

Understanding the structure of $d^*(2380)$ in a chiral quark model

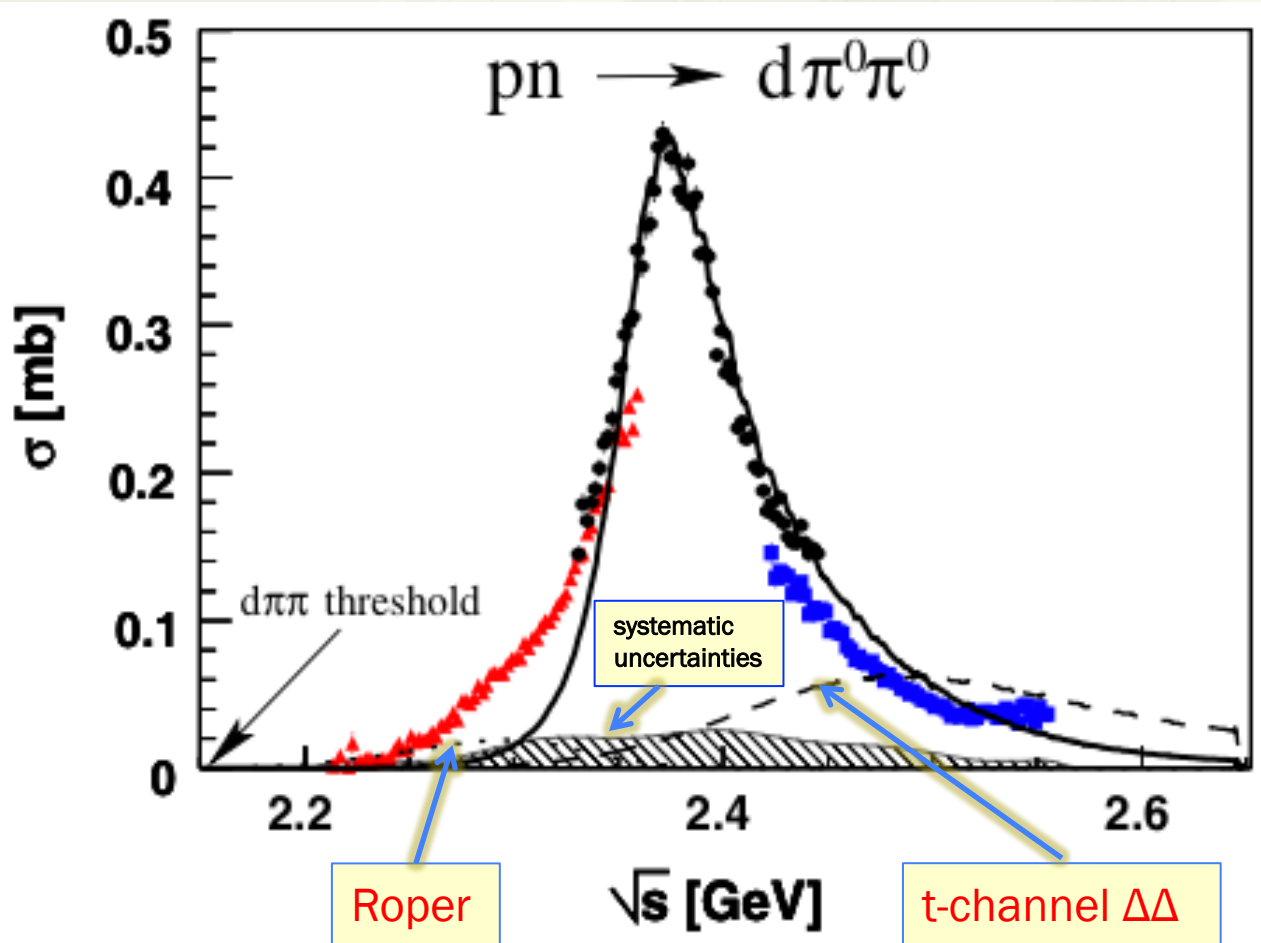
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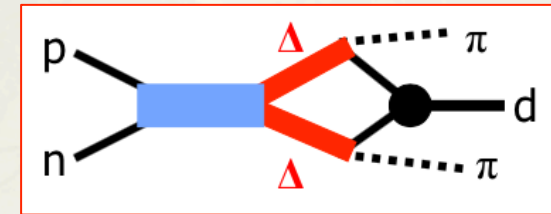
**Collaborators: Z.Y. Zhang, P.N. Shen, Y.B. Dong (IHEP, CAS)
W.L. Wang (Beihang U.)**

