$d^*(2380)$ in a chiral quark model

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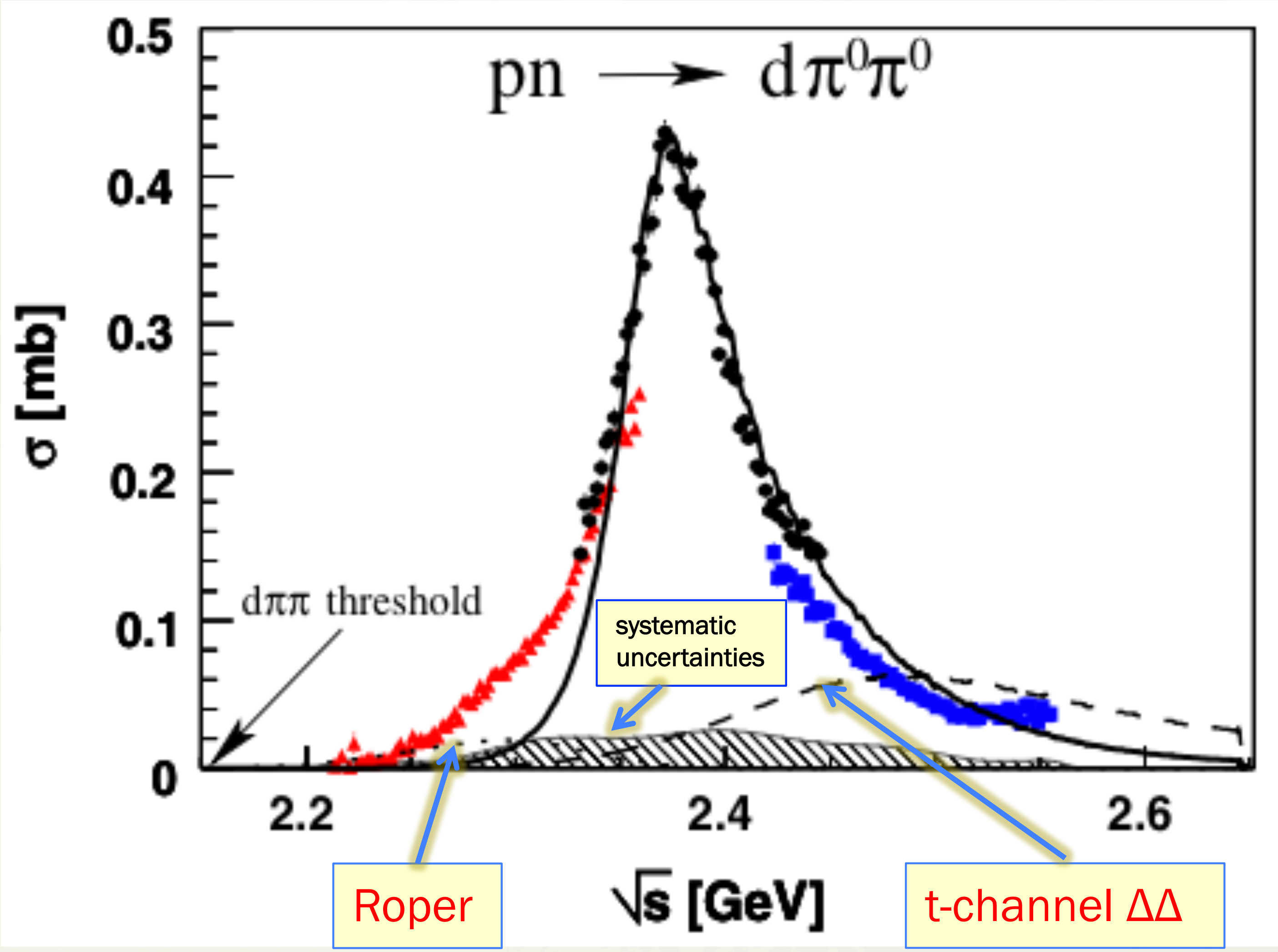
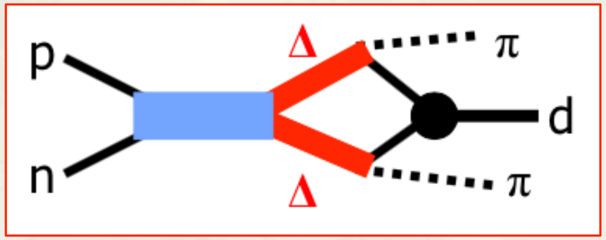
Experiments @ COSY

