An interpretation of d*(2380) with a chiral constituent quark model

Yubing Dong

Institute of High Energy Physics(IHEP)
Chinese Academy of Sciences(CAS), China

Collaborators:
(Fei Huang, Qifang Lv, Pengnian Shen, and Zongye Zhang)

Series papers
and
PPNP 131, 104045
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Outline

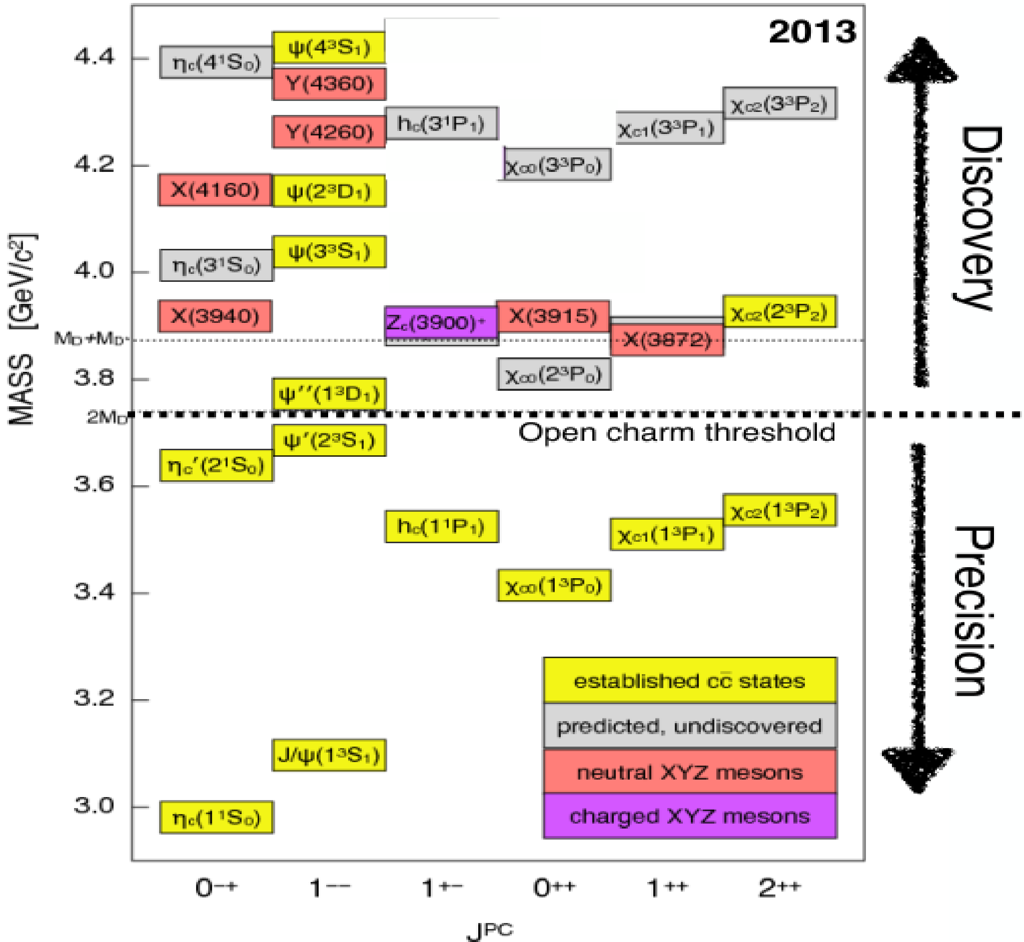
1, Introduction: Exotic states & d*(2380) dibaryon

2, ★SU(3) chiral constituent quark model……

3, ●Calculation and interpretation of d*(2380): Mass, wave function, decays, FFs……

4, Summary and discussion

1, Introduction: Recent studies on exotic particles ((4,5), 6)

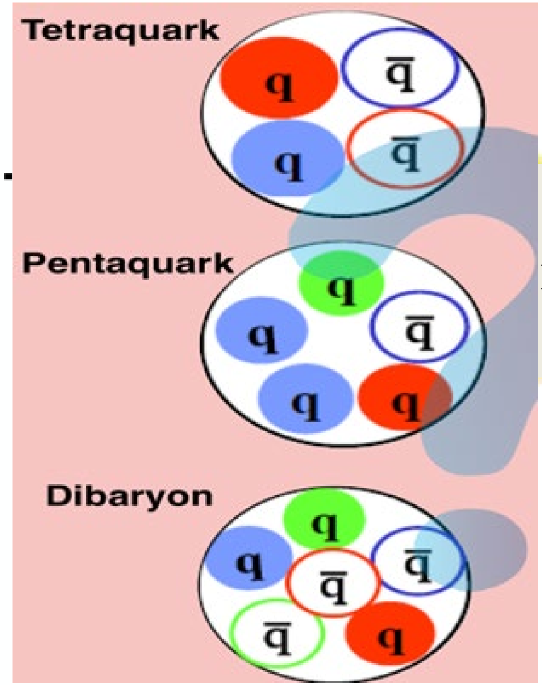


XYZ states 类粲介子

★Near threshold,

★Narrow width

"XYZ" Puzzle



normal mesons & baryons

Courtesy of Messchendorp

Dibaryon: deuteron--1932

- Binding energy ~2.2MeV, or 1.1MeV/A

  Which has to be compared to the averaged binding energy of 8 MeV/A in Nuclei

- Its charge radius of 2.1fm (loosely bounded)

  The centers of the proton and neutron are far apart from each other than the pion exchange range $r \sim hc/m\pi \sim 1.4fm$

- Proton-neutron (dominated),

  six-quark content (2-3% or 0.15-0.3%)+ ΔΔ(0.4%)

Beginning: (★Dyson and Xuong, 1964)

1964, when quarks were still perceived as merely mathematical entities

SU(6) multiplet in 56×56 product : contains the SU(3) \bar{10} and 27;

Deuteron D_{01} and NN virtual state D_{10} ➔ $D_{12}(N\Delta)$ and $D_{03}(\Delta\Delta)$

• $M \sim A + B\left[I(I+1) + S(S+1) - 2\right]$ with the NN threshold mass 1878, a value B ~ 47MeV was reached by assigning D_{12} to $pp \leftrightarrow \pi^+ d$ resonance at $\sqrt{s} = 2160\,MeV$ (near the NΔ threshold)

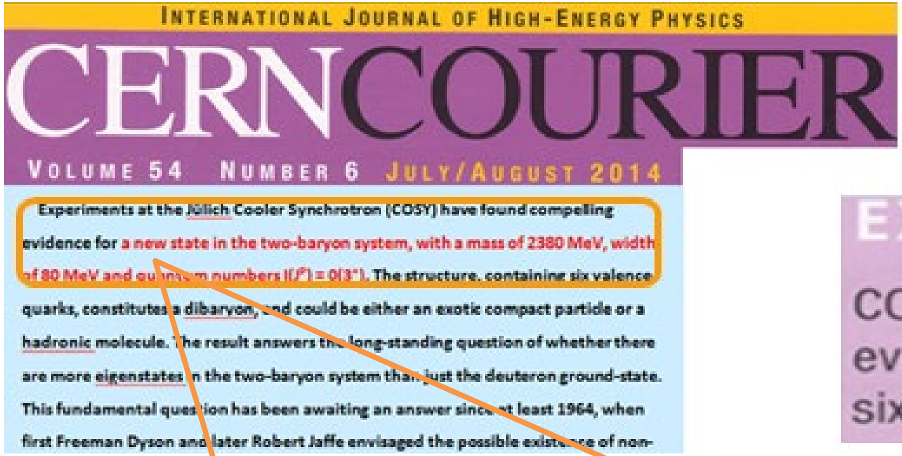
➔ $M(D_{03}) = 2350$MeV. This dibaryon has been the subject of several quark-based model calculations since 1980

Nonstrange s-wave dibaryon SU(6) predictions

D_{IS}

Mass$_{MeV}$	dibaryon	I	S	SU(3)	legend	mass
1876	$\mathcal{D}_{01}$	0	1	$\overline{10}$	deuteron	A
1876	$\mathcal{D}_{10}$	1	0	27	nn	A
2160	$\mathcal{D}_{12}$	1	2	27	$N\Delta$	$A + 6B$
2160	$\mathcal{D}_{21}$	2	1	35	$N\Delta$	$A + 6B$
2350	$\mathcal{D}_{03}$	0	3	$\overline{10}$	$\Delta\Delta$	$A + 10B$
2350	$\mathcal{D}_{30}$	3	0	28	$\Delta\Delta$	$A + 10B$

Observation: d*(2380)_light flavor dibaryon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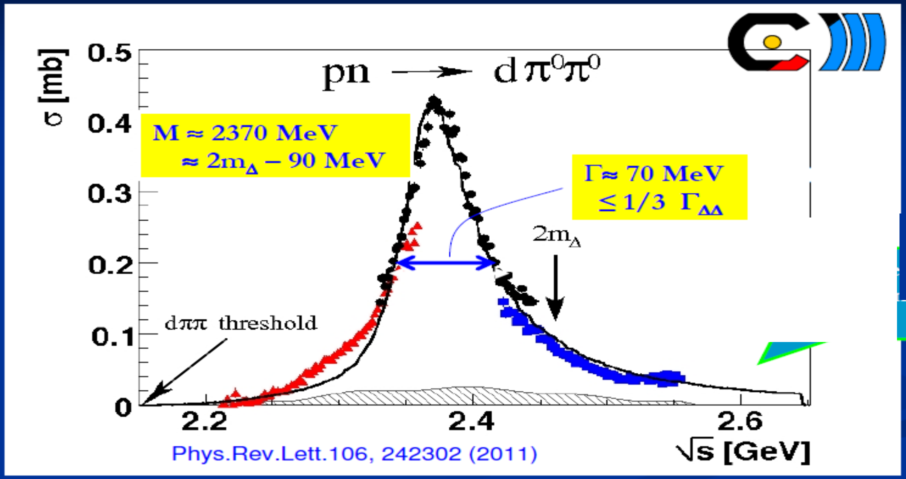
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers I(J^P) = 0(3^+). The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic compact particle or a hadronic molecule. The result answers the long-standing question of whether there are more eigenstates in the two-baryon system than just the deuteron ground-state. This fundamental question has been awaiting an answer since at least 1964, when first Freeman Dyson and later Robert Jaffe envisaged the possible existence of non-

