DN interaction, $\Lambda_c(2595)$, and DNN quasi-bound state

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Conventions for heavy mesons

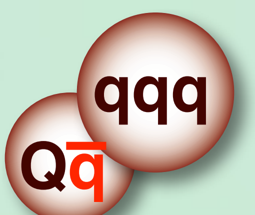
Convention of quantum number of quarks

strange	charm	bottom
S = -1	C = +1	B = -1

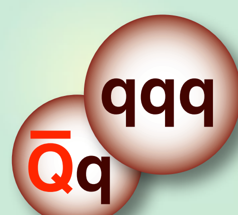
Heavy-light mesons: bar for negative flavor-ness (q~u,d)

with $\bar{q}$	$\bar{K}$ ($s\bar{q}$)	D ($c\bar{q}$)	$\bar{B}$ ($b\bar{q}$)
with q	K ($\bar{s}q$)	$\bar{D}$ ($\bar{c}q$)	B ($\bar{b}q$)

DN <--> $\bar{K}$N : non-exotic
light quark annihilation

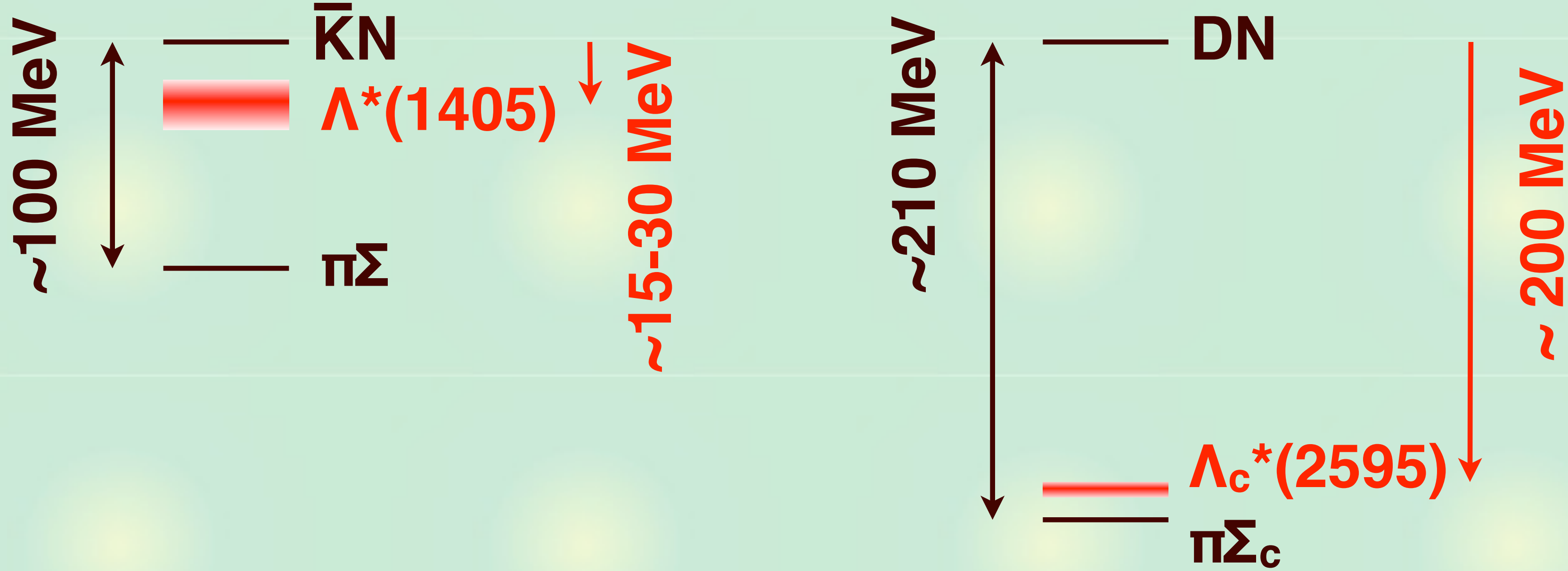


$\bar{D}$N <--> KN : exotic
Θ^+, Yasui-Sudoh



Why DN and DNN?

