the proton. The dashed line shows the model without the $D_{13}(1960)$ resonance, while the solid line is obtained by including the $D_{13}(1960)$ state. The new SAPHIR data [6] are denoted by the solid squares, old data [22] are shown by the open circles.

Experimental tests for the signature this resonance

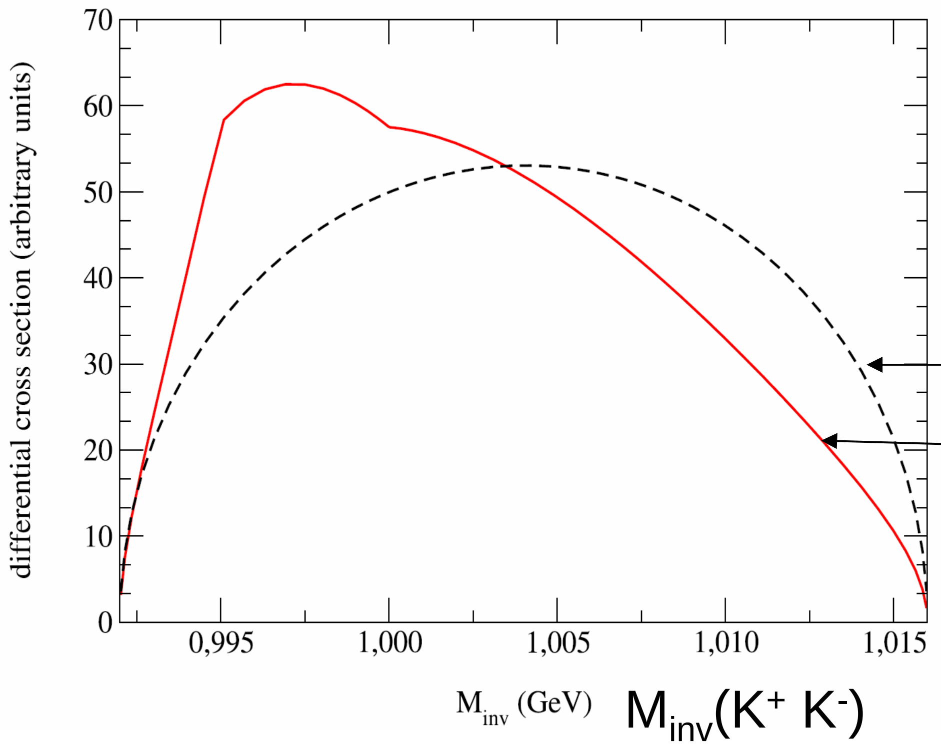
In $\gamma\, p \rightarrow K^{+}\, \Lambda$ use polarized beam and target and look for

S_z=3/2 and S_z=1/2 (standard technique since a few years)

Take S_z=3/2 : if the peak remains one cannot have J=1/2
if the peak disappears one does not have J=3/2

Schumacher has the key to that at Jeff Lab

$\gamma\, p \rightarrow K^+ K^- p$

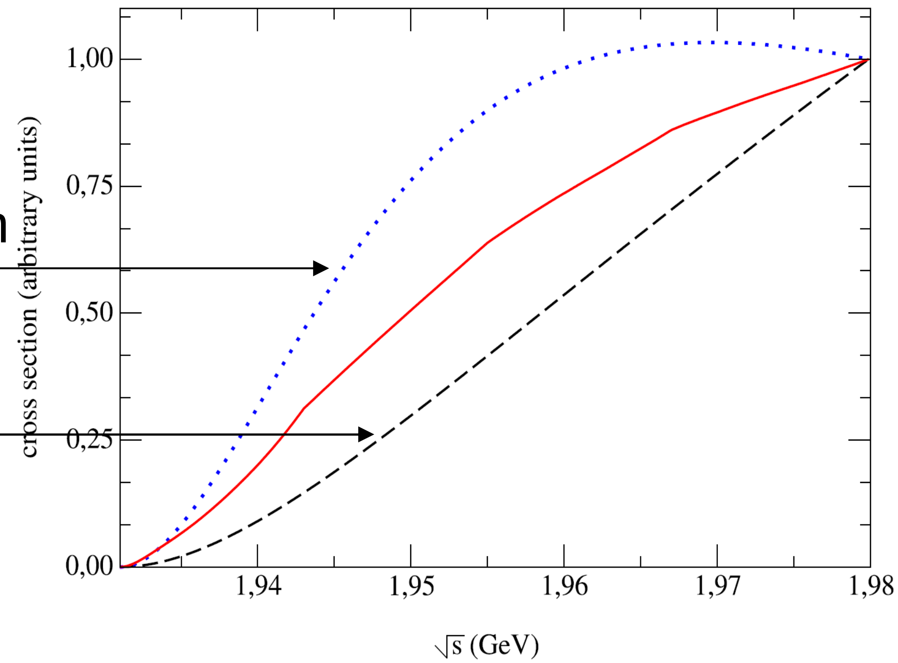


$M_{inv}(K^+ K^-)$

$d\sigma / d M_{inv}(K^+ K^-)$

Phase space

K Kbar N resonance
below threshold



Integrated
cross section

K Kbar N resonance
below threshold

Phase space

Preliminary experimental results
available from T. Nakano

Conclusions

Chiral dynamics plays an important role in hadron physics.