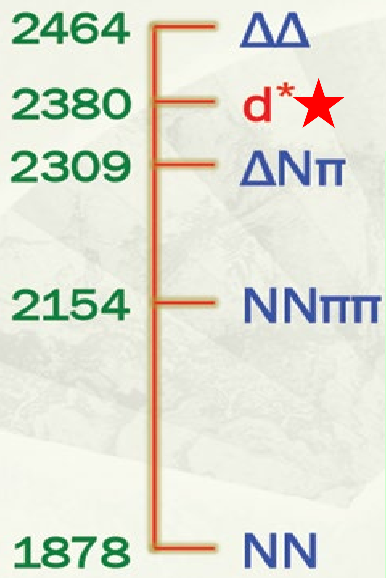
cerncourier.com/cws/article/cern/57836

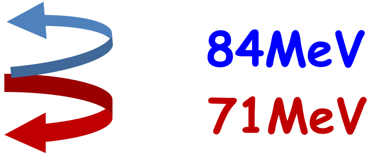
(2014)

Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of ~ 80MeV and quantum numbers-- $I(J^P) = 0(3^+)$ …Since 2009

The d* Resonance $I(J^P) = 0(3^+)$



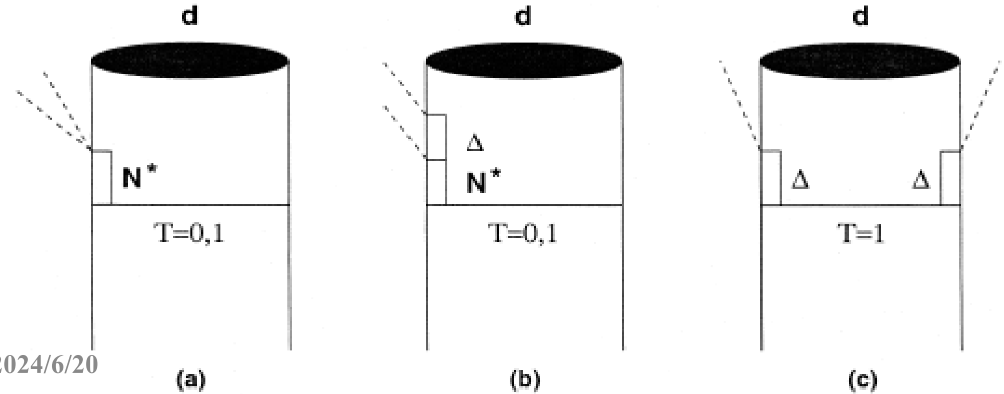




$$M_{d^*} \approx 2380\text{MeV}$$
$$\approx 2M_\Delta - 84\text{MeV}$$
$$> M_{\Delta N\pi}$$
$$> M_{NN\pi\pi}$$
$$> M_{NN}$$
$$2\Gamma_\Delta \approx 230\text{MeV}$$
$$\Gamma_{d^*} \approx 70\text{MeV}$$
$$< 1/3 \times (2\Gamma_\Delta)$$

?

★Baryon number=2 ★Unusual narrow width



Neither N*N (Roper), nor ΔΔ Intermediate state

They need this d*(2380)

Signals in np processes WASA @ COSY

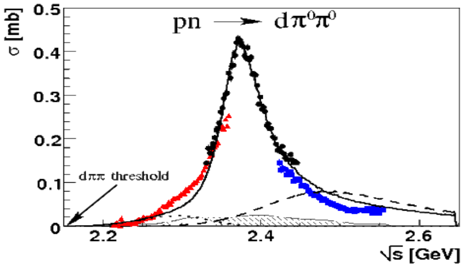
2π production processes

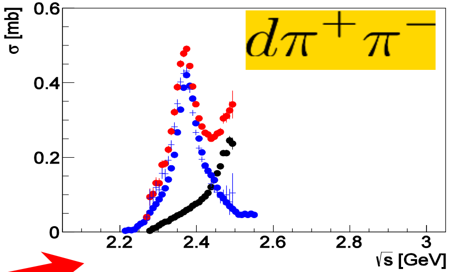
np scattering process

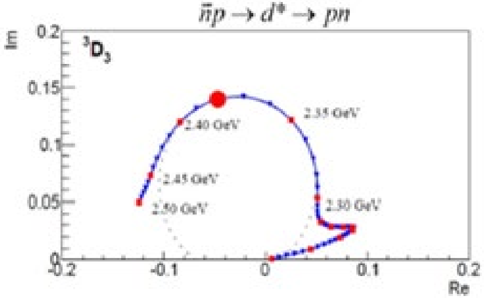
PRL 106 (2011) 242302

PLB 721 (2013) 229

● ● ● WASA data



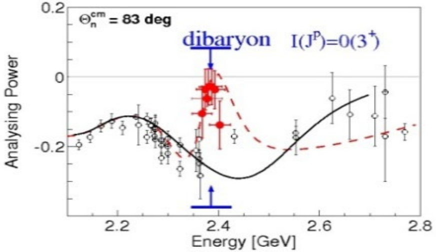




Fusion $d\pi^0\pi^0$

$$pn \to d^*$$

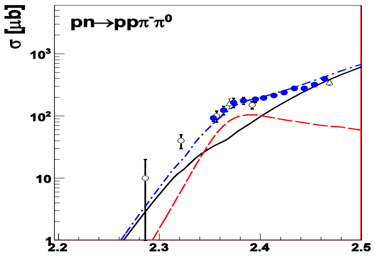
pn

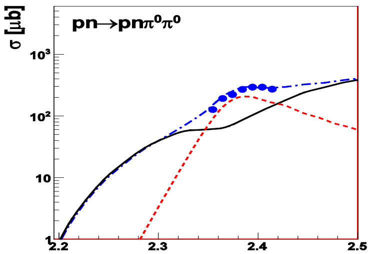


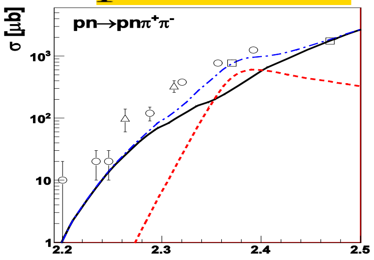
Non-fusion

fusion 2π processes

$pp\pi^-\pi^0$ $pn\pi^0\pi^0$ $pn\pi^+\pi^-$







Measured also in fusion reactions to helium isotopes:

$p + d \to {}^3He + \pi^0 + \pi^0$

$p + d \to {}^3He + \pi^+ + \pi^-$

$d + d \to {}^4He + \pi^0 + \pi^0$

$d + d \to {}^4He + \pi^+ + \pi^-$

A short summary of Characters of d*(2380): $0(3^+)$

- **d* mass locates between ΔΔ and ΔNπ thresholds**

Effect from threshold is expected small

$M_{\Delta N\pi} = 2310 MeV$

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

$\Gamma_{d^*} \approx 80 MeV$

$M_{\Delta\Delta} = 2460 MeV$

70MeV

80MeV

- **d* narrow width** → **Possible 6q structure**

be different from normal hadrons

Review articles: by Heinz Clement, PPNP, 93 (2017), 195-142

CPC,45 (2021), 022001

★ Possible interpretations of d*(2380)
compact 6q dominated d*(2380)

▲ After COSY's observations

- **Quark model**

J.Ping (09/14)-10 coupled channels QM

Bashkanov, Brodsky, Clement (13) -- ΔΔ+CC

★ F.Huang, YBD, Zhang. (14-18)--ΔΔ+CC QM

+……

A),a compact 6q dominated exotic state

- **Hadronic model**

Gal (14) ---ΔNπ

Kukulin (15,16) - $D_{12}\pi$

B), a ΔNπ (or $D_{12}\pi$) resonant state

- Some Other interpretations

2, ★SU(3) chiral constituent quark model: SU(3) CCQM

● **Quark model framework**

PRC 60 (1999) 045203
CPC 39 (2015) 071001

SU(3) chiral QM + RGM approach_ (light flavor)

▲ **Interactions:**

$$V_{ij} = V_{ij}^{Conf.} + V_{ij}^{OGE} + V_{ij}^{ch} + V_{ij}^{chv}$$

q-q potential:

$$V_{ij}^{ch} = \sum_a (V_{ij}^{s(a)} + V_{ij}^{ps(a)})_{scalar+PS}$$

Interactive Lagrangian

$$\mathcal{L}_I = -g_{ch}\bar{\Psi}\left(\sum_a^8 \sigma_a \lambda^a + i\sum_a^8 \pi_a \lambda^a \gamma_5\right)\Psi$$

$$\begin{cases} \sigma_a : scalar\ nonet\ fields \\ \pi_a : psudoscalar\ nonet\ fields \end{cases}$$

★Extended SU(3) chiral constituent quark model: SU(3)ECCQM

$$\mathcal{L}_I = -\bar{\Psi}\left(g_{chv}\gamma_\mu \sum_a^8 \rho_a^\mu \lambda^a + \frac{f_{chv}}{2M_N}\sum_a^8 \sigma_{\mu\nu}\partial^\mu \rho_a^\nu \lambda^a \right)\Psi$$