Experiments @ COSY

WASA-at-COSY, PRL106(2011)242302



- ✧ Exclusive
- ✧ Kinematically complete



$$I(J^p) = 0(3^+)$$

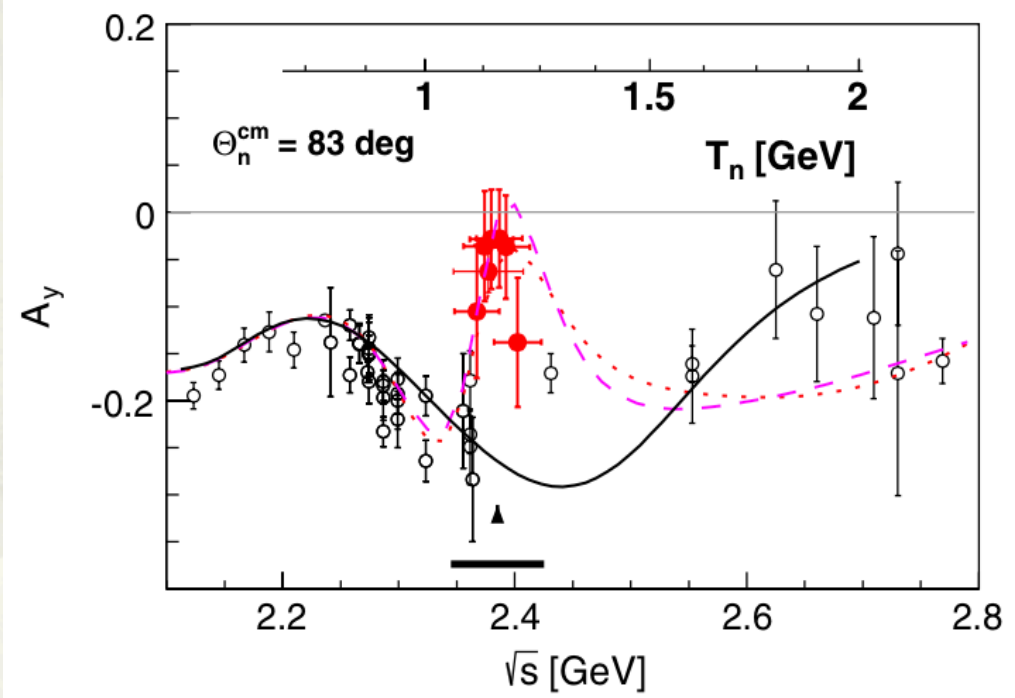
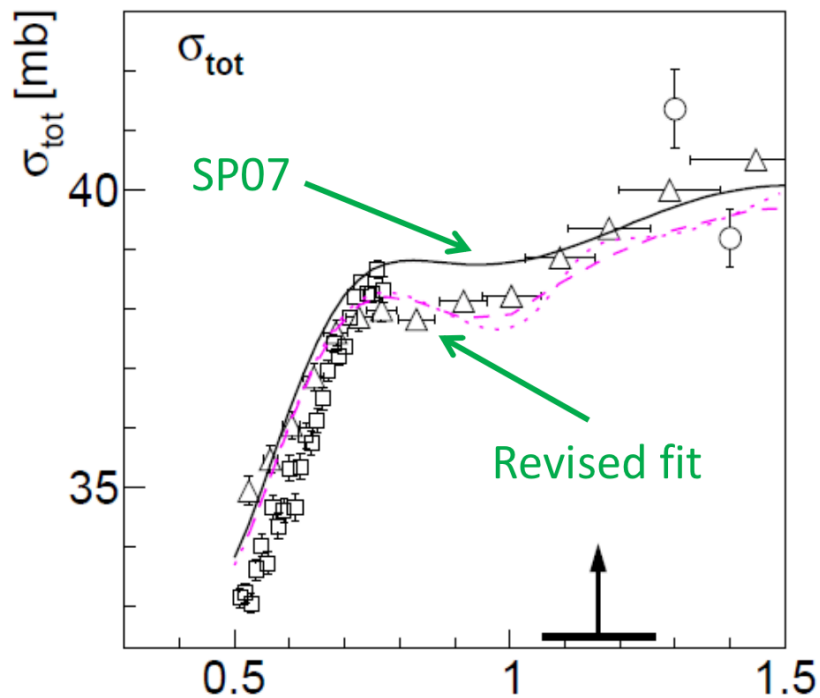
$$M \approx 2380 \text{ MeV}$$

$$\Gamma \approx 70 \text{ MeV}$$

Evidence from $\vec{n}p$ scattering

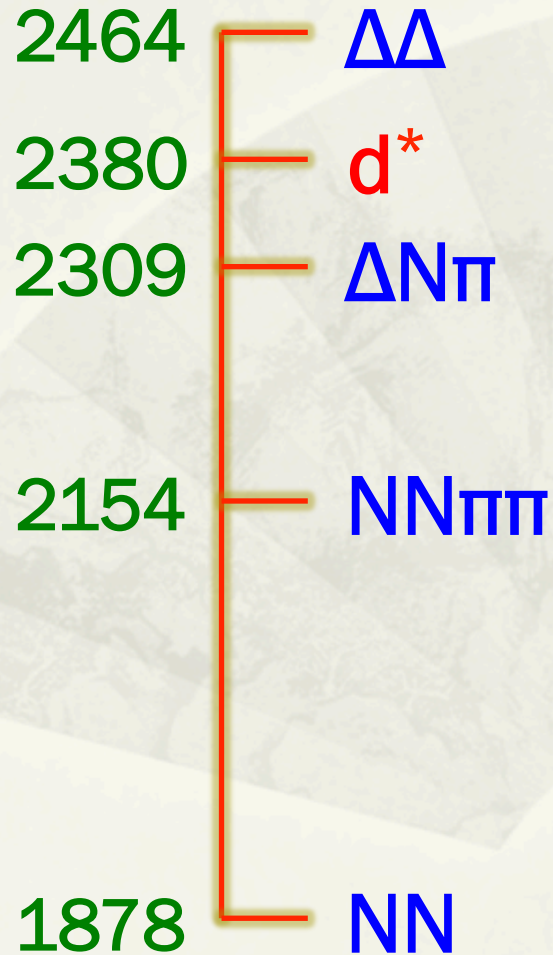
$\vec{d}p \rightarrow np + p_{\text{spectator}}$