Comparison with $\bar{K}N$ system in I=0 channel



- large mass splitting between DN and $\pi\Sigma_c$
- narrow negative parity Λ_c^*, analogous to $\Lambda(1405)$?

Λ^*: a $\bar{K}N$ bound state in the $\pi\Sigma$ continuum --> $\bar{K}$ nuclei

Λ_c^*: a DN bound state in the $\pi\Sigma_c$ continuum --> D nuclei?
(c.f. conventionally, Λ_c^* ~ 3-quark state)

DN bound state picture ?

Can Λ_c^* (with large binding) be a DN quasi-bound state?

- D (1867 MeV) is heavier than $\bar{K}$ (496 MeV).
  Kinetic energy is suppressed.
  If the DN interaction were the same with $\bar{K}$N,
  system would develop a deeper quasi-bound state.

- Vector meson exchange picture leads to a stronger DN interaction than $\bar{K}$N at threshold

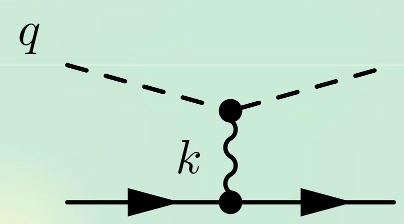
$$\frac{V_D}{V_K} = \frac{m_D}{m_K} \sim 3.8$$ (next slide)

DN system can generate a strongly bound state: Λ_c^*.

Vector meson exchange for DN

DN ($\bar{K}$N) interaction in vector meson exchange (low energy)

$$V \sim g\bar{u}\gamma^{\mu}u \times \frac{1}{k^2 - m_v^2}\left[g_{\mu\nu} - \frac{k_{\mu}k_{\nu}}{m_v^2}\right] \times g(q+q')^{\nu}$$



$$\to -\bar{u}\gamma^{\mu}u\frac{g^2}{m_v^2}g_{\mu\nu}(q+q')^{\nu} \quad (k \ll m_v)$$

$$\to -\frac{1}{2f^2}\bar{u}(\not{q} + \not{q}')u \quad (\text{KSRF relation})$$

(Weinberg-Tomozawa term)

$$\to -\frac{1}{2f^2}(q^0 + q^{0\prime}) \quad (\text{nonrel. leading})$$

$$\to -\frac{m}{f^2} \quad (\text{at threshold})$$

Interaction in DN-$\pi\Sigma_c$ system

$$V \sim \begin{pmatrix} -3m_D & \sqrt{\frac{3}{2}}\kappa_c\frac{m_D+m_\pi}{2} \\ \sqrt{\frac{3}{2}}\kappa_c\frac{m_D+m_\pi}{2} & -4m_\pi \end{pmatrix}$$

$$\kappa_c \sim \frac{m_{K^*}^2}{m_{D^*}^2} \sim \frac{1}{4}$$

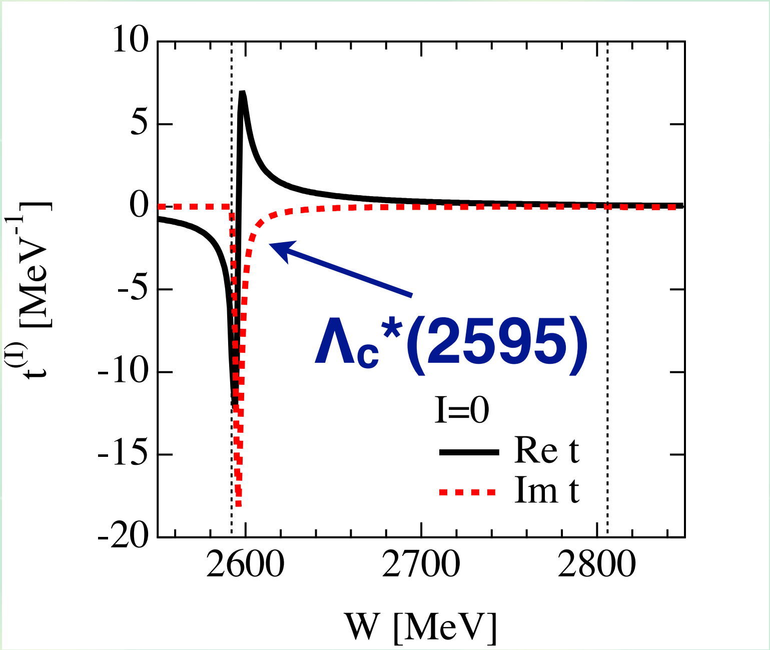
- strong DN interaction --> large binding energy
- suppressed off-diagonal coupling --> narrow width of Λ_c^*