ρ_a : *vector nonet fields*

★Model parameters: **could well-reproduce and match the experimental data for N-N scatterings**

--- NN phase shifts;

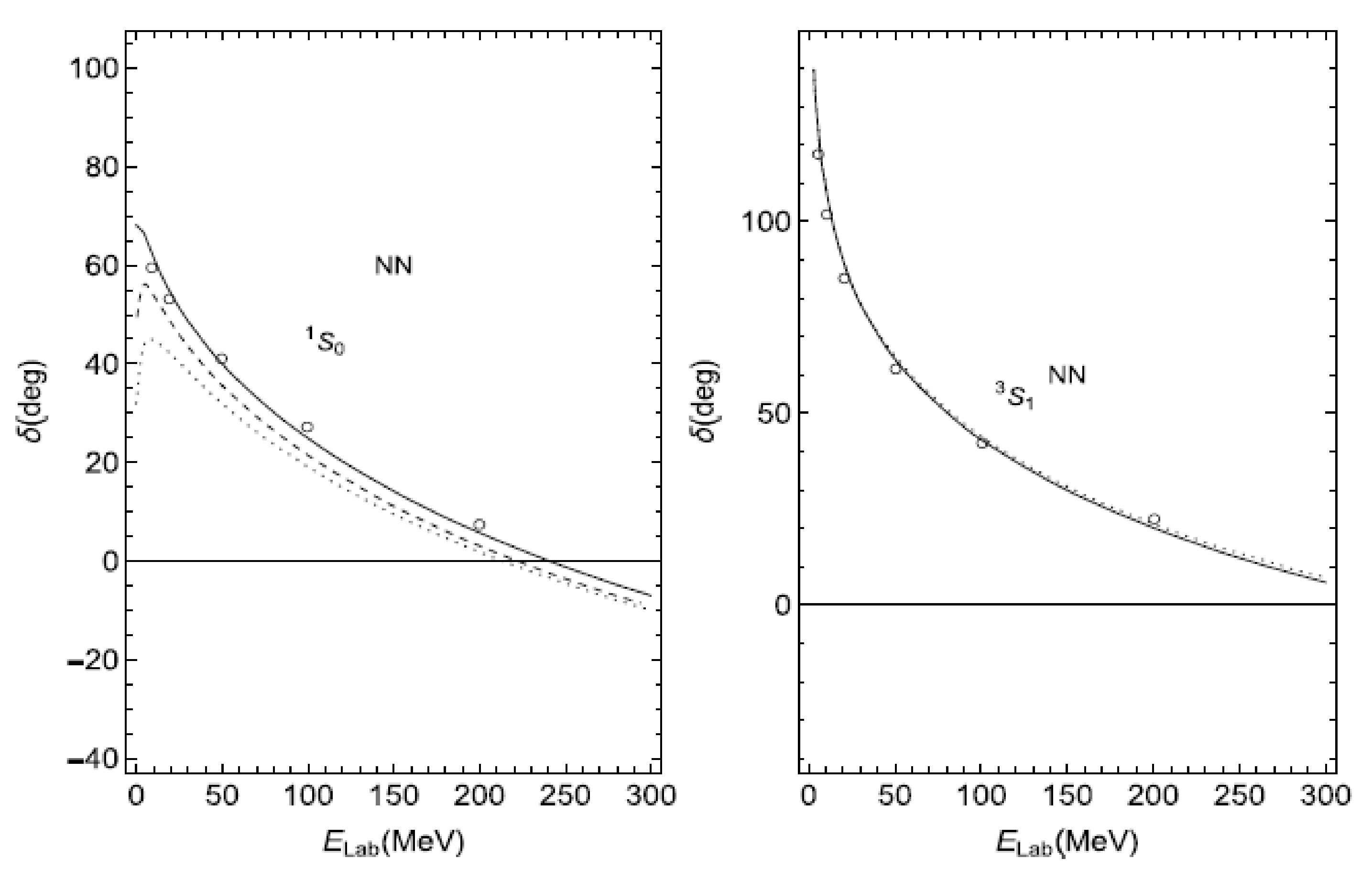
& hyper-nucleon interaction

+ deuteron properties: { *bingding* / *size* }

Binding Energy $(BE)_d^{Expt} = 2.22\,MeV$

Values of model parameters in *SU*(3)CCQM and *SU*(3)ECCQM

	SU(3)CCQM	*SU*(3)ECCQM	
		Set I	Set II
b_u (fm)	0.5	0.45	0.45
$g_{NN\pi}$	13.67	13.67	13.67
g_{ch}	2.621	2.621	2.621
g_{chv}	0	2.351	1.973
f_{chv}/g_{chv}	0	0	2/3
m_σ (MeV)	595	535	547
g_u	0.875	0.237	0.363
α_s (g_u^2)	0.766	0.056	0.132
a_{uu}^c (MeV/fm^2)	46.6	44.5	39.1
a_{uu}^{c0} (MeV)	−42.4	−72.3	−62.9
$B_{deuteron}$ (MeV)	2.09	2.24	2.20



The S-Wave phase shifts of the N-N scattering in SU(3)CCQM and SU(3) ECCQM. Dotted, dashed and solid curves: (f/g=0, 2/3).

▲ Trial wave function of d*

$\mathbf{I(J^P) = 0(3^+)}$

$$\Psi_{6q} = \mathcal{A}\left[\phi_\Delta(\xi_1,\xi_2)\,\phi_\Delta(\xi_4,\xi_5)\,\underline{\eta_{\Delta\Delta}(\boldsymbol{r})} + \phi_C(\xi_1,\xi_2)\,\phi_C(\xi_4,\xi_5)\,\underline{\eta_{CC}(\boldsymbol{r})}\right]_{S=3,I=0,C=(00)} .$$

★ 6-quark two clusters + RGM

★ $\Delta: \quad (0s)^3\,[3]_{\rm orb},\, S=3/2, I=3/2, C=(00),$

● $C: \quad (0s)^3\,[3]_{\rm orb},\, S=3/2, I=1/2, C=(11),$

$\eta_{\Delta\Delta}$ (r) and η_{CC} (r) are not orthogonal

▲ Hadronization----channel wave function:

Using the projection method to integrate out the internal coordinates inside the clusters (or Hadronization approach)

$$\Psi_{d^*} = |\Delta\Delta\rangle\,\chi_{\Delta\Delta}(\boldsymbol{r}) + |CC\rangle\,\chi_{CC}(\boldsymbol{r})$$

$$\chi_{\Delta\Delta}(\boldsymbol{r}) \equiv \langle\phi_\Delta(\xi_1,\xi_2)\,\phi_\Delta(\xi_4,\xi_5)\,|\,\Psi_{6q}\rangle\,,$$

$$\chi_{CC}(\boldsymbol{r}) \equiv \langle\phi_C(\xi_1,\xi_2)\,\phi_C(\xi_4,\xi_5)\,|\,\Psi_{6q}\rangle\,,$$

- **the two components orthogonal**
- **the quark exchange effect included**

3, On d*(2380)

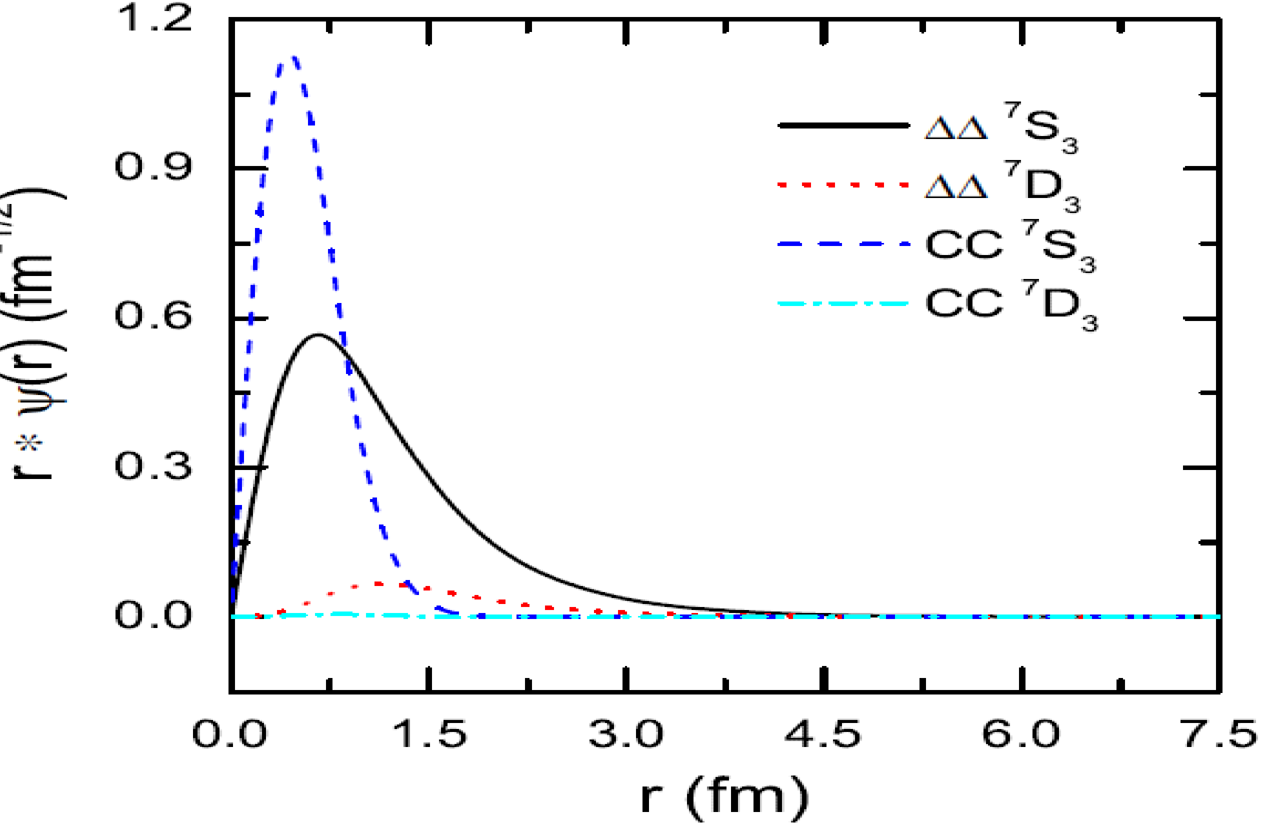
a, Mass & wave function of d*(2380)