Its combination with nonperturbative unitary techniques allows to study the interaction of hadrons. Poles in amplitudes correspond to dynamically generated
resonances. Many of the known meson and baryon resonances can be described in this way.

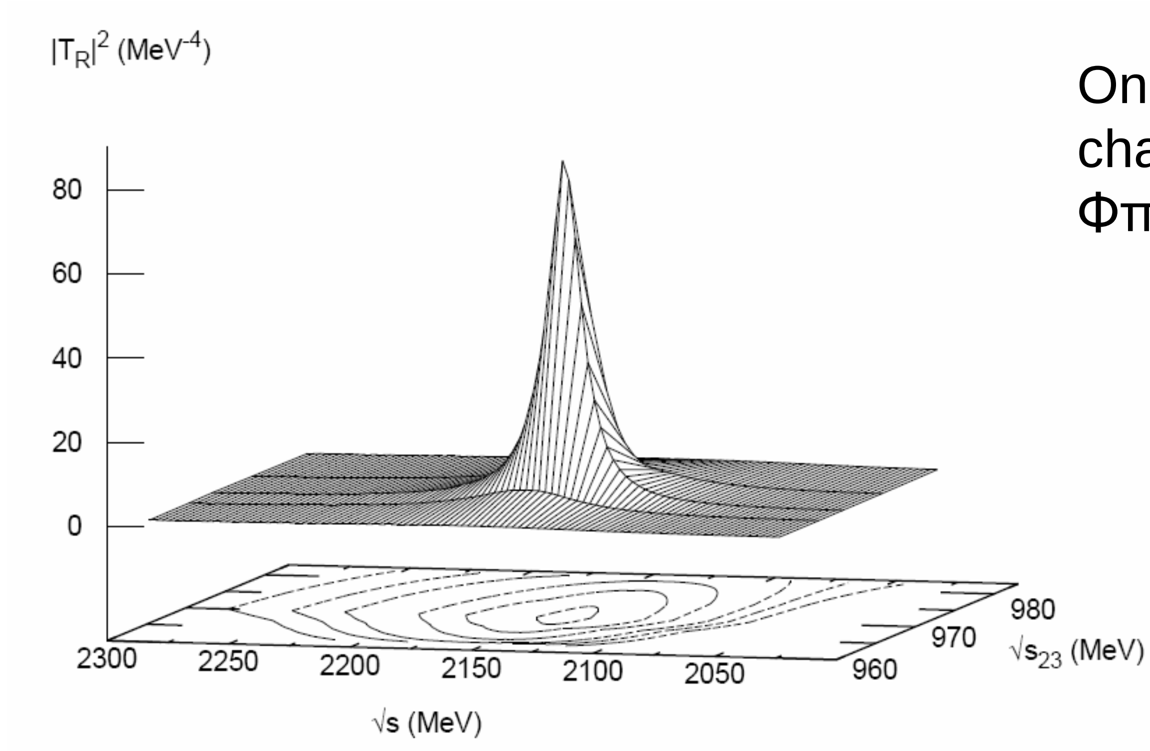
The introduction of vector mesons as building blocks brings a new perspective into the nature of higher mass mesons and baryons.

The systems of two mesons and one baryon have brought us surprises. Many known resonances qualify as such states and there has been some new prediction.

Experimental challenges to test the nature of these resonances looking for new decay channels or production modes. Plus the search for new predicted resonances.

The $\phi K\bar{K}$ system
and
its coupled channels

- We have taken into account the coupled channels ϕK^+K^- and $\phi K^0\bar{K}^0$



Only moderate changes when Φππ added

- We find a peak around 2150 MeV with a width of 16 MeV for a value of $\sqrt{s_{23}}$ close to 970 MeV (≈pole of the $f_0(980)$).
- We identify this peak with the X(2175) (width 58±16±20 MeV)

An extrapolation to the case of J/ψ K Kbar leads to a state which can be identified with the Y(4260) seen at Babar with $J^{PC}=1^{--}$

Martinez Torres, Khemchandani, Gamermann, E. O, (2009)