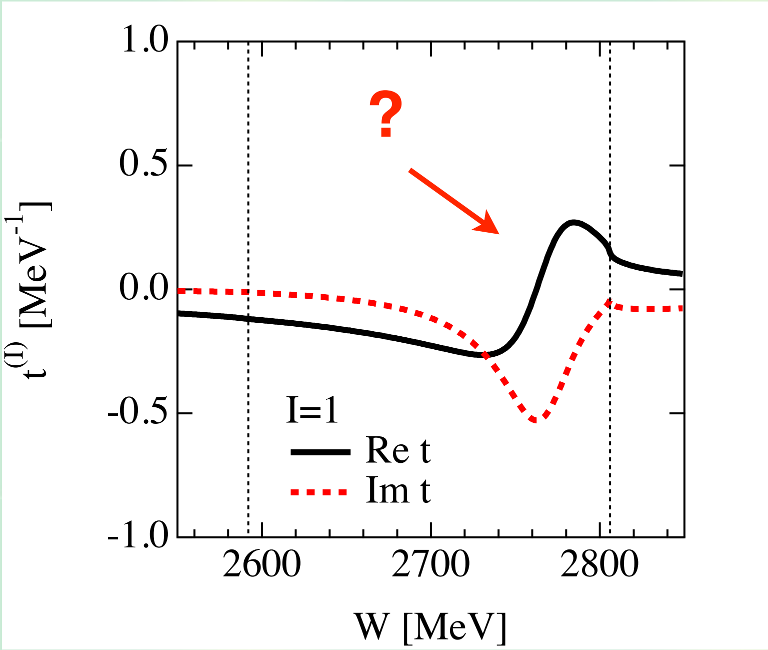
DN scattering amplitude

Coupled-channel DN ($\pi\Sigma_c$, $\eta\Lambda_c$, $K\Xi_c$, $K\Xi_c'$, $D_s\Lambda$, $\eta'\Lambda_c$) scattering

see T. Mizutani, A. Ramos, Phys. Rev. C74, 065201 (2006)

Subtraction constants (cutoff parameters) are chosen to reproduce Λ_c^* in I=0. Apply the same constants to I=1.





A resonance at ~ 2760 MeV is generated in I=1 channel.

c.f. PDG 1*: $\Lambda_c^*(2765)$ or $\Sigma_c^*(2765)$??