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

PRC 60 (1999) 045203
CPC 39 (2015) 071001

▲ **Results:**

d* (WFs)



- **Binding energy (BE)**

$$(BE)_{d^*}\begin{cases} Expt.\sim \ 80\,MeV \\ Theor.\sim 80\,MeV \end{cases}$$

PRC 60 (1999) 045203		Ext. SU(3) (f/g=0)	
$I(J^P)=0(3^+)$		ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)
d^* Binding Energy(MeV)		62.3	83.9
Fraction of Wave Function (%)	ΔΔ (L=0)	98.01	31.22
	ΔΔ (L=2)	1.99	0.45
	CC (L=0)	0	68.33
	CC (L=2)	0	0.00

■**Intrinsic character of d***

quark exchange

effect of sfc large (negative:-4/9)

2, Dynamical effect

(IS=03)

OGE & Vector meson exchange induced Δ-Δ short range interaction is attractive

**d*(2380) is deep bound & narrow width

Reason for large component of CC (67%) — Due to quark exchange effect

$P_{36} = P_{36}^{r} \; P_{36}^{sfc}$

$\langle P_{36}^{sfc} \rangle$ exchange effect in spin-flavor-color spaces

intrinsic	$(\Delta\Delta)_{SI=30}$	$(\Delta\Delta)_{SI=30}$	$(CC)_{SI=30}$
	$(\Delta\Delta)_{SI=30}$	$(CC)_{SI=30}$	$(CC)_{SI=30}$
$\langle P_{36}^{sfc} \rangle$	$-\frac{1}{9}$	$-\frac{4}{9}$	$-\frac{7}{9}$

$\langle P_{36}^{r} \rangle$ is determined by the dynamical wave function

For d* The effective Δ-Δ interaction induced by OGE and vector meson exchange enables the short range interaction attractive.

⟶ Two clusters ΔΔ closer,

1) d* special characters
   spin-flavor-color spaces exchange effect

should also large

2) ΔΔ (IS=03), Δ–Δ short range interaction is attractive

Dynamical effect ⟷ Model independent

d* might be a 6q dominant state

P_{36} Effect large, large CC component

⟶ d* deep bounded and narrow width

b, Strong decay$_I$: ▲ 2π decay widths

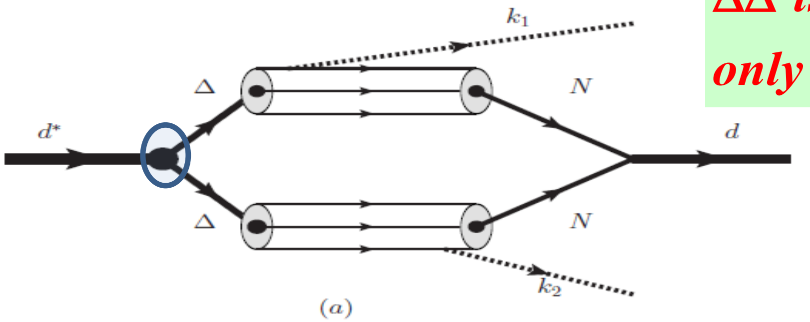
PRC91 064002, PRC94 014003

Three-body decay

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

$d^* \to d\pi^0\pi^0$

$d^* \to d\pi^+\pi^-$



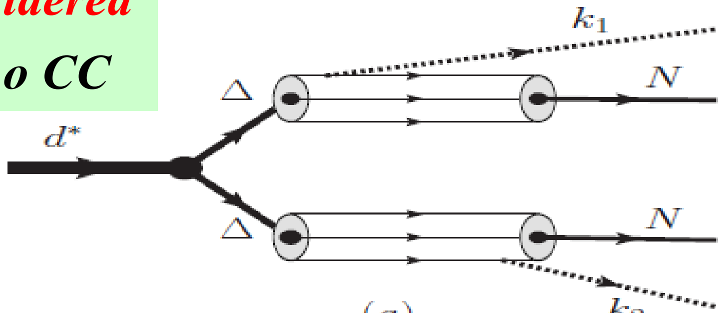
Typical diagram

ΔΔ is considered only and no CC

Four-body decay

$d^* \to pn\pi^0\pi^0 (pn\,\pi^+\pi^-)$

$d^* \to nn\pi^0\pi^+ (pp\pi^0\pi^-)$



Parameters: $qq\pi$

$\Delta \to N\pi$

Interaction

Coupling & form factor

$$\mathcal{H}_{qq\pi} = g_{qq\pi}\vec{\sigma}\cdot\vec{k}_\pi\tau\cdot\phi\frac{1}{(2\pi)^{3/2}\sqrt{2\omega_\pi}},$$

$$\Gamma_{\Delta\to\pi N} = \frac{4}{3\pi}k_\pi^3(g_{qq\pi}I_o)^2\frac{\omega_N}{M_\Delta},$$

Our interpretation of d*_Compact 6q dominated exotic state $I(J^P)=0(3^+)$

(wave function of SU(3) (CQM+ECQM))

"CC" fraction of 68% in d (ΔΔ+CC)*

PRC91,064002(15), PRC94,014003(16)

* **All partial and total widths agree with data reasonably**

$$\begin{cases}\Gamma^{\text{Expt}} = 70 \sim 75\text{MeV} \\ \Gamma^{\text{Theor.}} \approx 72\text{MeV}\end{cases}$$

	Theor.(MeV)	Expt.(MeV)
$d^* \to d\pi^+\pi^-$	16.8	16.7
$d^* \to d\pi^0\pi^0$	9.2	10.2
$d^* \to pn\pi^+\pi^-$	20.6	21.8
$d^* \to pn\pi^0\pi^0$	9.6	8.7
$d^* \to pp\pi^0\pi^-$	3.5	4.4
$d^* \to nn\pi^0\pi^+$	3.5	4.4
$d^* \to pn$	8.7	8.7
Total	71.9	74.9

▲ 2π decay widths

The narrow width is due to large CC component

①, *A compact system : size~~0.8fm*

②, *Components*

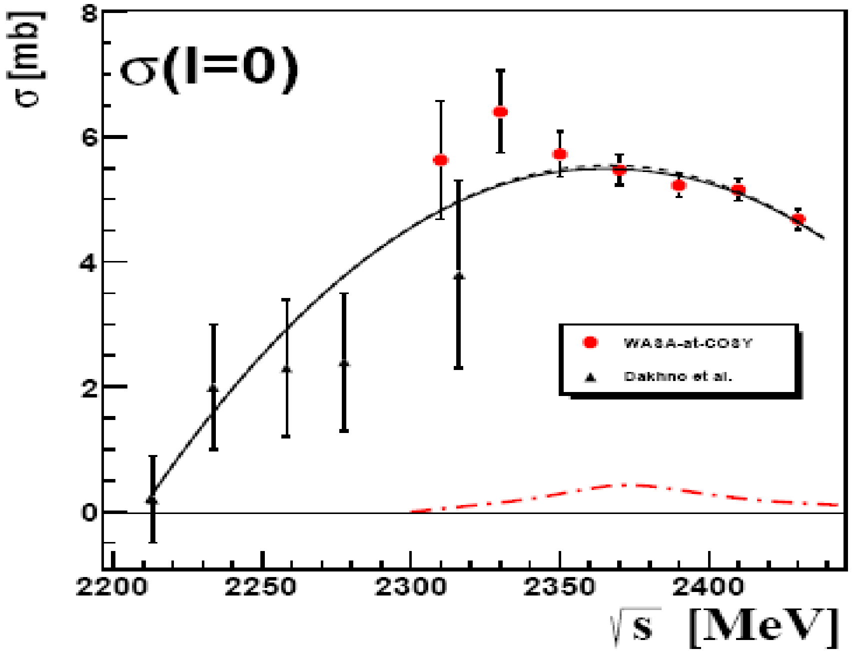
$$|d^* > \sim \sqrt{\frac{1}{3}}|\Delta\Delta > + \sqrt{\frac{2}{3}}|CC >,$$

③, ΔΔ component plays of the *most important role in the calculations*

c, Strong decay$_{II}$: Single-pion decay

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

$$\sigma_{NN\to NN\pi}(I=0) = 3(2\sigma_{np\to pp\pi^-} - \sigma_{pp\to pp\pi^0})$$



- **Experimental status**

The WASA-@-COSY Collaborations,

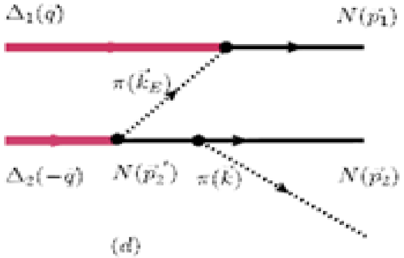
PLB774 (2017), 599-607

Dash-dotted line illustrates a 10% d* resonance contribution

Upper limit of branching ratio for "d*(2380)→NNπ" <u>is 9%.</u>

This channel might serve as a test!

