Θ^+ and exotic hadrons

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Contents

Exotic hadrons in QCD

Θ^+ : strangeness S=+1, baryon number B=1
minimal quark content ~ $uudd\bar{s}$: exotic!

c.f. Λ(1405) ~ $uud\, s\bar{u}$, Z(4430) ~ $c\bar{c}u\bar{d}$: crypto-exotic hadrons

Exotic hadrons are

- not well established in experiments (~300 normal hadrons).
- not excluded in QCD.
- easily constructed in effective models.

Saturation?

c.f. nucleus: Coulomb repulsion, drip line, ...
hydrogen molecule: covalent bond, ...

Exotic hadrons --> quark binding mechanism (confinement)

History of S=+1 baryon

1962: Goldhaber gap (absence of KN resonance)
--> "eightfold-way", SU(3) decuplet for Δ, Σ*, Ξ*

1964: Quark model

M. Gell-Mann, Phys. Lett. 8, 214 (1964)

> We then refer to the members $u^{\frac{2}{3}}$, $d^{-\frac{1}{3}}$, and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (q q q), (q q q q $\bar{q}$), etc., while mesons are made out of (q $\bar{q}$), (q q $\bar{q}$ $\bar{q}$), etc. It is assuming that the lowest

1992: Possible Z* with M > 1780 MeV and Γ > 190 MeV

J. S. Hyslop, *et al.*, Phys. Rev. D46, 961 (1992)

1997: Chiral quark soliton model: light mass, narrow width

D. Diakonov, V. Petrov, M. Polyakov, Z. Phys. A359, 305 (1997)

> **Abstract.** We predict an exotic Z^+ baryon (having spin 1/2, isospin 0 and strangeness +1) with a relatively low mass of about 1530 MeV and total width of less than 15 MeV. It seems that this region of masses has avoided thorough searches in the past.

2003~ : Positive experimental results for Θ^+

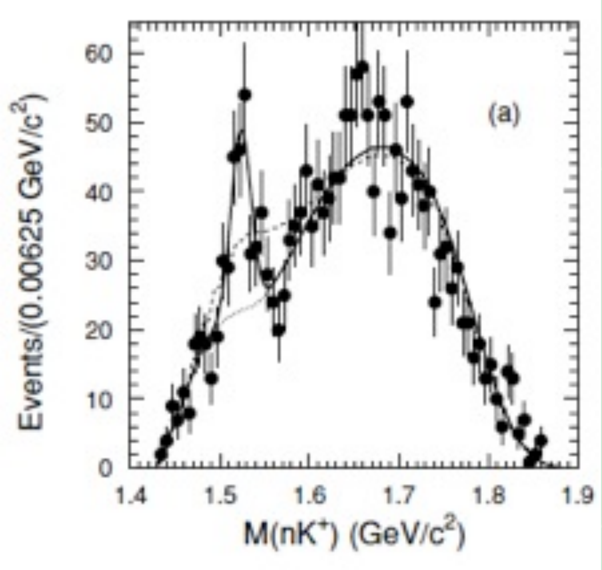
T. Nakano, *et al.*, Phys. Rev. Lett. 91, 012002 (2003)

2005~ : Negative results (dedicated experiments)

Experimental results which are still alive

LEPS: γd --> K^+K^-pn, 5.1 σ peak

T. Nakano, *et al.*, Phys. Rev. C79, 025210 (2009)



- inconsistent with CLAS upper limit

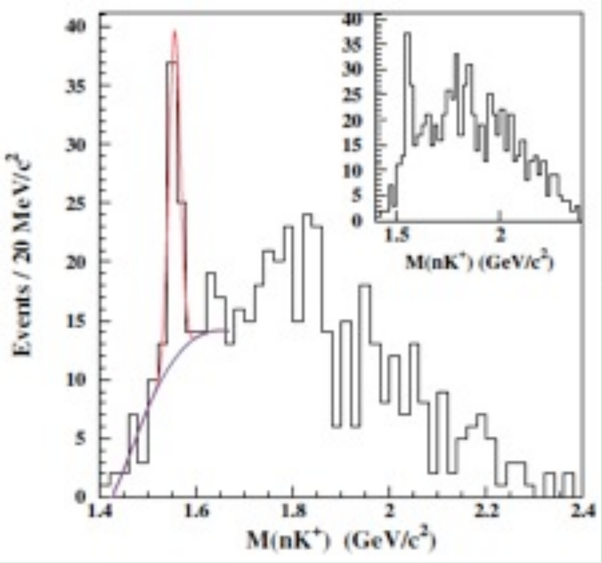
T. McKinnon, *et al.*, Phys. Rev. Lett. 96, 212001 (2006)