$$M = (2380 \pm 10) - i(40 \pm 5)$$



WASA-at-COSY & SAID DAC, PRL112(2014)202301

Unusual narrow width of d^*



$$M_{d^*} \approx 2380 \text{ MeV}$$

$$\approx 2M_{\Delta} - 84 \text{ MeV}$$

$$> M_{\Delta N\pi}$$

$$> M_{NN\pi\pi\pi}$$

$$> M_{NN}$$

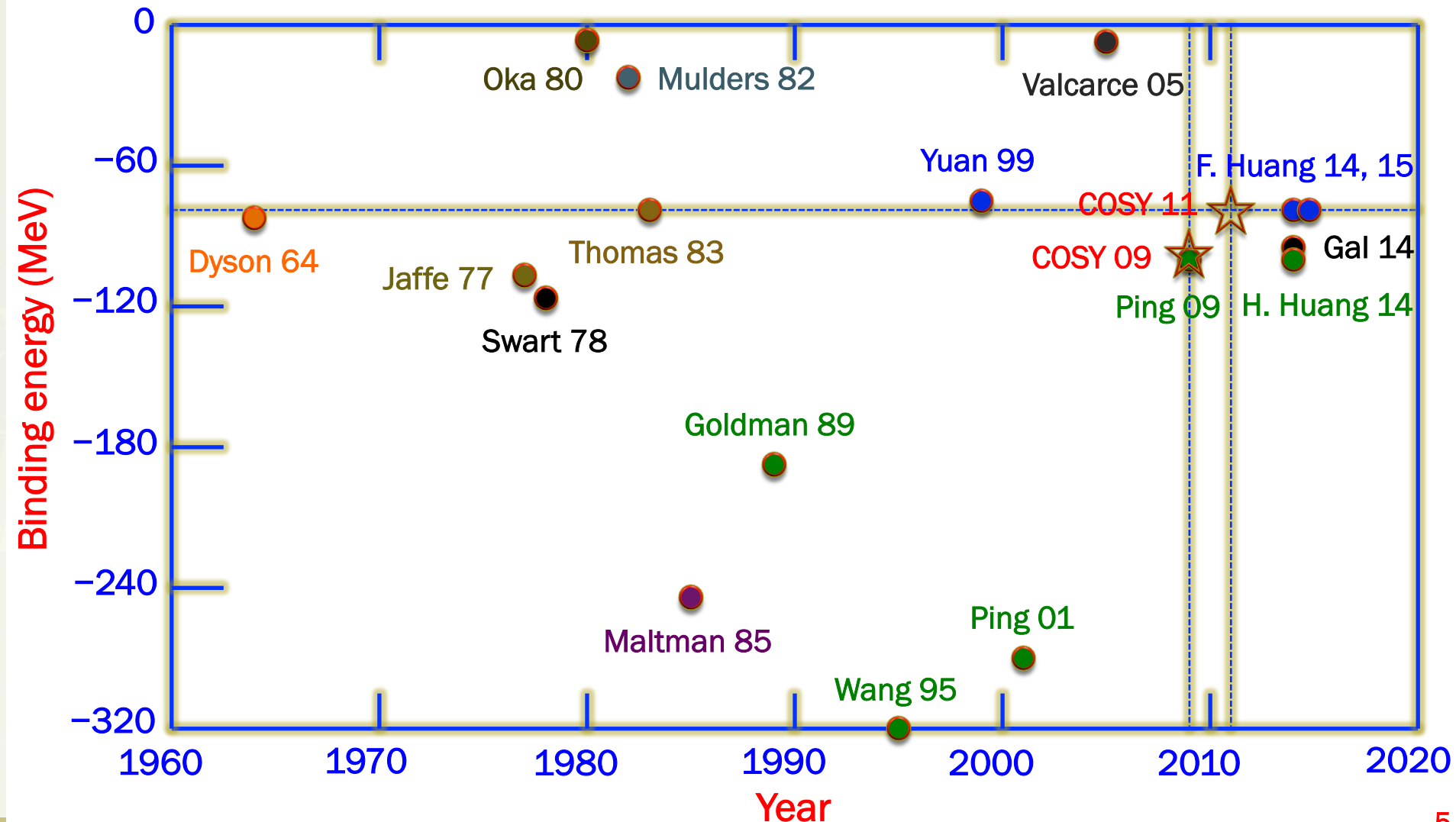
$$2\Gamma_{\Delta} \approx 230 \text{ MeV}$$

$$\Gamma_{d^*} \approx 70 \text{ MeV}$$

$$< 1/3 \times 2\Gamma_{\Delta}$$



Theoretical $\Delta\Delta$ binding energies



Our prediction in 1999

X. Q. Yuan, Z. Y. Zhang, Y. W. Yu, and P. N. Shen, Phys. Rev. C 60, 045203 (1999).

TABLE II. Binding energy B and rms \bar{R} of the deltaron $B = -(E_{\text{deltaron}} - 2M_{\Delta})$, $\bar{R} = \sqrt{\langle r^2 \rangle}$.