One of Typical diagrams



ΔΔ is considered only and no CC

Our prediction, ~1% is compatible with the Exp't upper-limit:

d, Form factors of d*

relative to size

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

Form factors: 2S+1

arXiv:1704.01253, PRD96,094001

$$\mathcal{M}^{\mu}_{\alpha'\beta'\gamma',\alpha\beta\gamma} = [G_1(Q^2)\mathcal{P}^{\mu}[g_{\alpha'\alpha}(g_{\beta'\beta}g_{\gamma'\gamma} + g_{\beta'\gamma}g_{\gamma'\beta}) + \text{permutations}]$$
$$+ G_2(Q^2)\mathcal{P}^{\mu}[q_{\alpha'}q_{\alpha}[g_{\beta'\beta}g_{\gamma'\gamma} + g_{\beta'\gamma}g_{\gamma'\beta}] + \text{permutations}]/(2M^2_{d^*})$$
$$+ G_3(Q^2)\mathcal{P}^{\mu}[q_{\alpha'}q_{\alpha}q_{\beta'}q_{\beta}g_{\gamma'\gamma} + \text{permutations}]/(4M^4_{d^*})$$
$$+ G_4(Q^2)\mathcal{P}^{\mu}q_{\alpha'}q_{\alpha}q_{\beta'}q_{\beta}q_{\gamma'}q_{\gamma}/(8M^6_{d^*}) + G_5(Q^2)[(g^{\mu}_{\alpha'}q_{\alpha} - g^{\mu}_{\alpha}q_{\alpha'})(g_{\beta'\beta}g_{\gamma'\gamma} + g_{\beta'\gamma}g_{\beta'\gamma}) + \text{permutations}]$$
$$+ G_6(Q^2)[(g^{\mu}_{\alpha'}q_{\alpha} - g^{\mu}_{\alpha}q_{\alpha'})(q_{\beta'}q_{\beta}g_{\gamma'\gamma} + q_{\gamma'}q_{\gamma}g_{\beta'\beta} + q_{\beta'}q_{\gamma}g_{\gamma'\beta} + q_{\gamma'}q_{\beta}g_{\gamma\beta'}) + \text{permutations}]/(2M^2_{d^*})$$
$$+ G_7(Q^2)[(g^{\mu}_{\alpha'}q_{\alpha} - g^{\mu}_{\alpha}q_{\alpha'})q_{\beta'}q_{\beta}q_{\gamma'}q_{\gamma} + \text{permutations}]/(4M^4_{d^*})],$$

$$\mathcal{J}^{\mu} = (\epsilon^*)^{\alpha'\beta'\gamma'}(p')\mathcal{M}^{\mu}_{\alpha'\beta'\gamma',\alpha\beta\gamma}\epsilon^{\alpha\beta\gamma}(p)$$

Electric multi-poles

$$G^E_l(Q^2) = \frac{(2M_{d^*})^l}{e}\sqrt{\frac{4\pi}{2l+1}}\frac{(2l+1)!!}{l!Q^l}\mathcal{I}_{El}(Q^2),$$

with e being the unit of charge and

$$\mathcal{I}_{El}(Q^2) = \langle d^*|\sum_{i=1}^{6}\int d^3r[d^3X]e_i j_l(Q|\vec{r}_i - \vec{R}|)Y_{l0}(\Omega_{r_i})|d^*\rangle$$
$$= 3\langle d^*|\int d^3r[d^3X][e_3 j_l(Q|\vec{r}_3 - \vec{R}|)Y_{l0}(\Omega_{\vec{r}_3-\vec{R}})$$
$$+ e_6 j_l(Q|\vec{r}_6 - \vec{R}|)Y_{l0}(\Omega_{\vec{r}_6-\vec{R}})]|d^*\rangle,$$

Magnetic multi-poles

$$\langle d^*|\rho^M(\vec{q})|d^*\rangle = e\sum_{l=0}^{+\infty} i^l\tau^{l/2}\frac{l+1}{C^{l-1}_{2l-1}}G_{Ml}(Q^2)Y_{l0}(\Omega_q), \quad (10)$$

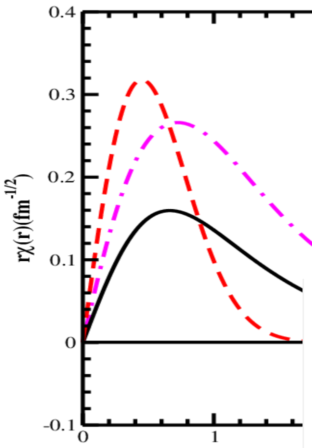
where $\rho^M(\vec{q})$ denotes the magnetic density of the system with $\tau = \frac{Q^2}{4M^2_{d^*}}$, and

(a) Compact quark model

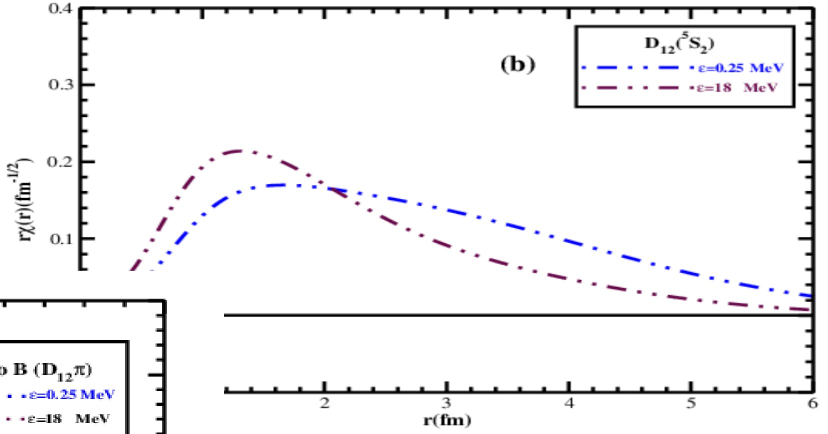
(b) πΔN three-body system

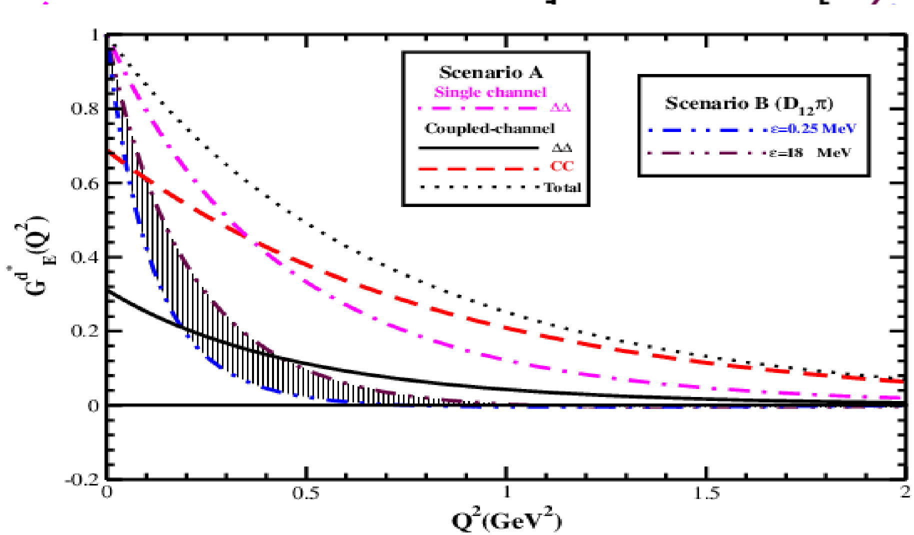
d*(2380) charge distributions

	$d^*(2380)$		D_{12}
	A1	A2	
$rms\ \ (fm)$	1.09	0.78	2.39



Wave functions





both ΔΔ and CC are considered

Magnetic Moment

Naïve quark model

Nucleon $\frac{\mu_p}{\mu_n} = -\frac{3}{2} \to -\frac{2.79}{1.91}_{EXPT.}$

d*(2380) ΔΔ+CC $\mu_{d^*} = \frac{M_{d^*}}{m_q} \approx 7.6$

d*(2380) $D_{12}\pi$ $\mu_{d^*} = \frac{2M_{d^*}}{3m_q} \approx 5.1$

4, Summary and discussion

★ ① Our SU(3)(CCQM & ECCQM) approaches are employed to study the mass, and wave function of [d*(2380), 3^+]. These approaches could well reproduce the experimental data for the N–N scatterings as well as the properties of deuteron and hyperon-nucleon interaction, and the model parameters are fixed.

★② Within the approaches and by employing the same set of parameters, the mass of d*(2380) is well–reproduced and its wave function is expressed as ΔΔ+CC， hidden color parts dominated. Vector meson exchange plays essential role.

novel

$$|d^* > \sim \sqrt{\frac{1}{3}}|\Delta\Delta > + \sqrt{\frac{2}{3}}|CC >,$$

★③ It is a compact 6-quark state with some large-portion |ΔΔ> component, due to its spin and quark exchange effect.

★ ④ We also obtained channel wave function for the two channels and they are orthogonal. Then, the channel wave function are employed to calculate the strong decays of d*(2380). Double pion decays are well reproduced comparing the available measurement, and the single pion decay is expected to be much small.