- "MMSA" (presumption of fermi motion)

A. Martinez Torres, E. Oset,
Phys. Rev. Lett. 105, 092001 (2010); C81, 055202 (2010)

CLAS: γp --> $\pi^+K^-K^+$n, 7.8 σ peak

V. Kubarovsky, *et al.*, Phys. Rev. Lett. 92, 032001 (2004)



- no dedicated confirmation

"Extraordinary claims require extraordinary evidence"

Theoretical status

Theoretical studies of Θ^+ structure (until March 2006):

http://www2.yukawa.kyoto-u.ac.jp/~hyodo/research/Thetapub.html

- Prediction of models is not reliable for exotic hadrons, due to new ingredients in five-body problem.
  e.g.) quark model: five-body force
- Results of lattice QCD are not straightforward to interpret.
  e.g.) separation of resonance out of scattering states

The best way in theory: KN scattering on lattice

- Phase shift can be calculated.
- Not direct information of the state, if Θ^+ is a resonance.

Today: Reaction study based on effective Lagrangian

- assume the existence and quantum numbers of Θ^+
- determine coupling constants and calculate cross section

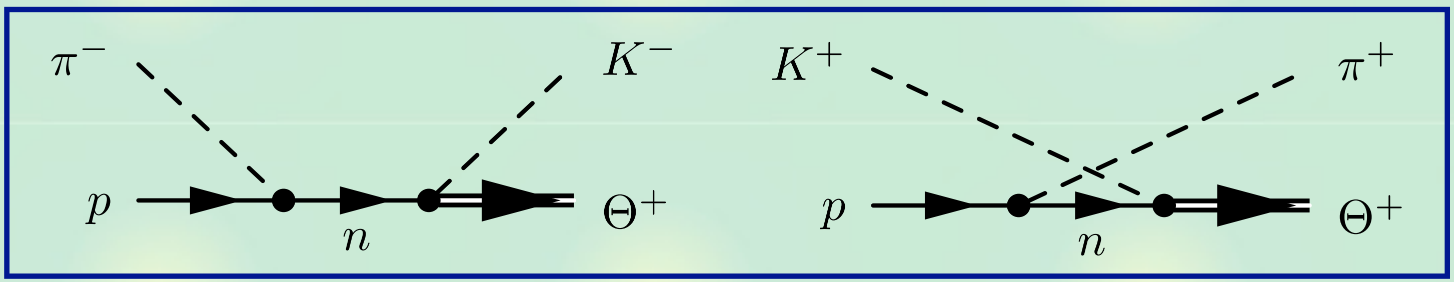
Theoretical study of reactions

Meson-induced Θ^+ production: relatively simple

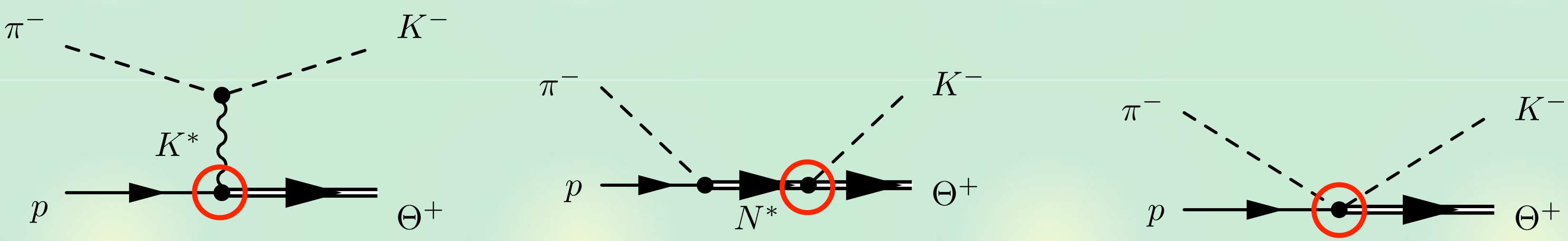
c.f. photo-production <-- Θ^+ magnetic moment,...

We examine isospin I=0, spin S=1/2, parity P=± cases.