		$\Delta\Delta(L=0)$	$\Delta\Delta\left(\begin{smallmatrix} L=0 \\ +2 \end{smallmatrix}\right)$	$\frac{\Delta\Delta}{CC}(L=0)$	$\frac{\Delta\Delta}{CC}\left(\begin{smallmatrix} L=0 \\ +2 \end{smallmatrix}\right)$
OGE	B (MeV)	29.8	29.9	41.0	42.0
	\bar{R} (fm)	0.92	0.92	0.87	0.87
OGE + π, σ	B (MeV)	50.2	62.6	68.6	79.7
	\bar{R} (fm)	0.87	0.86	0.84	0.83
OGE + SU(3)	B (MeV)	18.4	22.5	31.7	37.3
	\bar{R} (fm)	1.01	1.00	0.92	0.92

- Binding energy: 40 ~ 80 MeV
- CC: 10 ~ 20 MeV increase in binding energy

Our most recent work

F. Huang, P. N. Shen, Y. B. Dong, and Z. Y. Zhang, arXiv: 1505.05395

Total Hamiltonian for 6q systems:

$$H = \sum_{i=1}^6 \left(m_i + \frac{\vec{P}_i^2}{2m_i} \right) - T_{\text{cm}} + \sum_{1=i<j}^6 \left(V_{ij}^{\text{conf}} + V_{ij}^{\text{OGE}} + V_{ij}^{\text{ch}} \right)$$

Ch. SU(3) QM:

$$V_{ij}^{\text{ch}} = \sum_{a=0}^8 V_{ij}^{\sigma_a} + \sum_{a=0}^8 V_{ij}^{\pi_a}$$

Ext. Ch. SU(3) QM:

$$V_{ij}^{\text{ch}} = \sum_{a=0}^8 V_{ij}^{\sigma_a} + \sum_{a=0}^8 V_{ij}^{\pi_a} + \sum_{a=0}^8 V_{ij}^{\rho_a}$$

Determination of parameters

- **Input:** $m_u = m_d = 313 \text{ MeV}$,
 $b_u = 0.5 \text{ fm (SU(3))}$ & $0.45 \text{ fm (ex. SU(3))}$

- **Coupling between quark & chiral fields:**

$$\frac{g_{\text{ch}}^2}{4\pi} = \left(\frac{3}{5}\right)^2 \frac{g_{NN\pi}^2}{4\pi} \frac{m_u^2}{m_N^2}, \quad \frac{g_{NN\pi}^2}{4\pi} = 13.67$$

- **Mass of mesons:** experimental values except for m_σ

- **Coupling constant for OGE:** $g_u \propto m_\Delta - m_N$

- **Confinement strength & zero point energy:**

$$\frac{\partial m_N}{\partial b_u} = 0, \quad m_N = 939 \text{ MeV}$$

Parameter values

All parameters fixed already in our study of NN scattering.
No additional parameter is introduced in this work.

TABLE I. Model parameters. The meson masses and the cutoff masses: $m_{\sigma'} = 980$ MeV, $m_{\epsilon} = 980$ MeV, $m_{\pi} = 138$ MeV, $m_{\eta} = 549$ MeV, $m_{\eta'} = 957$ MeV, $m_{\rho} = 770$ MeV, $m_{\omega} = 782$ MeV, and $\Lambda = 1100$ MeV.

	Ch. SU(3)	Ext. Ch. SU(3)	
		f/g=0	f/g=2/3
b_u (fm)	0.5	0.45	0.45
m_u (MeV)	313	313	313
g_u^2	0.766	0.056	0.132
g_{ch}	2.621	2.621	2.621
g_{chv}		2.351	1.973
m_{σ} (MeV)	595	535	547
a_{uu}^c (MeV/fm ²)	46.6	44.5	39.1
a_{uu}^{c0} (MeV)	-42.4	-72.3	-62.9