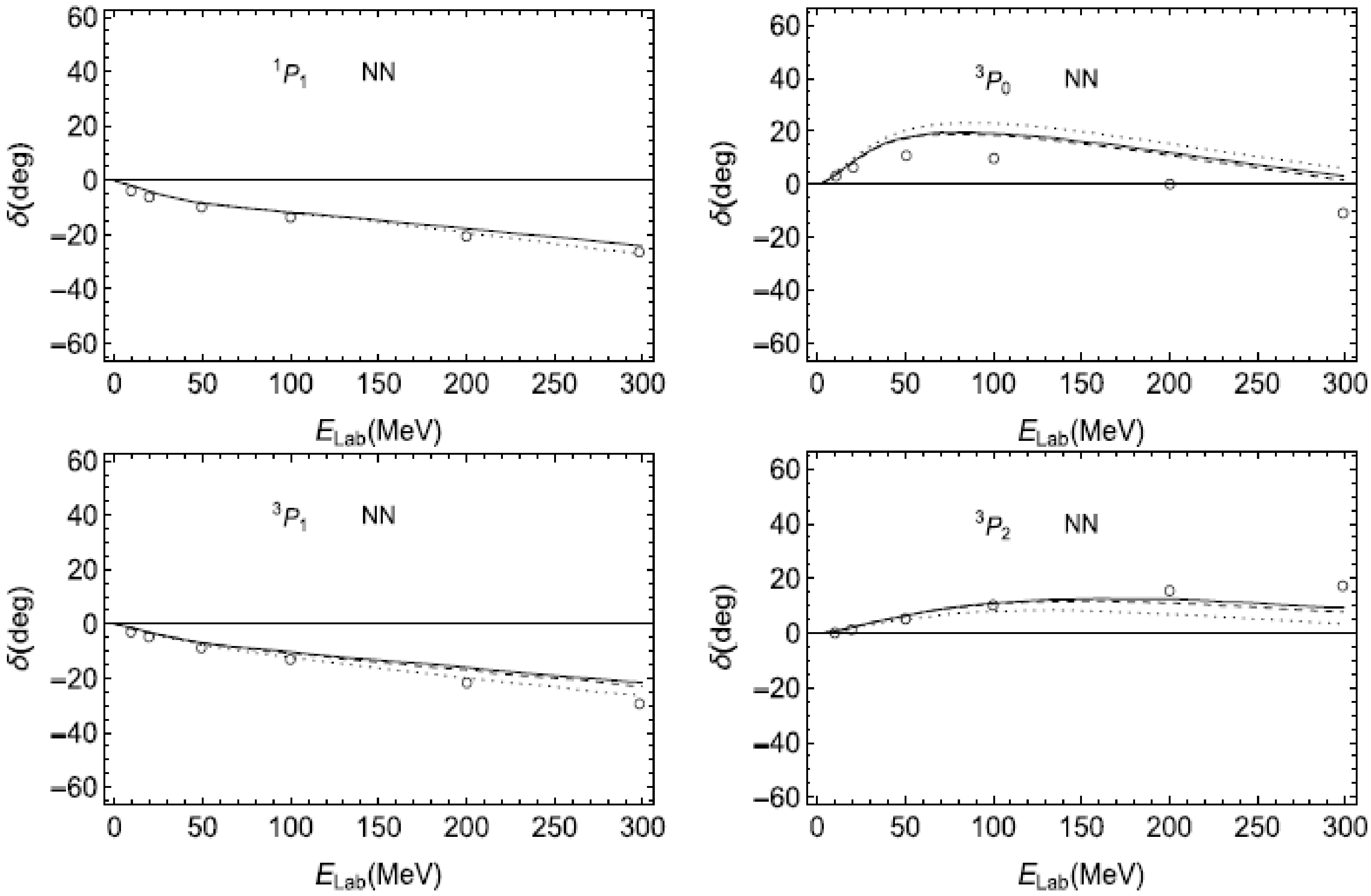
★⑤ The electromagnetic form factors of d*(2380) are also calculated and its charge radius, magnetic moments, quadupole moments are obtained. The scenarios of compact and loosely bounded are compared.

★⑥ More experimental information of this dibaryon is necessary to confirm its existence. Some possible observations are expected (BGOOD, ELPH)

● The study of dibaryons is not a new story. It is a window of multi-quark states.

Thanks for your attention

Backup



The P-wave phase shifts of the $N - N$ scattering in $SU(3)$CCQM and $SU(3)$ECCQM approaches.

comparison of two interpretations

(A) Compact quark model: (deeply) (B) ΔπN three-body system:

Good √ Quarks

Mass, energy and Double-pion strong decays

Good √ Hadrons

d*(2380) single-π decay

Our prediction 1% which is compatible with the experimental up-limits

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

The result of three-body (ΔπN) scenario is about 18%.

$$\Psi_{d^*} = |\Delta\Delta\rangle\, \chi_{\Delta\Delta}(r) + |CC\rangle\, \chi_{CC}(r)$$

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

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

Exp. gives 9% up-limit

Recently (PLB769) In order to match the up-limit of exp.

EM Form Factors：

More sophisticated admixture

Photo-absorption on deuteron by *d*(2380)*

Cloud

$$|d^*> \approx \sqrt{\frac{5}{7}}|\Delta\Delta> + \sqrt{\frac{2}{7}}|N\Delta\pi>$$

d, Form factors of d*

Form factors: 2S+1 relative to size **arXiv:1704.01253, PRD96,094001**

Nucleon(1/2):

$$< N(p') \mid J_N^\mu \mid N(p) >= \bar{U}_N(p')\Big[F_1(Q^2)\gamma^\mu + i\frac{\sigma^{\mu\nu}q_\nu}{2M_N}F_2(Q^2)\Big]U(p),$$

$$G_E(Q^2) = F_1(Q^2) - \eta F_2(Q^2), \qquad G_M(Q^2) = F_1(Q^2) + F_2(Q^2),$$

Breit frame

$$< N(\vec{q}/2) \mid J_N^0 \mid N(-\vec{q}/2) > \; = \; (1+\eta)^{-1/2}\chi_{s'}^+\chi_s G_E(Q^2)$$

$$< N(\vec{q}/2) \mid \vec{J}_N \mid N(-\vec{q}/2) > \; = \; (1+\eta)^{-1/2}\chi_{s'}^+\frac{\vec{\sigma}\times\vec{q}}{2M_N}\chi_s G_M(Q^2).$$

Deuteron(1):

$$J^\mu_{jk}(p',p) = \epsilon_j^{\prime *\alpha}(p')S^\mu_{\alpha\beta}\epsilon_k^\beta(p)$$

$$S^\mu_{\alpha\beta} = -\Big[G_1(Q^2)g_{\alpha\beta} - G_3(Q^2)\frac{Q_\alpha Q_\beta}{2m_D^2}\Big]P^\mu - G_2(Q^2)(Q_\alpha g^\mu_\beta - Q_\beta g^\mu_\alpha) ,$$

$$G_C(Q^2) \; = \; G_1(Q^2) + \frac{2}{3}\eta_D G_2(Q^2) , \qquad G_M(Q^2) = G_2(Q^2) ,$$

$$G_Q(Q^2) \; = \; G_1(Q^2) - G_2(Q^2) + (1+\eta_D)G_3(Q^2) ,$$

Breit frame

$$G_C(Q^2) \longrightarrow \frac{1}{3}\sum_\lambda < p', \lambda \mid J^0 \mid p, \lambda > .$$

c, Form factors of d*(2380)

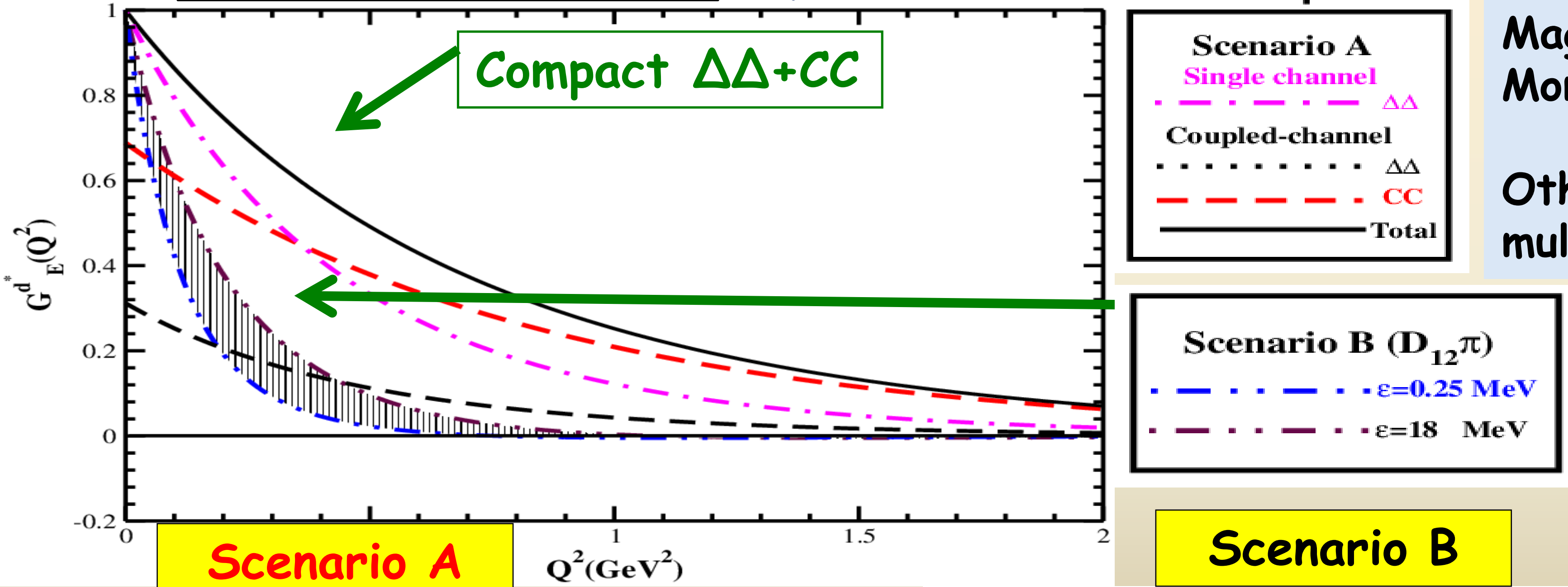
$I(J^P) = 0(3^+)$, *high spin*

PRD96 094001 (2017)
PRD97 114002 (2018)

spin=3 system, 2S+1=7 form factors

Charge Distributions

(related to the size of system)