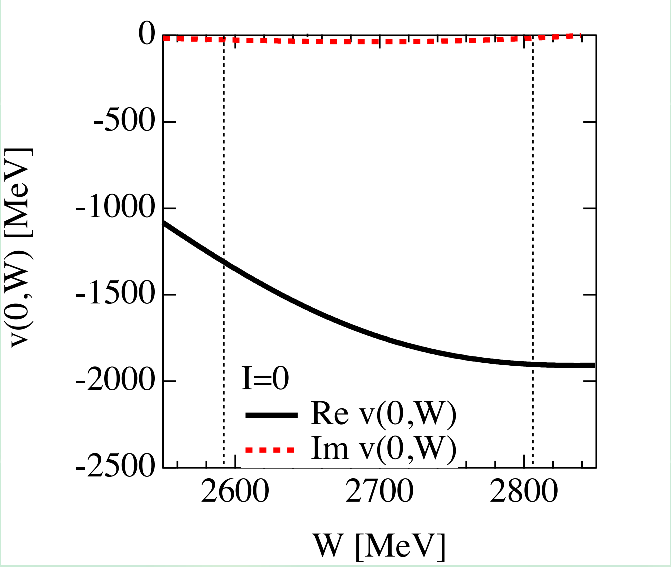
DN local potential

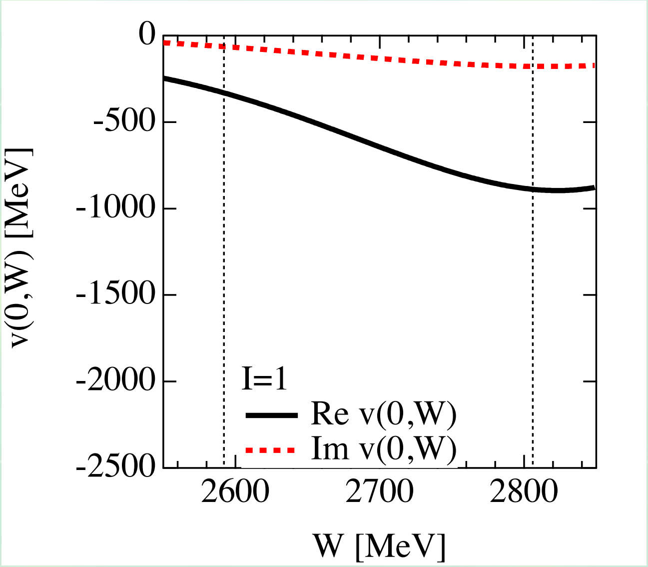
Equivalent single-channel local potential

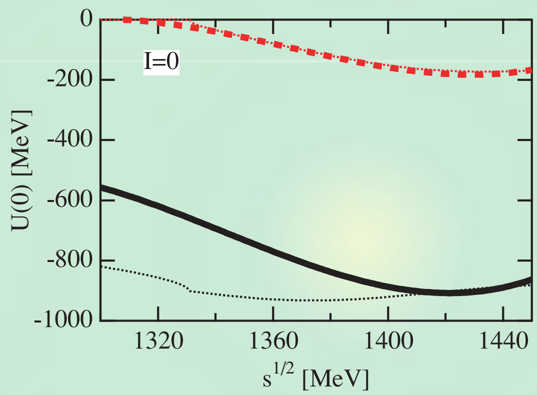
see T. Hyodo, W. Weise, Phys. Rev. C77, 035204 (2008)

$$v_{DN}(r;W) = \frac{M_N}{2\pi^{3/2}a_s^3\tilde{\omega}(W)}[v^{\rm eff}(W) + \Delta v(W)]\exp[-(r/a_s)^2]$$

- reproduces the coupled channel amplitude







c.f. $\bar{K}N$ case

This potential reproduces the DN amplitude in CC model.

Larger (smaller) real (imaginary) part than $\bar{K}N$

DN molecule?

Our model space: meson-baryon channels. No bare field.

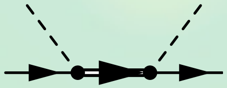
- Is the quasi-bound state a DN molecule?

No. Pole contribution can be hidden in the cutoff.

T. Hyodo, D. Jido, A. Hosaka, Phys. Rev. C78, 025203 (2008)

$$T = \frac{1}{(V^{(1)})^{-1} - G(\underline{a})}$$

$$T = \frac{1}{(V^{(1)} + V^{(2)})^{-1} - G(\underline{a'})}$$

↑pole 

Once the cutoff parameter is chosen to reproduce data, it can play a role of bare field as well as other coupled channels ($\pi\Sigma_c^*$, D*N, etc.), which are not included in the model space.

Strategy for DNN bound state

Coupled-channel model
DN amplitude, $\Lambda_c(2595)$

→ **DN single-channel potential**

→ real part

→ **Three-body variational calculation**

- Structure from wave function
- NN dynamics is dynamically solved.