WASA-at-COSY, PRL106(2011)242302



- ✧ Exclusive
- ✧ Kinematically complete

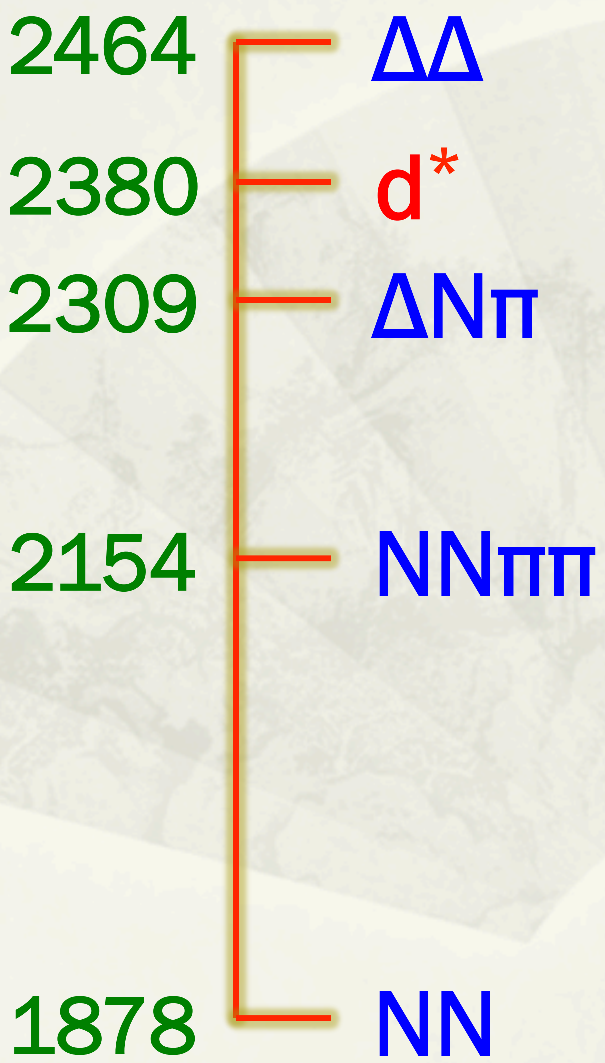


$I(J^p) = 0(3^+)$

$M \approx 2380$ MeV

$\Gamma \approx 70$ MeV

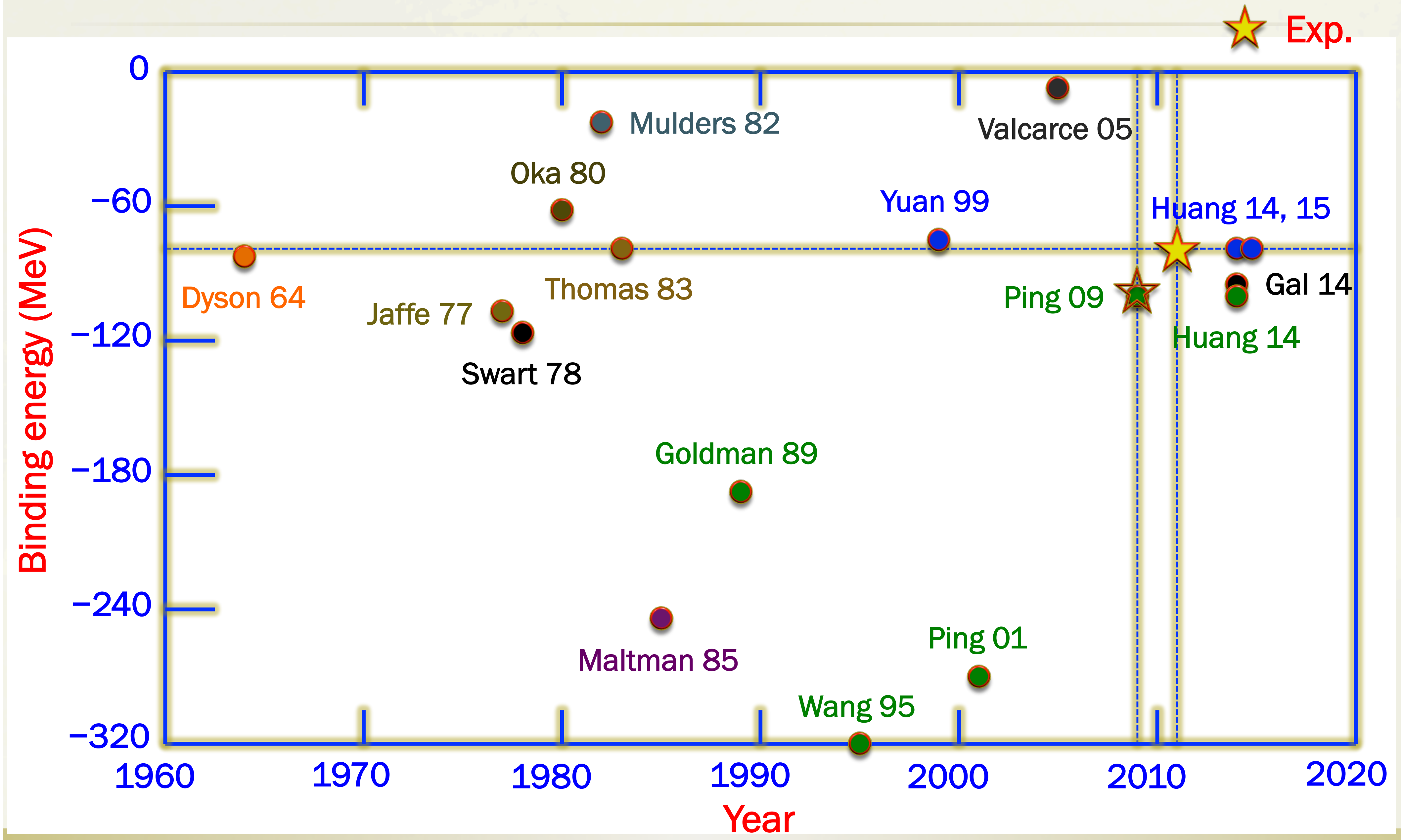
Unusual narrow width of d*



$$M_{d*} \approx 2380 \text{ MeV}$$
$$\approx 2M_{\Delta} - 84 \text{ MeV}$$
$$> M_{\Delta N\pi}$$
$$> M_{NN\pi\pi}$$
$$> M_{NN}$$

$$\Gamma_{d*} \approx 70 \text{ MeV}$$
$$< 1/3 \times 2\Gamma_{\Delta}$$

Theoretical ΔΔ binding energies



Our recent work

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

Total Hamiltonian for 6q systems:

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

Ch. SU(3) QM:

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

Ext. Ch. SU(3) QM:

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

Determination of parameters

- Input: $m_u = m_d = 313$ MeV,
  $b_u = 0.5$ fm (SU(3)) & 0.45 fm (ex. SU(3))
- Coupling between quark & chiral fields:

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

- 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:

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

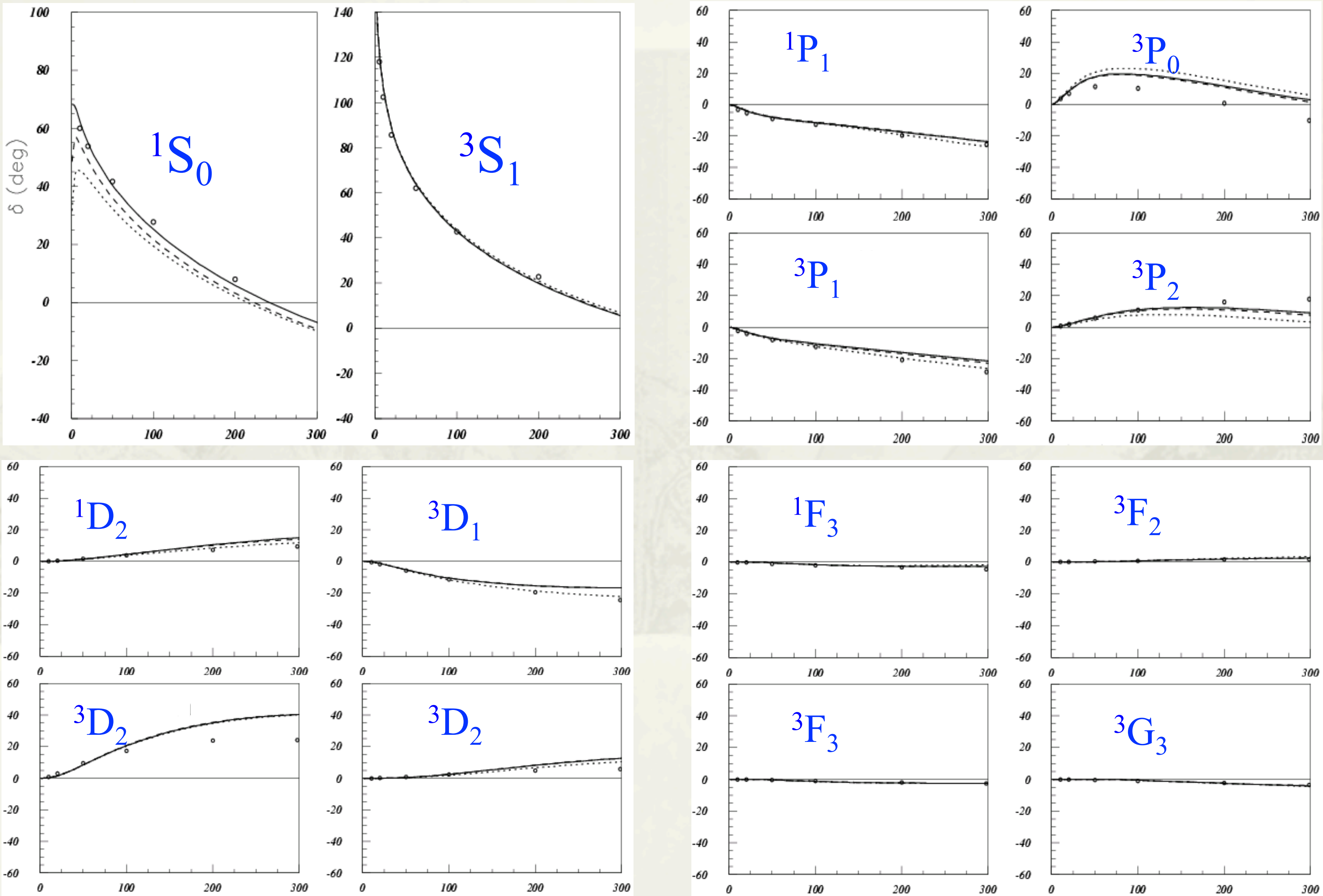
Parameter values

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
$g_{\rm ch}$	2.621	2.621	2.621
$g_{\rm chv}$		2.351	1.973
m_σ (MeV)	595	535	547
a^c_{uu} (MeV/fm^2)	46.6	44.5	39.1
a^{c0}_{uu} (MeV)	−42.4	−72.3	−62.9