Magnetic Moment

Other multipoles

Scenario A

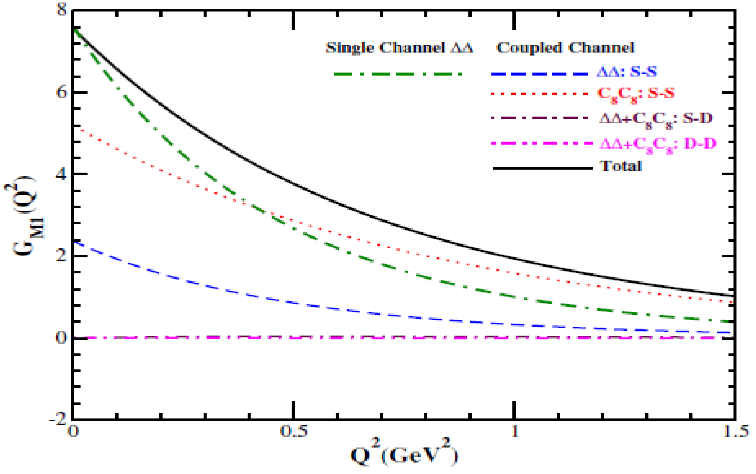
Scenario B

rms

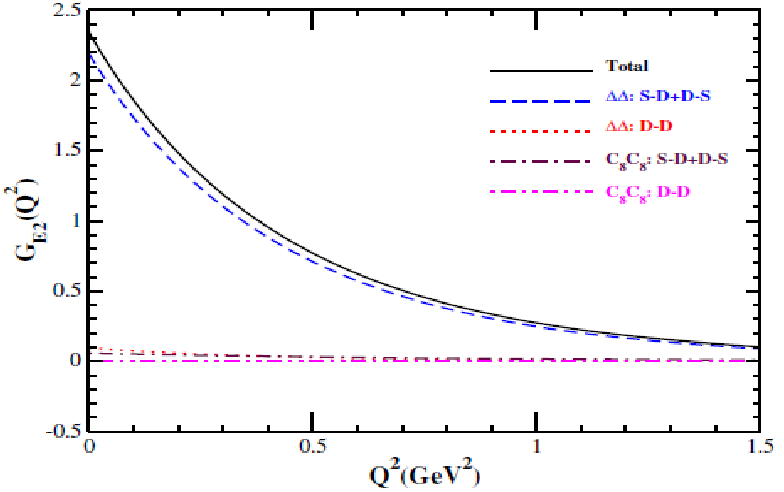
$d^*(2380)$		
Cases	A1	A2
rms (fm)	1.09	0.72

D_{12}		
Cases	B1	B2
rms (fm)	2.64	1.87

2024/6/20



The magnetic dipole form factor $M1$ of d^*.

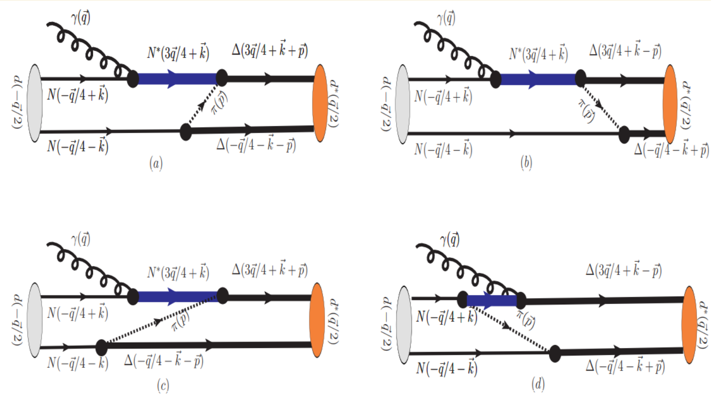


The quadrupole form factor of d^*.

e, Productions at other facilities

Photo-absorption on deuteron contributed by d*(2380) resonance

IJMPA34, 1950100(2019)



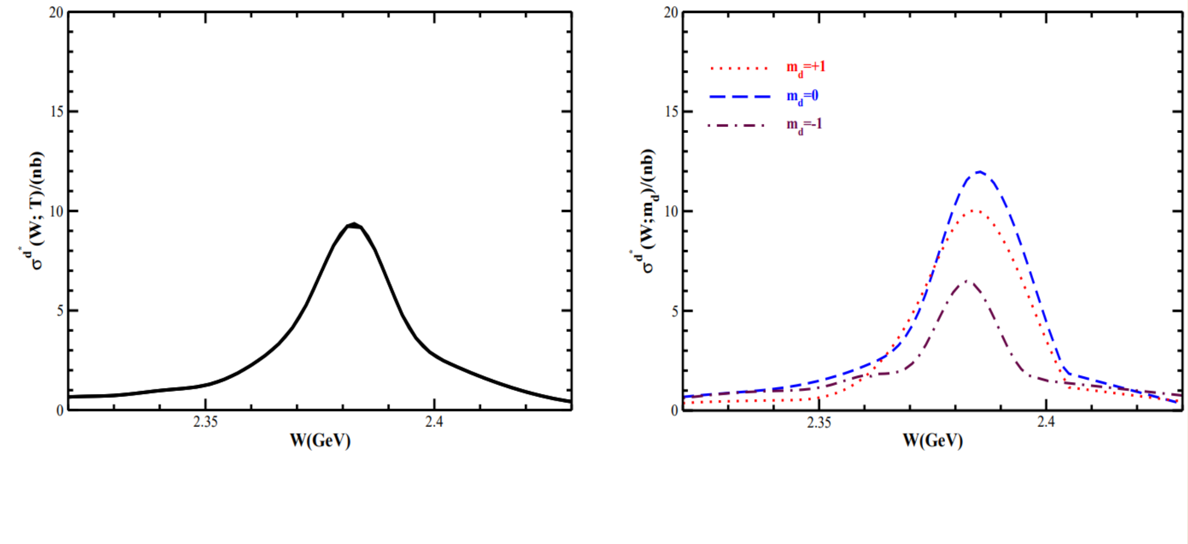
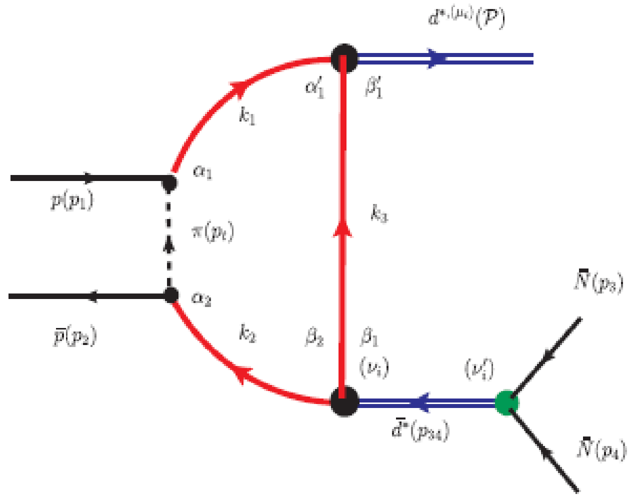
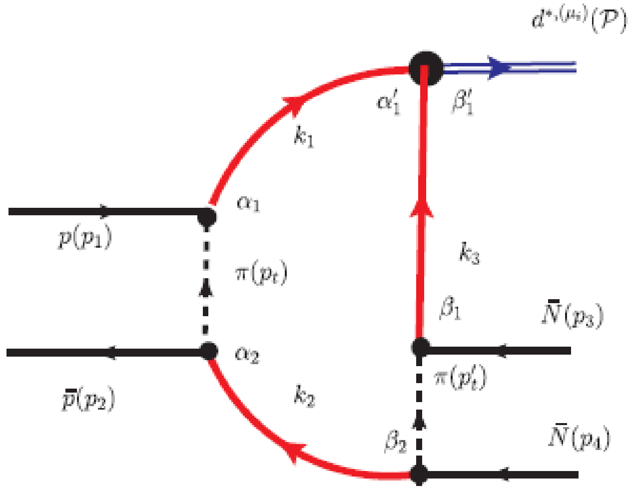


FIG. 2: Total photon-absorption cross section $\sigma^{d^*}(W;T)$ on the deuteron target in the d^* resonance region (left) and the individual contributions $\sigma^{d^*}(W;m_d)$ with $m_d = 1, 0, -1$ deuteron target (right).

e, Productions at other facilities

$$p+\bar{p}\rightarrow d^*(2380)+(\bar{p}+\bar{n})$$





$$\mathcal{L}_{d^*pn} = g_{d^*pn} q^{(pn)}_{\mu_1} q^{(pn)}_{\mu_2} \bar{\psi}_N \gamma_{\mu_3} \psi_N^C \times (d^*(\mathcal{P}))^{(\mu_i)} + \text{h.c.},$$