- Born terms (must exist if Θ^+ decays into KN)



- Other possible contributions: unknown couplings



T. Hyodo, A. Hosaka, Phys. Rev. C72, 055202 (2005)

We start with the unambiguous Born terms.

Effective Lagrangians

Pseudoscalar (PS) scheme

$$\mathcal{L}^{1/2^\pm}_{KN\Theta} = g^{1/2^\pm}_{KN\Theta}\bar{\Theta}^+\Gamma K N + \text{h.c.}$$

$$\Gamma = \begin{cases} i\gamma_5 & \text{(positive parity)} \\ 1 & \text{(negative parity)} \end{cases}$$

$$\mathcal{L}_{\pi NN} = i g_{\pi NN}\bar{N}\gamma_5 \boldsymbol{\pi} N$$

- coupling constants: decay width of Θ+

$$g^{1/2^\pm}_{KN\Theta} = \sqrt{\frac{2\pi M_\Theta \Gamma_\Theta}{|\boldsymbol{k}|(E \mp M)}}, \quad g_{\pi NN} = 13.5$$

Pseudovector (PV) scheme

$$\mathcal{L}^{1/2^\pm}_{KN\Theta} = \frac{-i g^{*\pm}_A}{2f}\bar{\Theta}^+\gamma_\mu\Gamma\partial^\mu K N + \text{h.c.}$$

$$\mathcal{L}_{\pi NN} = \frac{g_A}{2f}\bar{N}\gamma_\mu\gamma_5\partial^\mu\boldsymbol{\pi} N$$

- generalized GT relation

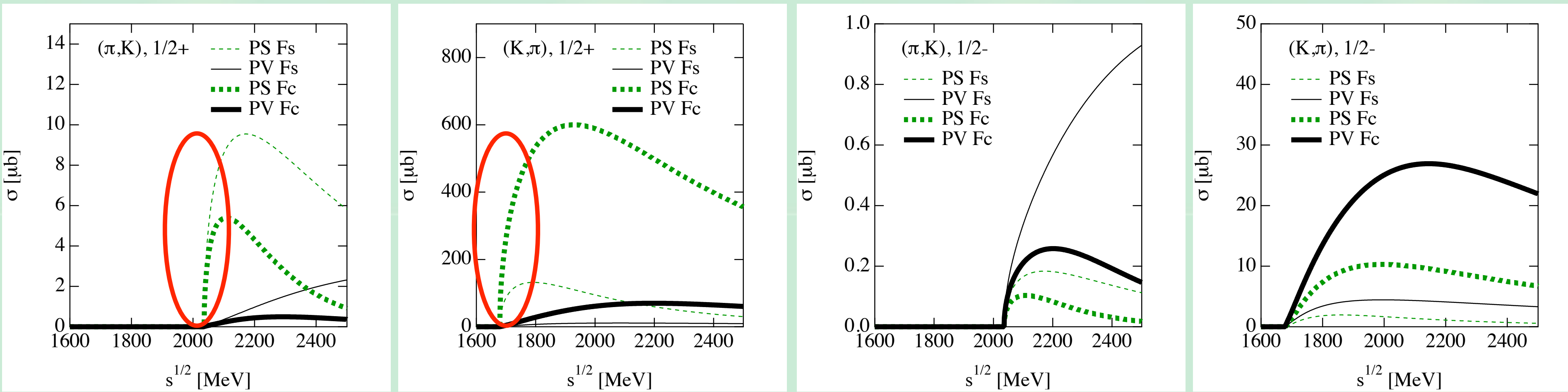
$$g^{*\pm}_A = \frac{2f}{M_\Theta \pm M_N} g^{1/2^\pm}_{KN\Theta}, \quad g_A = 1.25, \quad f = 93 \text{ MeV}$$

Estimation of the cross section

Cross section is straightforwardly calculated.

- Γ = 1 MeV (cross section is proportional to the width).

$$\sigma \propto g^2 \propto \Gamma$$



- Fs, Fc: form factors <-- hyperon production, etc.