NN phase shifts



RGM study of ΔΔ-CC

RGM wave functions for ΔΔ-CC system:

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

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

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

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

RGM equation for a bound state problem:

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

Calculated d* mass

Without CC: BE ≈ 29 – 62 MeV

	ΔΔ (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 ≈ 47 – 84 MeV

	ΔΔ – 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
$(CC)_{L=0}$ (%)	66.25	68.33	66.98
$(CC)_{L=2}$ (%)	0.02	0.00	0.00

- d^*: a deeply bound & compact ΔΔ-CC state
- Coupling to CC plays a significant role
- Predicted binding energy agrees with experiment

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

Distinctive features of ΔΔ: why

Quark-exchange effect:

- 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"!

Oka & Yazaki, PLB90(1980)41:
For all non-strange BB systems, $(\Delta\Delta)_{S=3,I=0}$ is the only one in which OGE provides attraction at short-range.

Short-range interaction:

OGE: attractive + VMEs: attractive

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

OGE: repulsive + VMEs: repulsive

Channel wave functions

RGM wave functions:

Not orthogonal

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

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

Channel wave functions:

$$\chi_{\Delta\Delta}(\vec{r}) = \left\langle \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\,\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5)\middle|\psi_{6q}\right\rangle$$

$$\chi_{CC}(\vec{r}) = \left\langle \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\,\hat{\phi}_{C}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5)\middle|\psi_{6q}\right\rangle$$

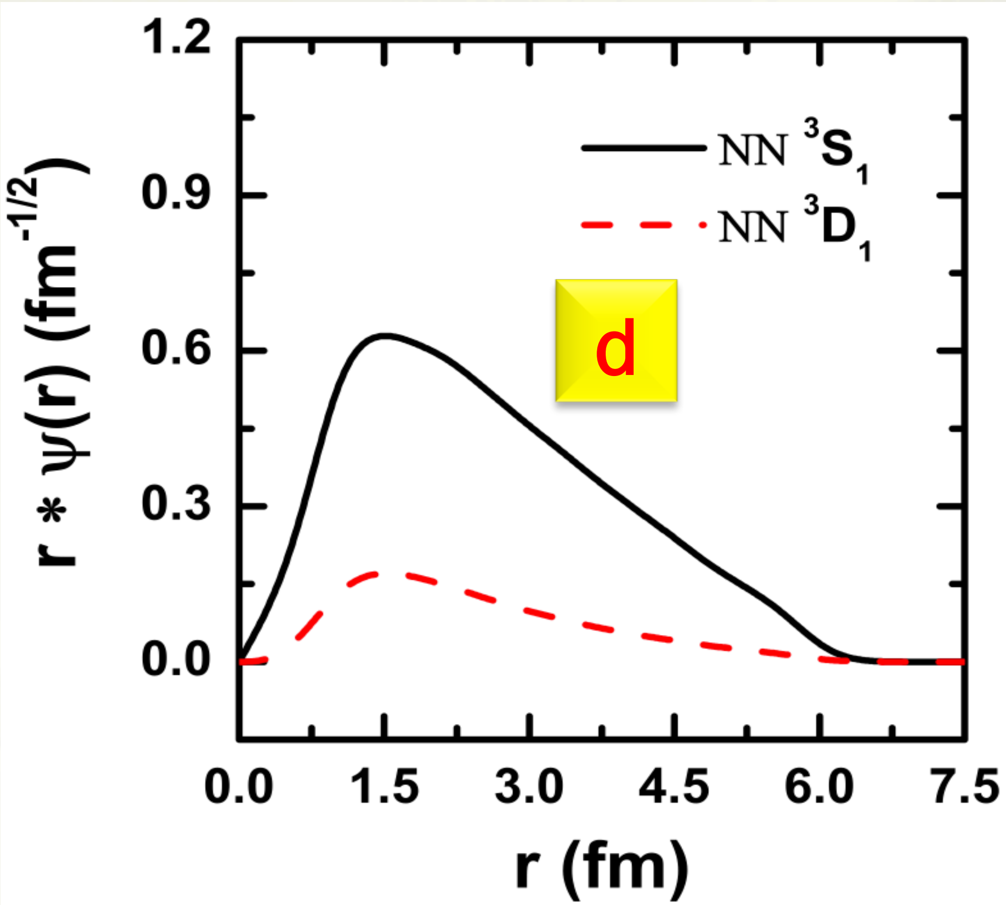
Wave function of d*:

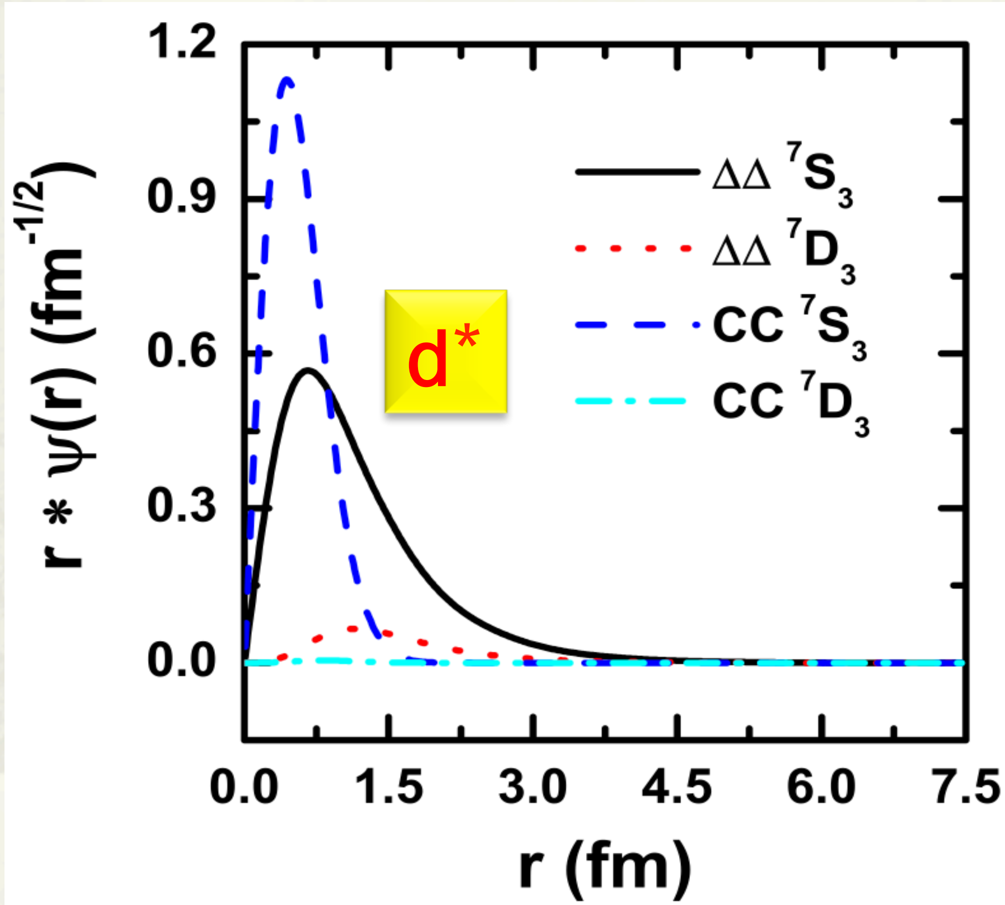
Orthogonal

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

$$= \sum_{L=0,2}\left[|\Delta\Delta\rangle\frac{\chi_{\Delta\Delta}^{L}(r)}{r} + |CC\rangle\frac{\chi_{CC}^{L}(r)}{r}\right]Y_{L0}(\hat{r})$$

Relative wave function





Unlike deuteron, d* is rather narrowly distributed!