→ Assume NN distribution

→ **Fixed-center approximation to Faddeev equation**

- Two-body absorption
- Imaginary part of the amplitude is treated.

Coupled-channel ($\pi Y_c N$) effect is partly included.

Variational calculation: setup

Quantum number: $I=1/2$, $J^P=0^-$, 1^-

- $J^P=0^-$ "D^+nn"

  $S_{NN}=0$
  $I_{NN}=1$ (s-wave) --> $DN(I=0)$:$DN(I=1)$ = 3:1

- $J^P=1^-$ "D^+d"

  $S_{NN}=1$
  $I_{NN}=0$ (s-wave) --> $DN(I=0)$:$DN(I=1)$ = 1:3

Two-body interactions

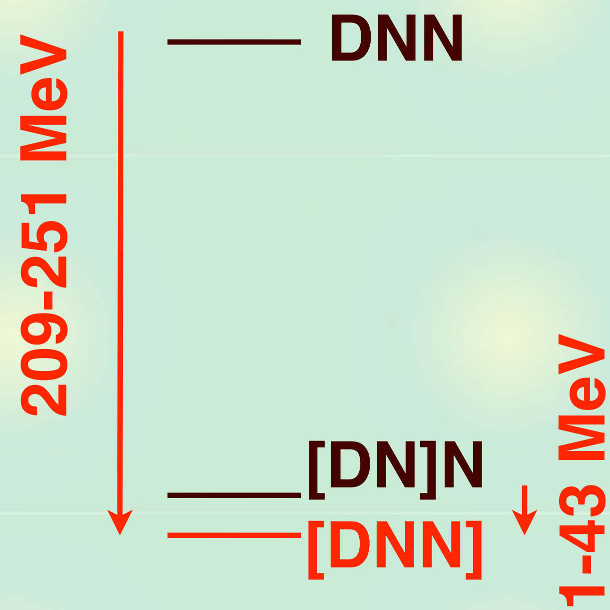
- DN imaginary part is neglected
- energy dependence is fixed at Λ_c^* (I=1 QBS disappears)
- three kinds of NN forces (Av18, HN1R, Minnesota)

Variational calculation: results

Results of the DNN system

- J=0 bound, J=1 unbound w.r.t. [DN]N
- mesonic decay width is small
- softer the core, larger the binding