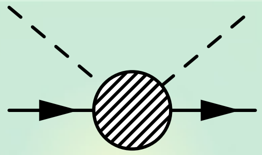
$$F_s(\sqrt{s}) = \frac{\Lambda_s^2}{\Lambda_s^2 + |\boldsymbol{k}|^2}, \quad F_c(x, M_{ex}) = \frac{\Lambda_c^4}{\Lambda_c^4 + (x - M_{ex}^2)^2}$$

- For 1/2+, threshold behavior of PS is different from PV.
  --> chiral low energy theorem

Relation with chiral low energy theorem

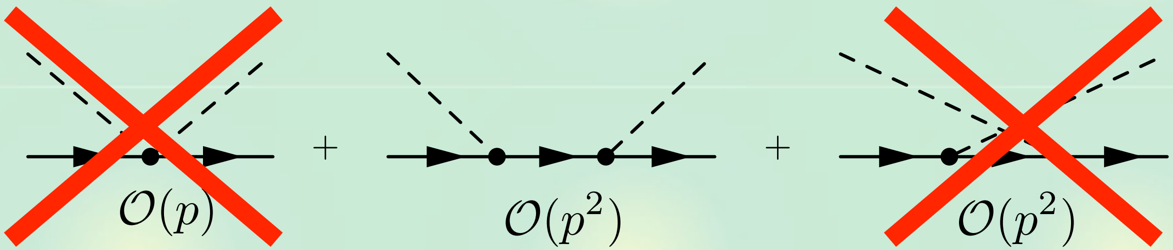
NG boson-hadron scattering: chiral low energy theorem

ex) low energy πN scattering; external momentum p

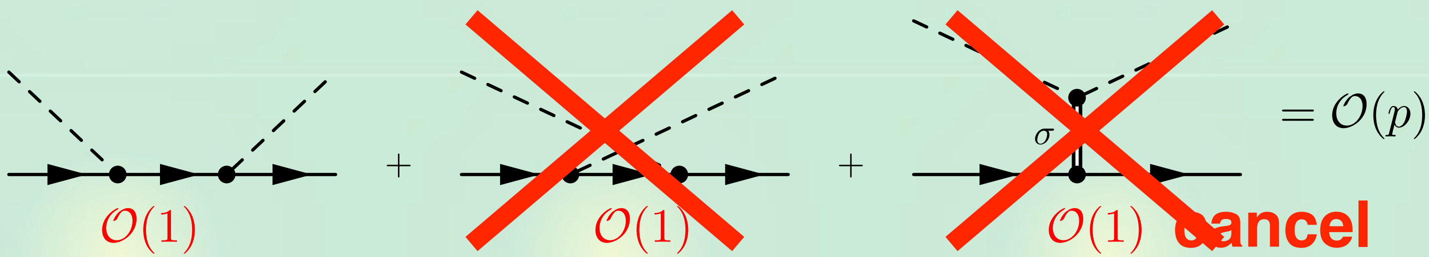


$= \mathcal{O}(p)$

- PV coupling (nonlinear sigma model)



- PS coupling (linear sigma model)



πN --> KΘ: cancellation in PS does not work.

--> large cross section in PS scheme

Comparison with J-PARC data

Total cross section at P_{lab} = 1.92 GeV (M_Θ = 1540 MeV)

Γ_Θ = 1 MeV	1/2+		1/2-	
	(PS)	PV	PS	PV
Fs	(9.2 μb)	0.51 μb	0.18 μb	0.40 μb
Fc	(5.3 μb)	0.29 μb	0.10 μb	0.23 μb

- J-PARC E19: σ < 0.3 μb (assumed to be isotropic)

$$\Rightarrow \Gamma_\Theta \lesssim \mathcal{O}(1)\ \mathrm{MeV}$$

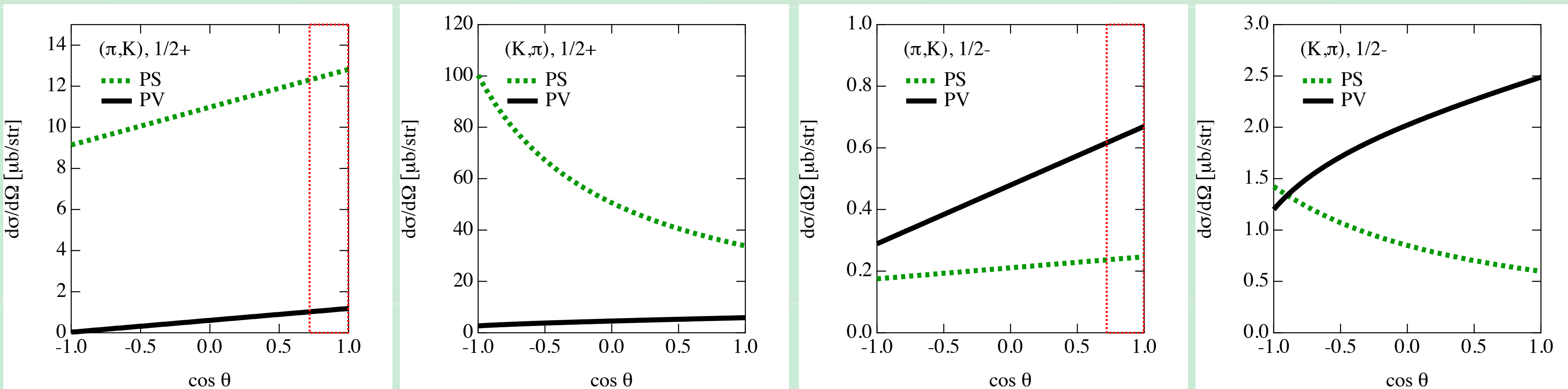
Isotropic distribution may be justified by s-channel diagram.