Masses of baryons and deuteron

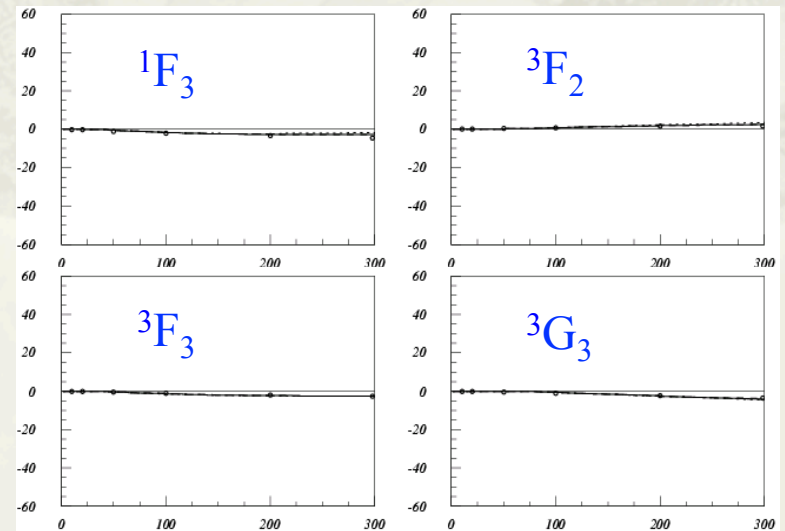
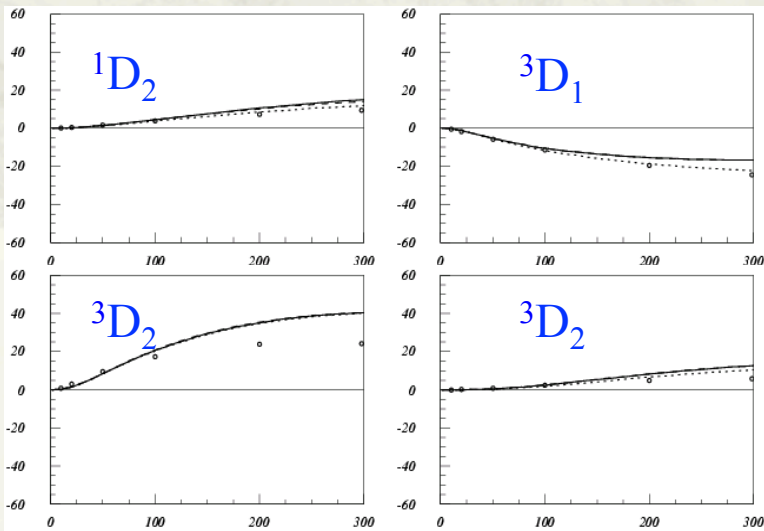
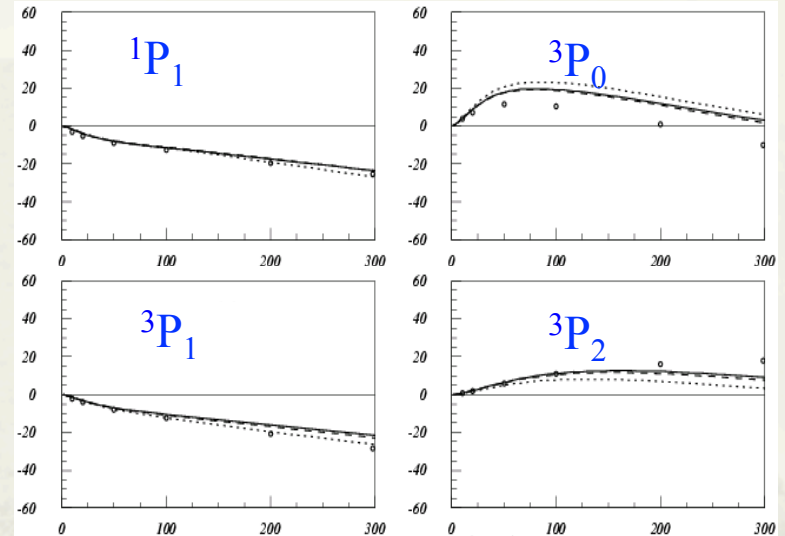
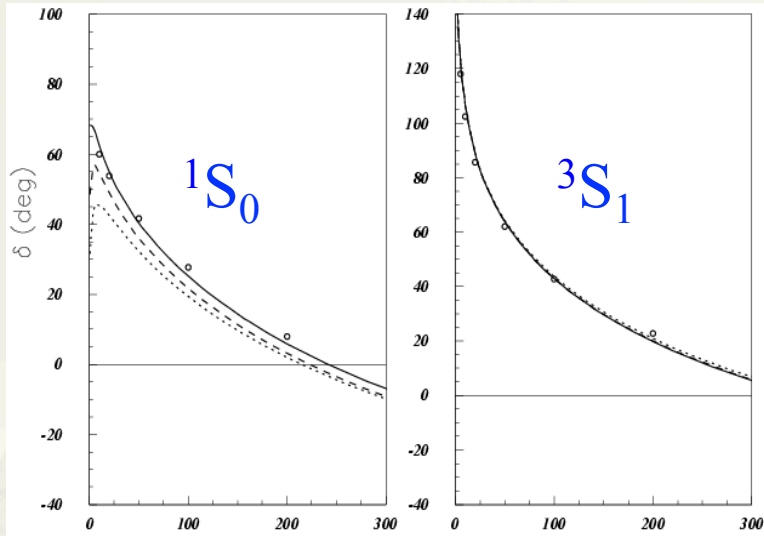
The masses of baryons

	N	Σ	Ξ	Λ	Δ	Σ^*	Ξ^*	Ω
Theor.	939	1194	1335	1116	1232	1370	1511	1656
Expt.	939	1194	1319	1116	1232	1385	1530	1672

The binding energy of deuteron

	Chiral SU(3) quark model	Extended chiral SU(3) quark model	
		$f_{chv}/g_{chv} = 0$	$f_{chv}/g_{chv} = 2/3$
B_{deu} (MeV)	2.13	2.19	2.14

NN phase shifts



RGM study of $\Delta\Delta$ -CC

RGM wave functions for $\Delta\Delta$ -CC system:

$$\begin{aligned} \Psi_{6q} = & \mathcal{A} \left[\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{\Delta\Delta}(\vec{r}) \right]_{S=3, I=0, C=(00)} \\ & + \mathcal{A} \left[\hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{CC}(\vec{r}) \right]_{S=3, I=0, C=(00)} \end{aligned}$$

$$\Delta: \quad (0S)^3 [3]_{\text{orb}}, \quad S = \frac{3}{2}, \quad I = \frac{3}{2}, \quad C = (00)$$

$$C: \quad (0S)^3 [3]_{\text{orb}}, \quad S = \frac{3}{2}, \quad I = \frac{1}{2}, \quad C = (11)$$