★1, *ΔΔ Contribution*

★2, *Compact system*

★3, *Breit-Wigner form considered*

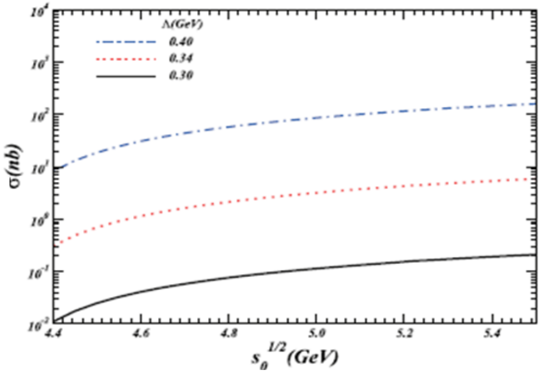
Panda

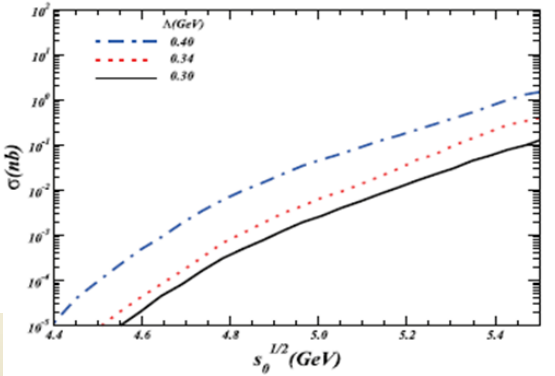
LM: $2\times10^{32}cm^{-2}/s$

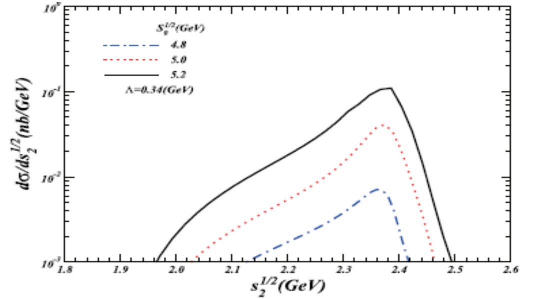
$\sqrt{s_0}=(4.8,5.0,5.2,5.4)GeV$

$(3.6,5.6,7.2,9.3)\times10^4{}_{evens}$

$(20,100,600,3200)_{evens}$







d, Productions at other facilities

other than
$p+n$
$p+d$
$d+d$

▲ *Suggest other experimental search and study for possible dibaryon signals:*

● $\gamma + d$ *Process (Mainz, Jlab., ELPH, BGOOD)* Int.J.Mod.Phys.A34,1950100(2019)

◆ $\Upsilon \rightarrow \bar{d}^* + X$ Process (Belle) PRD99 036015 (2019) CPC42 064012 (2018)

[BR($\Upsilon \rightarrow \bar{d} + X$) ~ 2.86×10^{-5}]

■ $e^+ + e^- \rightarrow \bar{d}^* + p + n$ *Processes (BEPC, Babar, Belle)*

★ $p + \bar{p} \rightarrow \bar{d}^* d^* + X$
$\rightarrow d^* + \bar{p}\bar{n}$
Processes (Panda) CPC46 113102(2022) CPC45 023105(2022)

Theoretical study of other dibaryon candidates:

$$|d^*> \sim \sqrt{\frac{1}{3}}|\Delta\Delta> + \sqrt{\frac{2}{3}}|CC>,$$

[$d^*_{(S=3,I=0)}$(2380), $d^*_{(S=0,I=3)}$], [$D_{(S=2,I=1)}$, $D_{(S=1,I=2)}$]

● ***Suggest other possible experimental searching for it***

and study for possible dibaryon signals (non-strange):

① *Process* (*Mainz, Jlab., ELPH, BGOOD*): $\gamma + d$

② *Process* (*Belle*), *Y-decays:* $\Upsilon \to \bar{d}^* + X$

$BR(\Upsilon \to \bar{d} + X)_{已知} \sim 2.9 \times 10^{-5}$

③ *Processes* (*BEPC, Babar, Belle?*): $e^+ + e^- \to \bar{d}^* + p + n$

④ *Processes* (*Panda*): $p + \bar{p} \to \bar{d}^* d^* + X$

Other Than $p + n$, $p + d$, $d + d$

WASA@COSY

NICA

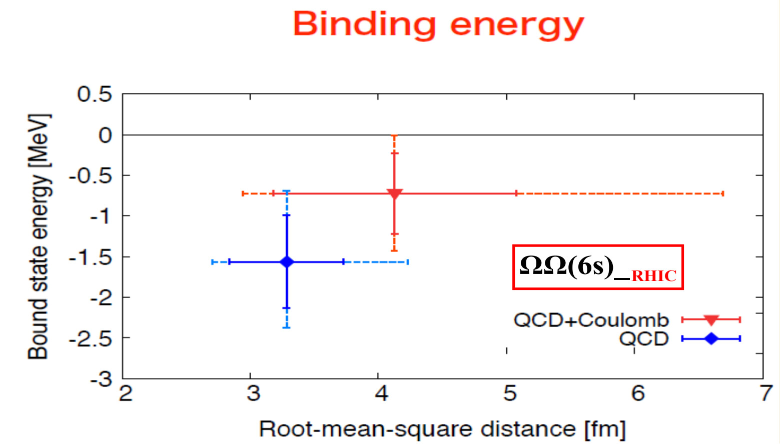
● ***Theoretical study of other dibaryon candidates:***

[★ $d_{(S=3,I=0)}^*(2380)$: $|d^* > \sim \sqrt{\frac{1}{3}}|\Delta\Delta> + \sqrt{\frac{2}{3}}|CC>$, $d_{(S=0,I=3)}^*(2380)$],

[$D_{(S=2,I=1)}$, $D_{(S=1,I=2)}$], [Roper+Δ]_Wasa@Cosy

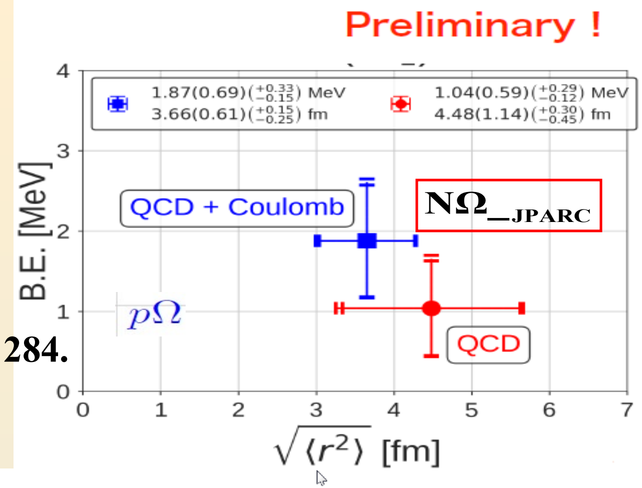
If the d* is further confirmed by experiments, Our interpretation looks reasonable. Thus, it might be a state with 6q structure dominant. Moreover, the more information about the short range interaction is expected.

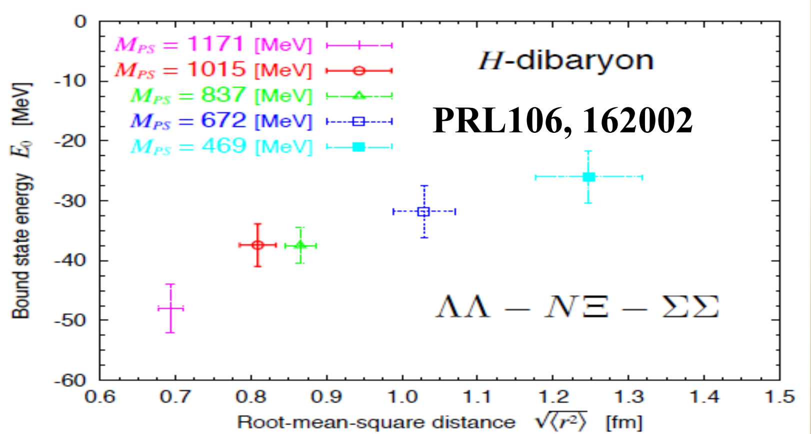
♣Some Lattice Calculations (HALQCD)



Other Di-baryons_Lattice

PLB 792, 284.

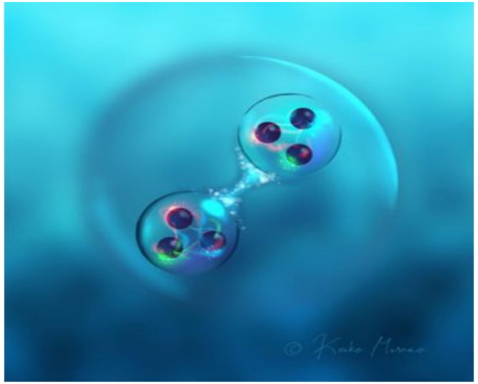




An H-dibaryon exists in the flavor SU(3) limit.
Binding energy = 25-50 MeV at this range of quark mass.
A mild quark mass dependence.

Dibaryon with Highest Charm Number near Unitarity from Lattice QCD

Yan Lyu, Hui Tong, Takuya Sugiura, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Jie Meng, and Takaya Miyamoto
Phys. Rev. Lett. **127**, 072003 – Published 11 August 2021



チャームダイオメガ（ΩcccΩccc）のイメージ図

Some others:
deuteron-like (shallow bounded) heavy dibaryons, PRL123,162003

Summarizing, in the baryon-baryon (BB) system we have so far clear-cut experimental evidence only for a single boundstate, which is the deuteron groundstate known since 1932. In particular, there is no boundstate in the hyperon-nucleon system with strangeness $S = -1$. In the strangeness $S = -2$ sector the existence of a possible boundstate, the H dibaryon, has not yet been ruled out completely at present.