More quantitative comparison: angular dependence

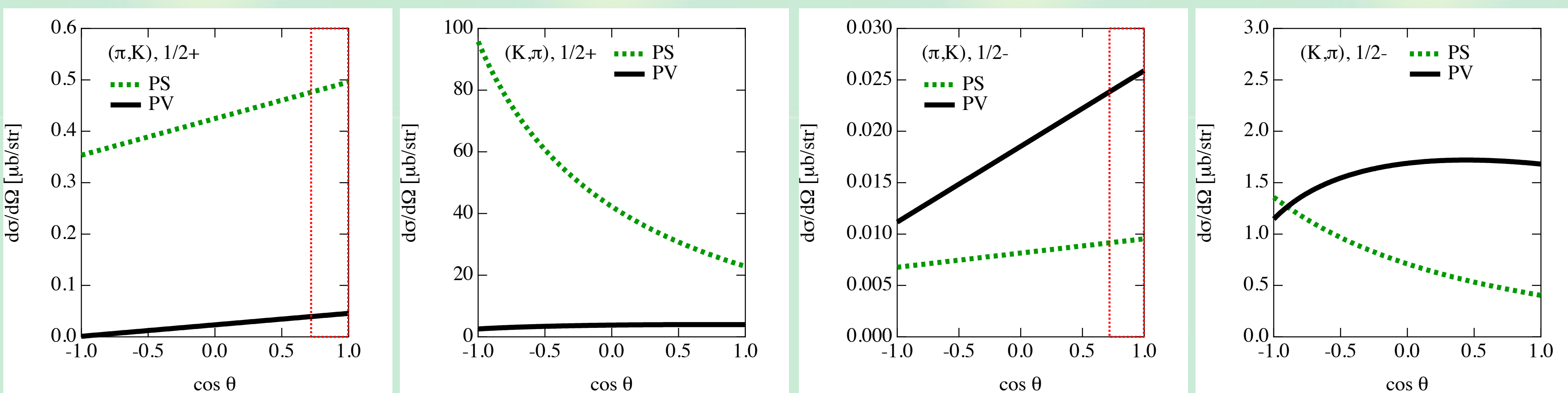
Differential cross section

Angular distribution @ P_{lab} = 1.92 GeV

- Fs form factor



- Fc form factor



Coupling constants

KNΘ coupling (width):

- Kaon secondary interaction by Belle

R. Mizuk, *et al.*, Phys. Lett. B632, 173 (2006)

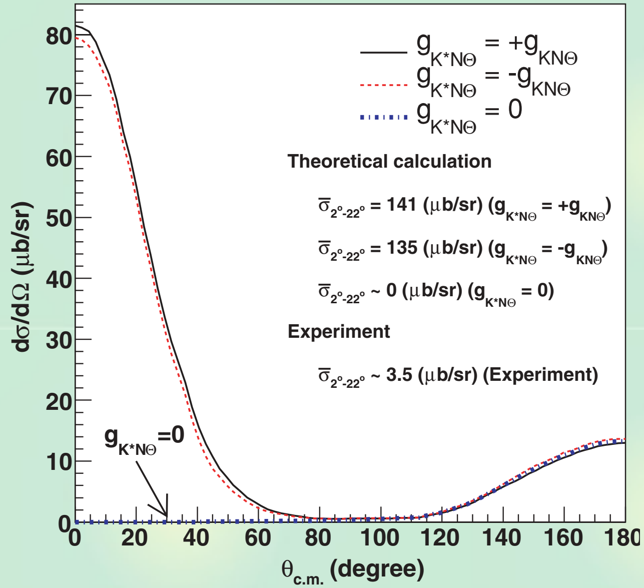
$$\Gamma_\Theta < 0.64 \text{ MeV}$$

K*NΘ coupling:

- K$^+$ induced reaction at KEK

K. Miwa, *et al.*, Phys. Rev. D75, 054014 (2007)

==> coupling should be small



- symmetry + GLAAL result of N* (Θ$^+$: 1/2$^+$)

Y. Azimov, *et al.*, Phys. Rev. D75, 054014 (2007)

- Chiral quark soliton model (Θ$^+$: 1/2$^+$)

T. Ledwig, H.-C. Kim, K. Goeke, Nucl. Phys. A811, 353 (2008)

$$g_{K^*N\Theta} = 0.74\text{-}0.87, \quad f_{K^*N\Theta} = 0.53\text{-}1.16$$

FAQ on Θ^+

Q: Is J-PARC data consistent with LEPS data?

A: Strictly speaking, no direct connection.
It is, however, very difficult to explain LEPS data, with other negative results being reproduced.

Q: Is $\Gamma < 1$ MeV realistic?

A: Strictly speaking, there is no limitation in QCD.
It is, however, extremely difficult to construct a state with such strong decay, except for kinematical reason (small phase space, etc.).

Q: What is the structure of Θ^+

A: (Almost?) all possibilities have been studied.
No satisfactory answer.

Theoretical framework of chiral dynamics

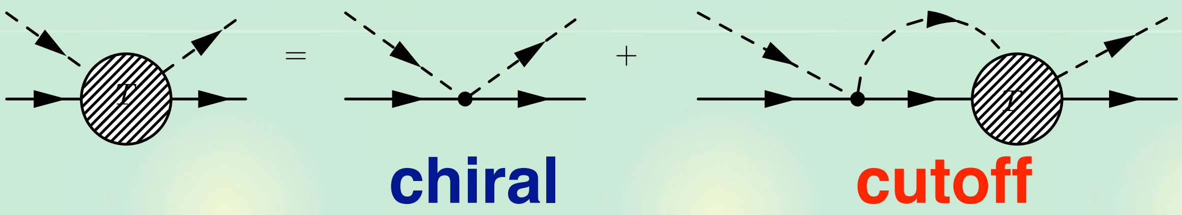
No exotic hadrons are well established in experiments. Why?

Chiral unitary approach

T. Hyodo, D. Jido, arXiv:1104.4474, to appear in Prog. Part. Nucl. Phys.

- Interaction <-- chiral symmetry
- Amplitude <-- unitarity in coupled channels

$$T = \frac{1}{1 - VG} V$$



Sufficient attraction --> hadron resonances

Target	Ref.	J^P	Resonances
$J^P = 1/2^+$ **8** baryon		$1/2^-$	$\Lambda(1405)$, $\Lambda(1650)$, $N(1535)$, $N(1670)$, $\Sigma(1620)$, $\Xi(1620)$
$J^P = 3/2^+$ **10** baryon	[193]	$3/2^-$	$\Lambda(1520)$, $\Sigma(1670)$, $\Sigma(1940)$, $N(1520)$, $\Xi(1820)$, $\Omega(2250)$
Heavy **3**, **6** baryon	[198]	$1/2^-$	$\Lambda_c(2595)$, $\Lambda_c(2880)$, $\Xi_c(2790)$
$J^P = 0^-$ meson	[191]	0^+	$\sigma(600)$, $\kappa(900)$, $f_0(980)$, $a_0(980)$
		1^-	$\rho(770)$, $K^*(892)$, $\phi(1020)$
$J^P = 1^-$ meson	[197]	1^+	$b_1(1235)$, $h_1(1170)$, $h_1(1380)$, $a_1(1260)$, $f_1(1285)$, $K_1(1270)$
Heavy **3** meson	[199]	0^+	$D_s(2317)$

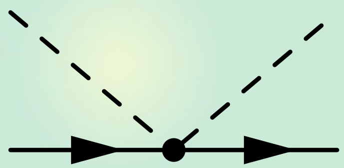
Only the non-exotic states are generated.

Chiral low energy interaction

Exotic hadron in chiral dynamics

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. Lett. 97, 192002 (2006); D75, 034002 (2007)

- Chiral interaction: low energy theorem



$\propto C$ determined by flavor representation and SU(3) group theory

- Exoticness quantum number for R=[p,q]

$$E = \epsilon\theta(\epsilon) + \nu\theta(\nu), \quad \epsilon = \frac{p+2q}{3} - B, \quad \nu = \frac{p-q}{3} - B,$$

minimal number of ($q\bar{q}$) pair to construct R.