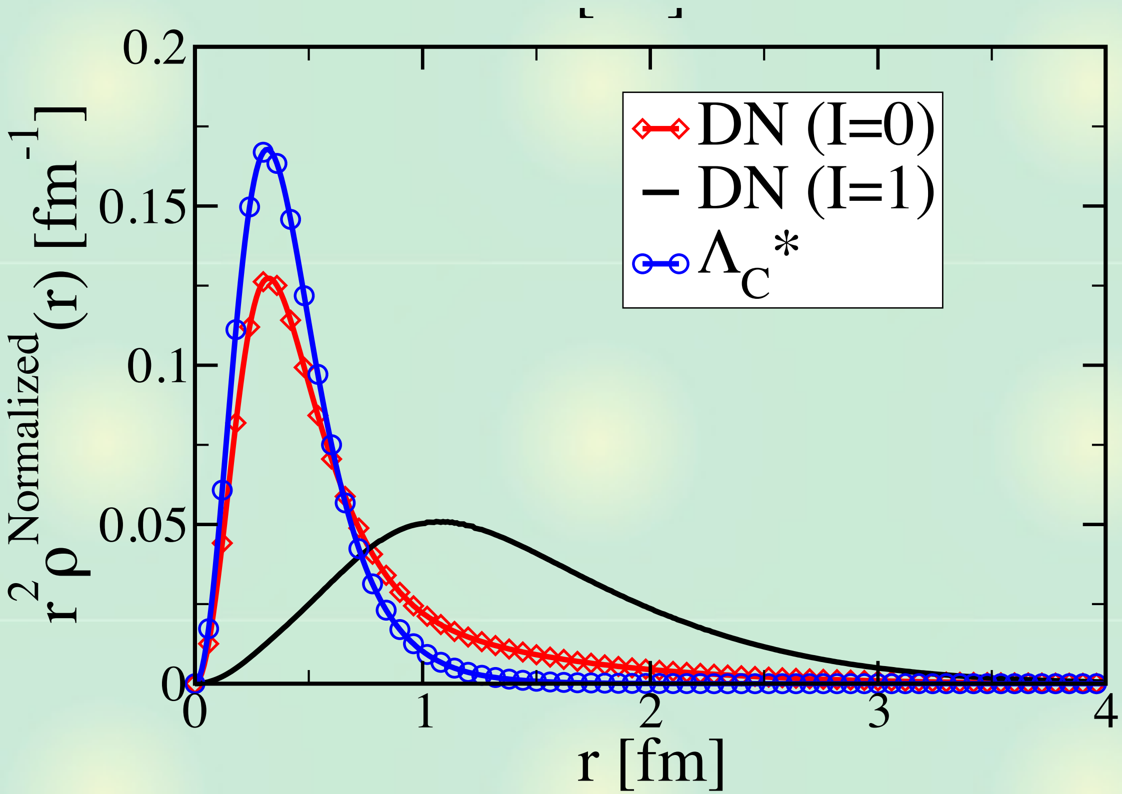
	HN1R		Minnesota	Av18
	$J=1$	$J=0$	$J=0$	$J=0$
	unbound	bound	bound	bound
B	208	225	251	209
M_B	3537	3520	3494	3536
$\Gamma_{\pi Y_c N}$	-	26	38	22
$E_{\rm kin}$	338	352	438	335
$V(NN)$	0	-2	19	-5
$V(DN)$	-546	-575	-708	-540
$T_{\rm nuc}$	113	126	162	117
E_{NN}	113	124	181	113
P(Odd)	75.0 %	14.4 %	7.4 %	18.9 %

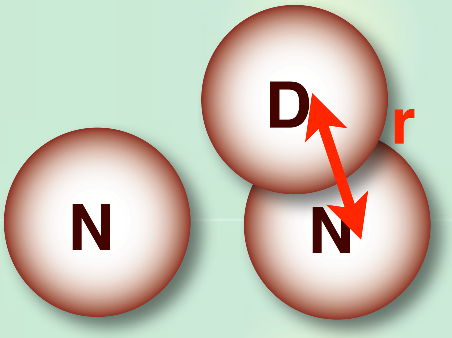


Variational calculation: DN correlation

Isospin decomposition of DN two-body correlation

$$\rho_{DN}(r) = \langle\Psi| \sum_{i=1,2} \delta^3(|\boldsymbol{r}_D - \boldsymbol{r}_i| - r)|\Psi\rangle$$