CC component

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

	$\Delta\Delta - CC\ (L=0,2)$		
	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
$(CC)_{L=0}$ (%)	66.25	68.33	66.98
$(CC)_{L=2}$ (%)	0.02	0.00	0.00

- A pure hexaquark state of ΔΔ system has 4/5 CC fraction

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

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

Stability against confinement

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

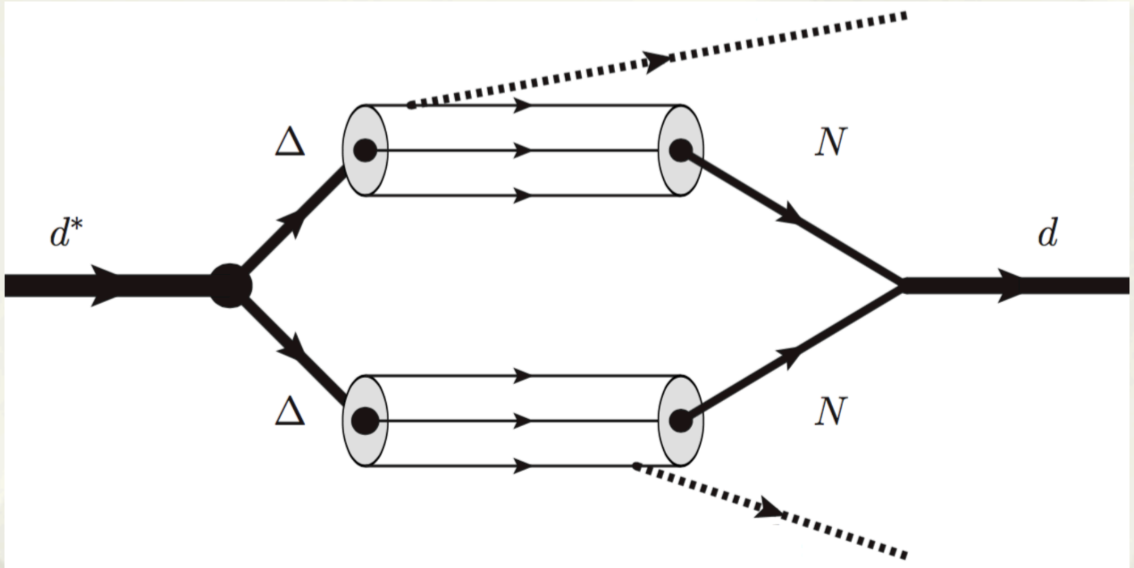
Check for ΔΔ-CC system:

	$\Delta\Delta - CC\ (L = 0, 2)$		
	r^2	r	$\mathrm{Erf}\,(r)$
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 $(CC)_{L=0}$ (%)	68.33	68.92	69.19
Fraction of $(CC)_{L=2}$ (%)	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

Decay width of d*



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

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

$$\Gamma = \frac{\Gamma_{d^* \to d\pi^+\pi^-}}{\mathcal{B}r\left(d^* \to d\pi^+\pi^-\right)} \approx \frac{16.8\ \text{MeV}}{23\%} \approx 73\ \text{MeV}$$

$$\Gamma = \frac{\Gamma_{d^* \to d\pi^0\pi^0}}{\mathcal{B}r\left(d^* \to d\pi^0\pi^0\right)} \approx \frac{9.2\ \text{MeV}}{14\%} \approx 66\ \text{MeV}$$

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

Summary

- d*(2380) has been reported by WASA-at-COSY with an unusual narrow width ($\Gamma \approx 70$ MeV)
- ΔΔ-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 → 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)