Chiral interaction in exotic channel

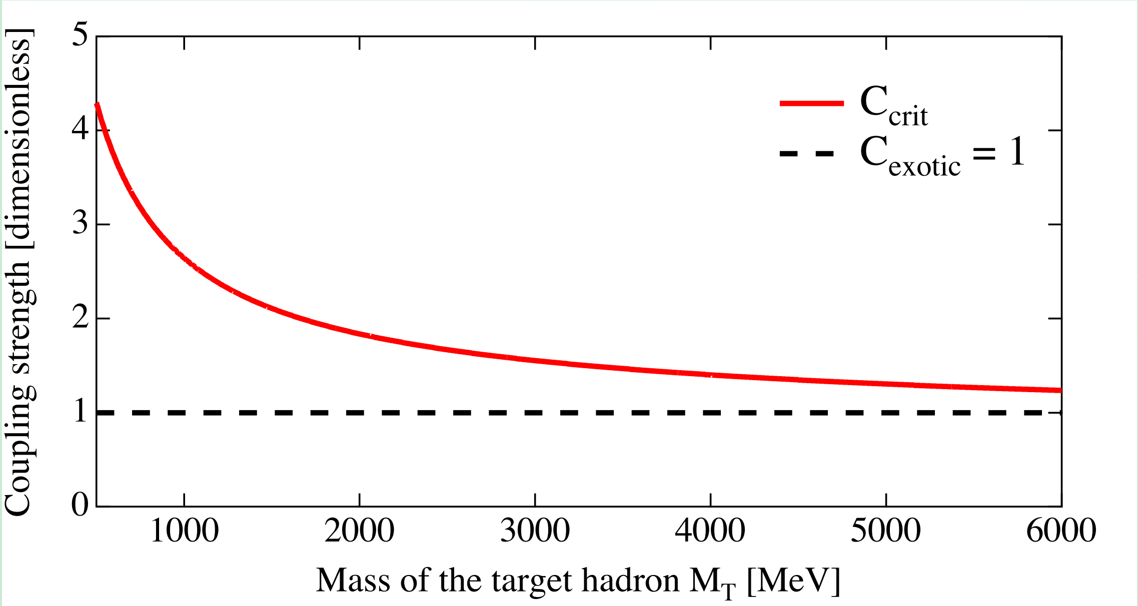
--> mostly repulsive, and attractive strength is bounded by

$$C_{\text{exotic}} \leq 1$$

Critical coupling strength

Critical strength to generate a bound state

$$C_{\text{crit}} = \frac{2f^2}{m[-G(M_T+m)]}$$



Chiral dynamics:

- Normal hadrons are dynamically generated.
- Exotic hadrons are difficult to generate.

A kind of “saturation” is achieved.

Exotics with charm

Observed (crypto-)exotic hadrons

- New charmonia and heavy mesons

E.S. Swanson, Phys. Rept. 429, 243 (2006);
M. Nielsen, F. Navarra, S.H. Lee, Phys. Rept. 497, 41 (2010);
many more...

Predicted exotic hadrons

- $\bar{D}N$ bound (resonance) state: $uudd\bar{c}$

S. Yasui, K. Sudoh, Phys. Rev. D80, 034008 (2009);
Y. Yamaguchi, S. Ohkoda, S. Yasui, A. Hosaka, Phys. Rev. D84, 014032 (2011);
see also T. D. Cohen, P. M. Hohler, R. F. Lebed, Phys. Rev. D72, 074010 (2005)

- Tetraquark Tcc: $\bar{u}\bar{d}cc$

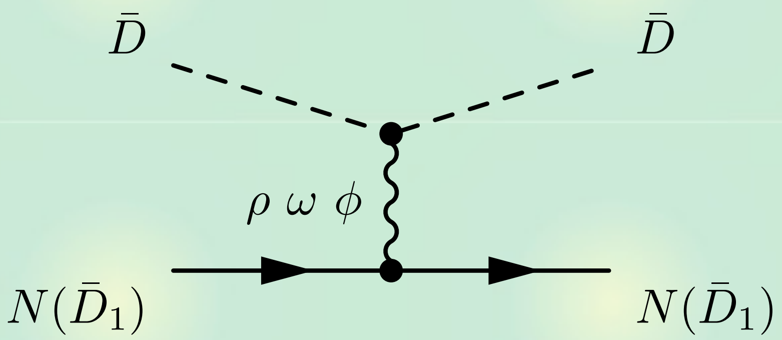
S. Zouzou, et al., Z. Phys. C30, 457 (1986);
A. Selem, F. Wilczek, hep-ph/0602128;
J. Vijande, A. Valcarce, K. Tsushima, Phys. Rev. D74, 054018 (2006)

Relation with chiral dynamics

Driving mechanism is different for DN and Tcc.