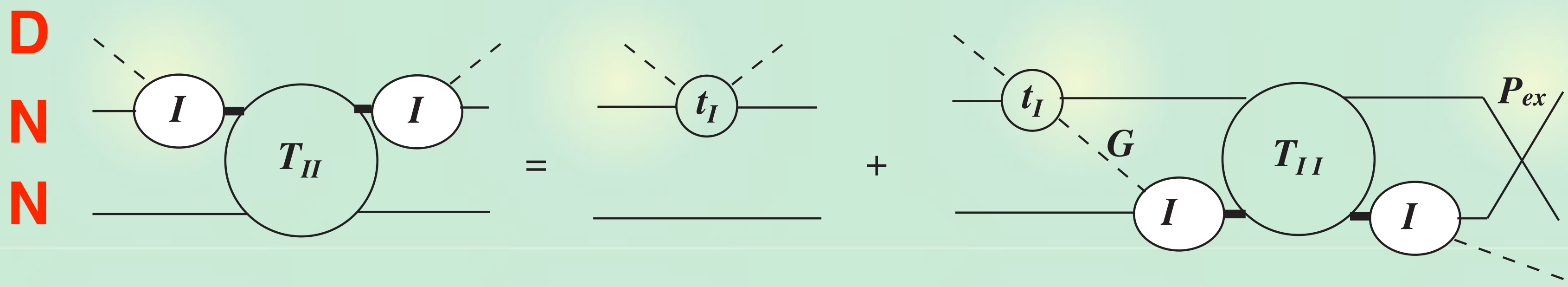




DN (I=0) correlation is similar to Λ_c*

FCA calculation

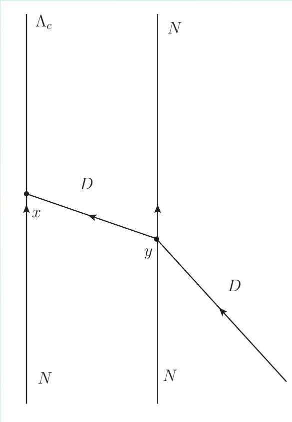
Fixed-center approximation to Faddeev equation

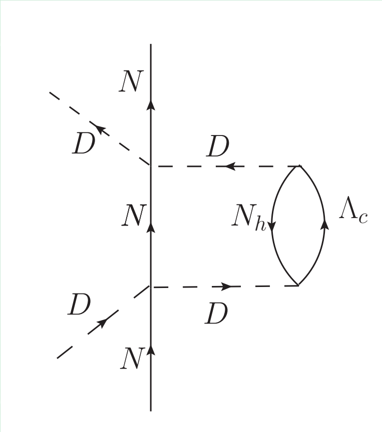


- Complex DN amplitude
- all two-body pairs are in s-wave
- NN distribution is assumed
  (chosen to be smaller than the deuteron)