RGM equation for a bound state problem:

$$\langle \delta\psi_{6q} | H - E | \psi_{6q} \rangle = 0$$

Calculated d^* mass

Without CC: BE \approx 29 – 62 MeV

	$\Delta\Delta (L = 0, 2)$		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	28.96	62.28	47.90
RMS (fm)	0.96	0.80	0.84

With CC: BE \approx 47 – 84 MeV

	$\Delta\Delta - \text{CC} (L = 0, 2)$		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	47.27	83.95	70.25
RMS (fm)	0.88	0.76	0.78
$(\Delta\Delta)_{L=0}$ (%)	33.11	31.22	32.51
$(\Delta\Delta)_{L=2}$ (%)	0.62	0.45	0.51
$(\text{CC})_{L=0}$ (%)	66.25	68.33	66.98
$(\text{CC})_{L=2}$ (%)	0.02	0.00	0.00

- d^* : a deeply bound & compact $\Delta\Delta$ -CC state

- Coupling to CC plays a significant role

- Predicted binding energy agrees with experiment

$$M_{d^*} \approx 2M_{\Delta} - 84 \text{ MeV}$$

Distinctive features of $\Delta\Delta$: why

Quark-exchange effect:

$$\psi_{6q} = \mathcal{A} \left[\hat{\phi}^{\text{int}}(\bar{\xi}_1, \bar{\xi}_2) \hat{\phi}^{\text{int}}(\bar{\xi}_4, \bar{\xi}_5) \eta(\vec{r}) \right]$$

- For 6 identical quarks: $\mathcal{A} = 1 - 9P_{36}$
- Quark-exchange effect: $\langle \mathcal{A}^{sfc} \rangle \in [0, 2]$
- $(\Delta\Delta)_{S=3, I=0}$: $\langle \Delta\Delta | \mathcal{A}^{sfc} | \Delta\Delta \rangle_{S=3, I=0} = 2$

Strongly “attractive”!

Short-range interaction:

OGE: **attractive** + VMEs: **attractive**

Oka & Yazaki, PLB90(1980)41:

For non-strange BB systems, $(\Delta\Delta)_{S=3, I=0}$ is the only one in which OGE provides attraction at short-range.

Deuteron: $\langle NN | \mathcal{A}^{sfc} | NN \rangle_{S=1, I=0} = 10/9 \sim 1$

OGE: **repulsive** + VMEs: **repulsive**

RGM wave functions

RGM wave functions:

$$\begin{aligned} \psi_{6q} = & (1 - 9P_{36}) \left[\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{\Delta\Delta}(\vec{r}) \right]_{S=3, I=0, C=(00)} \\ & + (1 - 9P_{36}) \left[\hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{CC}(\vec{r}) \right]_{S=3, I=0, C=(00)} \end{aligned}$$

Terms on r.h.s. not orthogonal to each other:

$$\langle \Delta\Delta | P_{36}^{sfc} | \Delta\Delta \rangle_{S=3, I=0} = -\frac{1}{9}$$

$$\langle CC | P_{36}^{sfc} | \Delta\Delta \rangle_{S=3, I=0} = -\frac{4}{9}$$

$$\langle CC | P_{36}^{sfc} | CC \rangle_{S=3, I=0} = -\frac{7}{9}$$

Not suitable for clarification of $\Delta\Delta$, CC components in d^*

Channel wave functions

Channel wave functions (Relative wave functions in physical basis):

$$\begin{aligned}
 \chi_{\Delta\Delta}(\vec{r}) &= \left\langle \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \middle| \psi_{6q} \right\rangle \\
 &= \left\langle \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \middle| (1 - 9P_{36}) \left[\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{\Delta\Delta}(\vec{r}) \right] \right\rangle \\
 &\quad - 9 \left\langle \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \middle| P_{36} \left[\hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{CC}(\vec{r}) \right] \right\rangle
 \end{aligned}$$

$$\begin{aligned}
 \chi_{CC}(\vec{r}) &= \left\langle \hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \middle| \psi_{6q} \right\rangle \\
 &= \left\langle \hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \middle| (1 - 9P_{36}) \left[\hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{CC}(\vec{r}) \right] \right\rangle \\
 &\quad - 9 \left\langle \hat{\phi}_C^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_C^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \middle| P_{36} \left[\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1, \vec{\xi}_2) \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4, \vec{\xi}_5) \eta_{\Delta\Delta}(\vec{r}) \right] \right\rangle
 \end{aligned}$$

Wave function of d^*

Reorganize the wave function of d^* :