- $\bar{D}$N state: π exchange, tensor force, ...
- Tcc state: diquark correlation (or π exchange), ...

D ≠ NG boson, but vector-meson exchange is equivalent



In the SU(3) limit,

- interaction **vanishes** (C=0) for I=0
- interaction is **repulsive** (C<0) for I=1

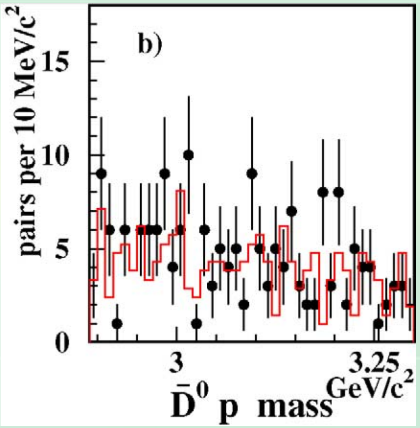
see also Y. Yamaguchi, S. Ohkoda, S. Yasui, A. Hosaka, Phys. Rev. D84, 014032 (2011)

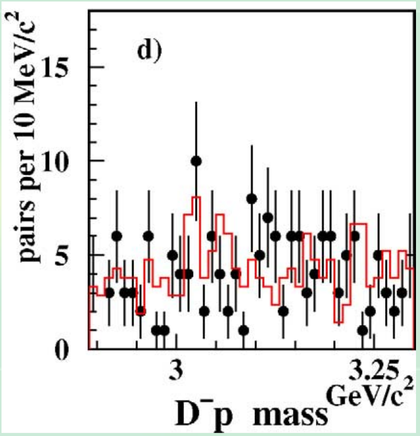
Vector-meson exchange does not break up the I=0 states.

Experimental constraints

Charmed pentaquark search

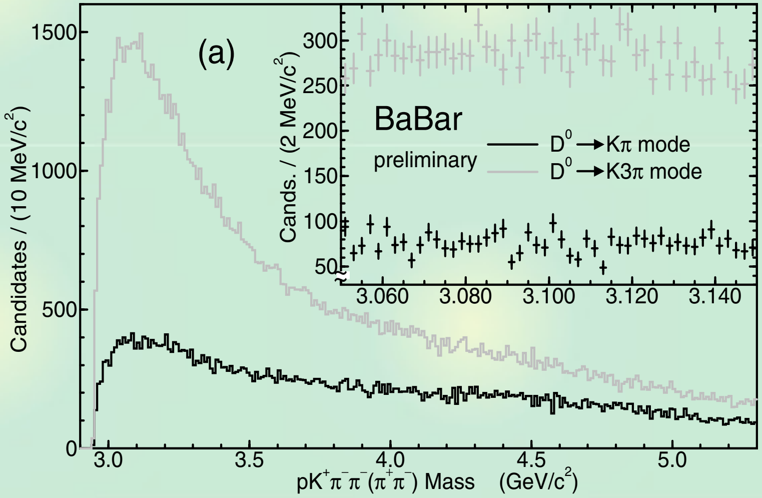
S. Schael, *et al.*, ALEPH Collaboration, Phys. Lett. B599, 1 (2004)





$\bar{D}N$ spectrum

T. Berger-Hryn'ova, *et al.*, Babar Collaboration, AIP Conf. Proc. 814, 320 (2006)



$\bar{D}^*N$ spectrum

Summary

We discuss the Θ^+ and exotic hadrons

- Study of exotic hadrons is important to understand the low energy QCD.
- With the simplest (but mandatory) model, J-PARC E19 result is interpreted as:

$$\Gamma_\Theta \lesssim \mathcal{O}(1)\ \mathrm{MeV}$$

- Chiral dynamics disfavors the generation of exotic hadrons.
- More exotic hadrons may be observed in heavy quark sector.