FCA calculation: two-body absorption

Two-body absorption --> imaginary part of DN amplitude

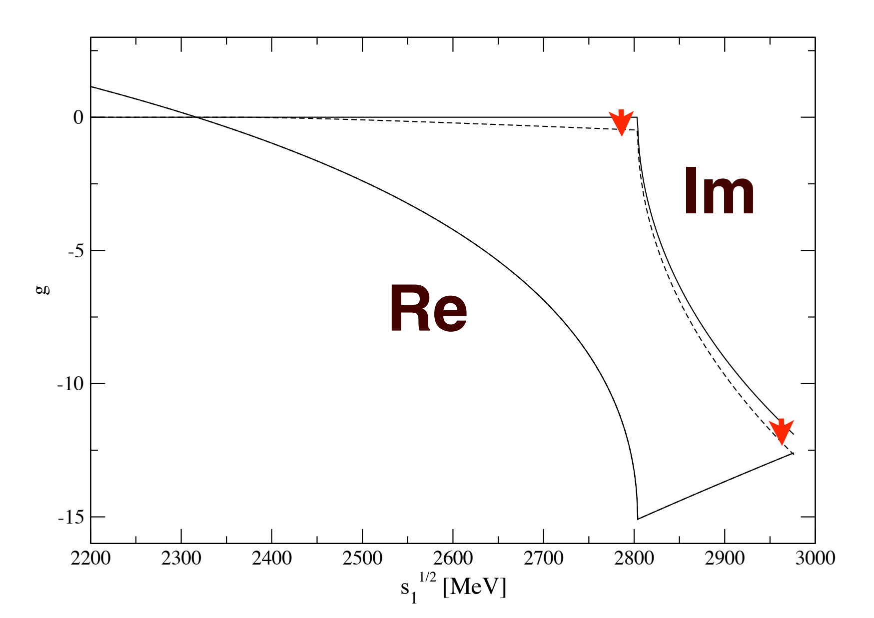




$$g_{DN} \to g_{DN} + i\,\boxed{\mathrm{Im}\ \delta\tilde{g}}$$

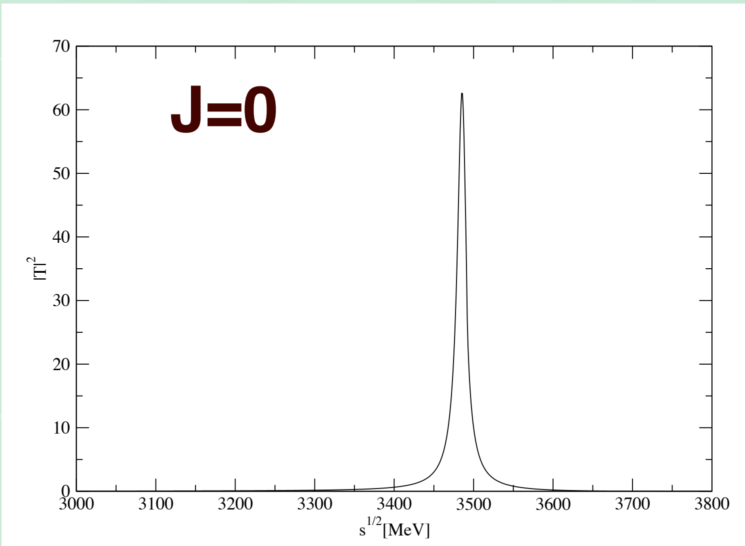
DN loop

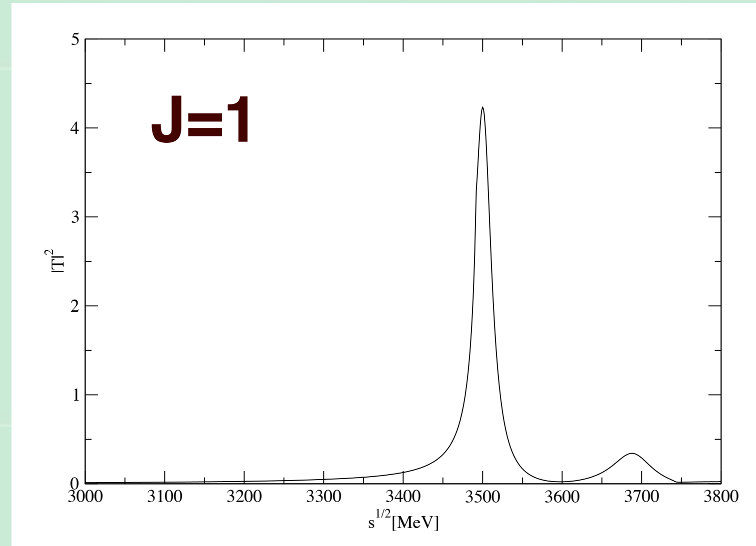
two-body absorption contribution



FCA calculation: result

Magnitude of the three-body amplitude square





J=0 channel: M ~ 3500 MeV

- strong signal, consistent with the variational calculation

J=1 channel: M ~ 3500 MeV and M ~ 3700 MeV?

- week signal, not found in the variational calculation??

- I=1 DN interaction is important for this channel.

Possible experiments

Antiproton beam

$$\bar{p} + {}^3\mathrm{He} \to \bar{D}^0 D^0 pn \to \bar{D}^0[DNN]$$

- PANDA?

Pion beam

$$\pi^- + d \to D^- D^+ np \to D^-[DNN]$$

$$\pi^- + d \to D^- \Lambda_c^+ n \to D^-[DNN]$$

- J-PARC high momentum beamline?

Heavy Ion collision

Coalescence DNN (large binding), Λ_c*N (small binding)

- RHIC, LHC,...

S. Cho, *et al*, Phys. Rev. Lett. 106, 212001 (2011); Phys. Rev. C 84, 064910 (2011)

Summary

We study DN interaction and DNN system

- DN interaction is constructed by regarding Λ_c^* as "DN quasi-bound state".
- A narrow DNN quasi-bound state in spin J=0 channel.

  $B_{DNN} \sim 250$ MeV, $B_{\Lambda_c^* N} \sim 40$ MeV

  $\Gamma \sim 20\text{-}40$ MeV

- DN forms a compact cluster, but Λ_c^*N bounds loosely.

M. Bayar *et al.*, arXiv:1205.2275 [hep-ph]