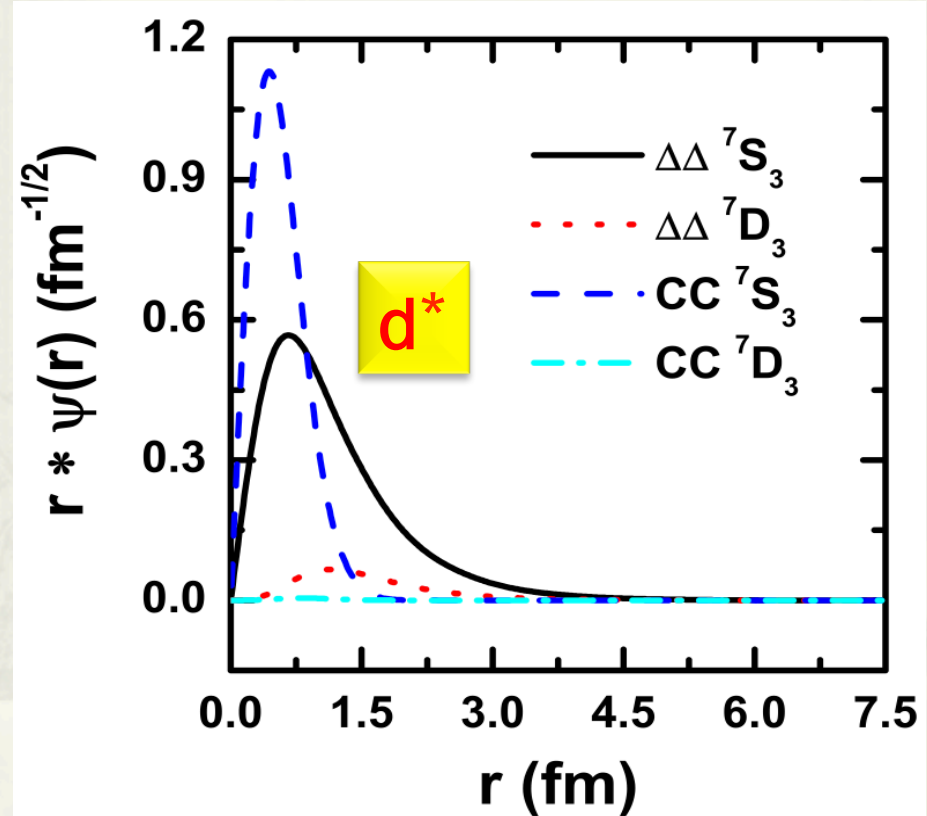
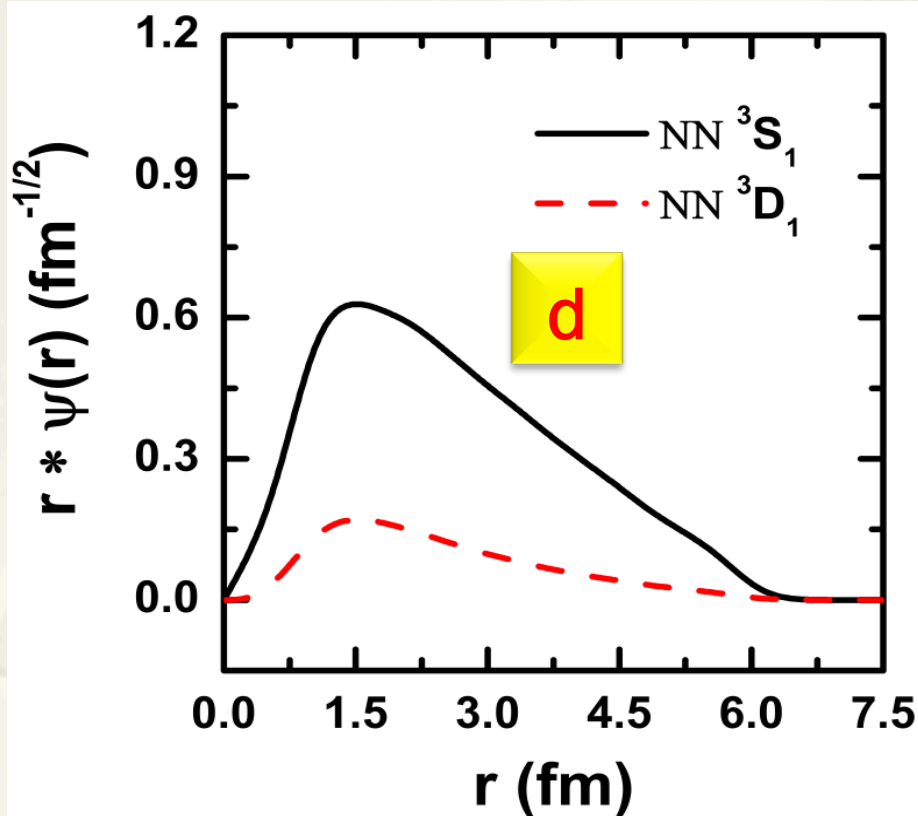
$$\begin{aligned}\psi_{d^*} &= |\Delta\Delta\rangle \chi_{\Delta\Delta}(\vec{r}) + |CC\rangle \chi_{CC}(\vec{r}) \\ &= \sum_{L=0,2} \left[|\Delta\Delta\rangle \frac{\chi_{\Delta\Delta}^L(r)}{r} + |CC\rangle \frac{\chi_{CC}^L(r)}{r} \right] Y_{L0}(\hat{r})\end{aligned}$$

$\Delta\Delta$ & CC parts are now orthogonal to each other:

$$\langle CC | \Delta\Delta \rangle = 0$$

$\chi_{\Delta\Delta}$, χ_{CC} are used to discuss the spatial distribution of d^* and its individual components of $\Delta\Delta$ & CC

Relative wave function



Unlike deuteron, d^* is rather narrowly distributed!

CC component

- d^* has a CC fraction of about 2/3

	$\Delta\Delta - \text{CC} (L = 0, 2)$		
	SU(3)	Ext. SU(3) (f/g=0)	Ext. SU(3) (f/g=2/3)
B (MeV)	47.27	83.95	70.25
RMS (fm)	0.88	0.76	0.78
$(\Delta\Delta)_{L=0}$ (%)	33.11	31.22	32.51
$(\Delta\Delta)_{L=2}$ (%)	0.62	0.45	0.51
$(\text{CC})_{L=0}$ (%)	<u>66.25</u>	<u>68.33</u>	<u>66.98</u>
$(\text{CC})_{L=2}$ (%)	0.02	0.00	0.00

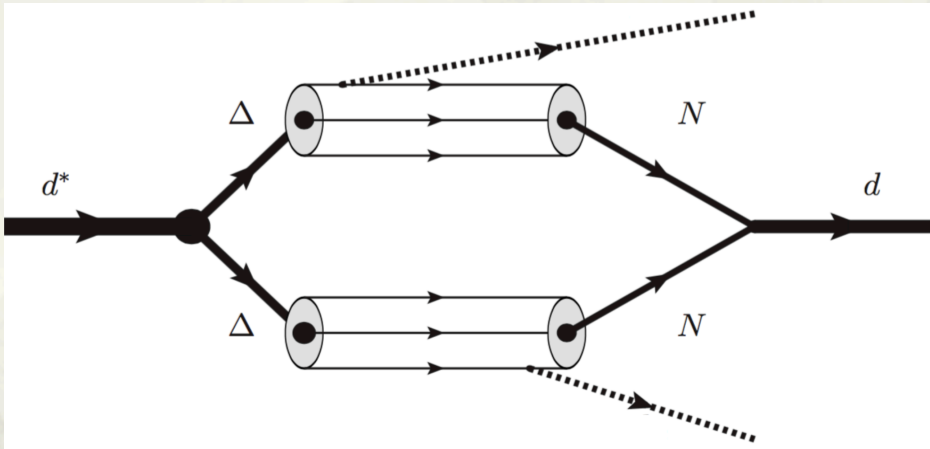
- A pure hexaquark state of $\Delta\Delta$ system has 4/5 CC fraction

$$[6]_{\text{orb}}[33]_{IS=03} = \sqrt{\frac{1}{5}} |\Delta\Delta\rangle_{IS=03} + \sqrt{\frac{4}{5}} |CC\rangle_{IS=03}$$

- d^* is a hexaquark-dominated exotic state!

Decay width of d^*

Details will be given by Prof. Y. B. Dong at 12:00–12:30 in this session.



$$\Gamma_{d^* \rightarrow d\pi^+\pi^-} \approx 17 \text{ MeV}$$

$$\Gamma_{d^* \rightarrow d\pi^0\pi^0} \approx 9 \text{ MeV}$$

$$\Gamma = \frac{\Gamma_{d^* \rightarrow d\pi^+\pi^-}}{\text{Br}(d^* \rightarrow d\pi^+\pi^-)} \approx \frac{16.8 \text{ MeV}}{23\%} \approx 73 \text{ MeV}$$

$$\Gamma = \frac{\Gamma_{d^* \rightarrow d\pi^0\pi^0}}{\text{Br}(d^* \rightarrow d\pi^0\pi^0)} \approx \frac{9.2 \text{ MeV}}{14\%} \approx 66 \text{ MeV}$$

$$\Gamma_{\text{exp}} \approx 70 \text{ MeV}$$

Stability against confinement

1 channel & 2 color-singlet clusters: free from any types of confinement

Check for $\Delta\Delta$ -CC system:

	$\Delta\Delta - \text{CC} (L = 0, 2)$		
	r^2	r	$\text{Erf}(r)$
Binding energy (MeV)	83.95	86.17	87.63
RMS of $6q$ (fm)	0.76	0.76	0.76
Fraction of $(\Delta\Delta)_{L=0}$ (%)	31.22	30.66	30.41
Fraction of $(\Delta\Delta)_{L=2}$ (%)	0.45	0.42	0.40
Fraction of $(\text{CC})_{L=0}$ (%)	68.33	68.92	69.19
Fraction of $(\text{CC})_{L=2}$ (%)	0.00	0.00	0.00

Results of d^* are rather stable against the types of confinement

Why: d^* is rather compact, thus not sensitive to long-range confinement

Explanations from other groups

◆ A. Gal & H. Garcilazo, NPA928(2014)73

- Dynamically generated $\Delta N\pi$ 3-body resonance
- Binding energy: 101 MeV
- Width: 66 MeV

$$B_{\text{exp}} \approx 84 \text{ MeV}$$

$$\Gamma_{\text{exp}} \approx 70 \text{ MeV}$$

◆ H.X. Huang, J.L. Ping, & F. Wang, PRC89(2014)034001

- $\Delta\Delta$ bound state
- Binding energy: 71 MeV (QDCSM), 107 MeV (ChQM)
- Width: 110 MeV (QDCSM), 150 MeV (ChQM)

Summary

- $d^*(2380)$ has been reported by WASA-at-COSY with an **unusual narrow width** ($\Gamma \approx 70$ MeV)
- $\Delta\Delta$ -CC with $I(J^P)=0(3^+)$ is dynamically investigated in our chiral SU(3) quark model and its extended version
- d^* has a CC fraction of about $2/3 \rightarrow$ **it is a hexaquark-dominated exotic state**
- **The calculated binding energy (47–84 MeV) & decay width (66–73 MeV) are consistent with the data ($M \sim 2M_\Delta - 84$ MeV, $\Gamma \sim 70$ MeV)**
- More experimental & theoretical works needed to further test the properties of $d^*(2380)$



Thank you for your attention!