# Progress on $d^*(2380)$ in a chiral SU(3) quark model

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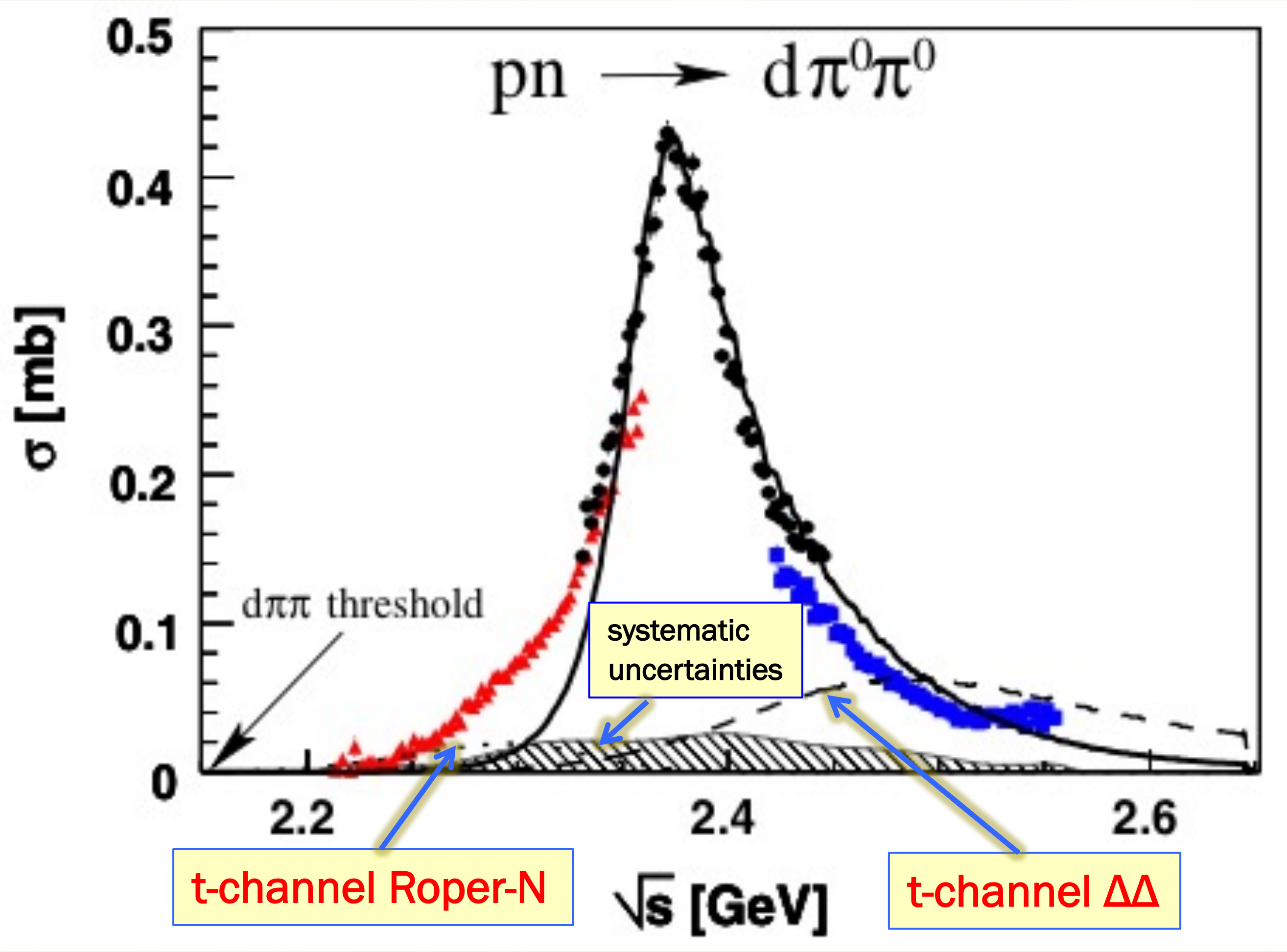
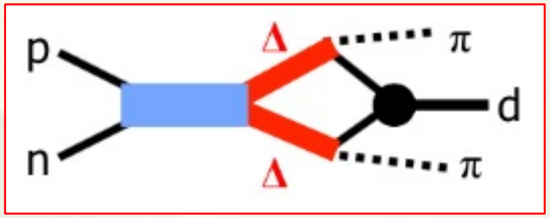
# Outline

- Introduction
  - Experimental status of d*(2380)
  - Theoretical predictions
- The chiral SU(3) quark model
- Previous calculations and results
- Problems and results from new calculations
- Summary

# Experiments @ COSY

**WASA-at-COSY, PRL 106 (2011) 242302**



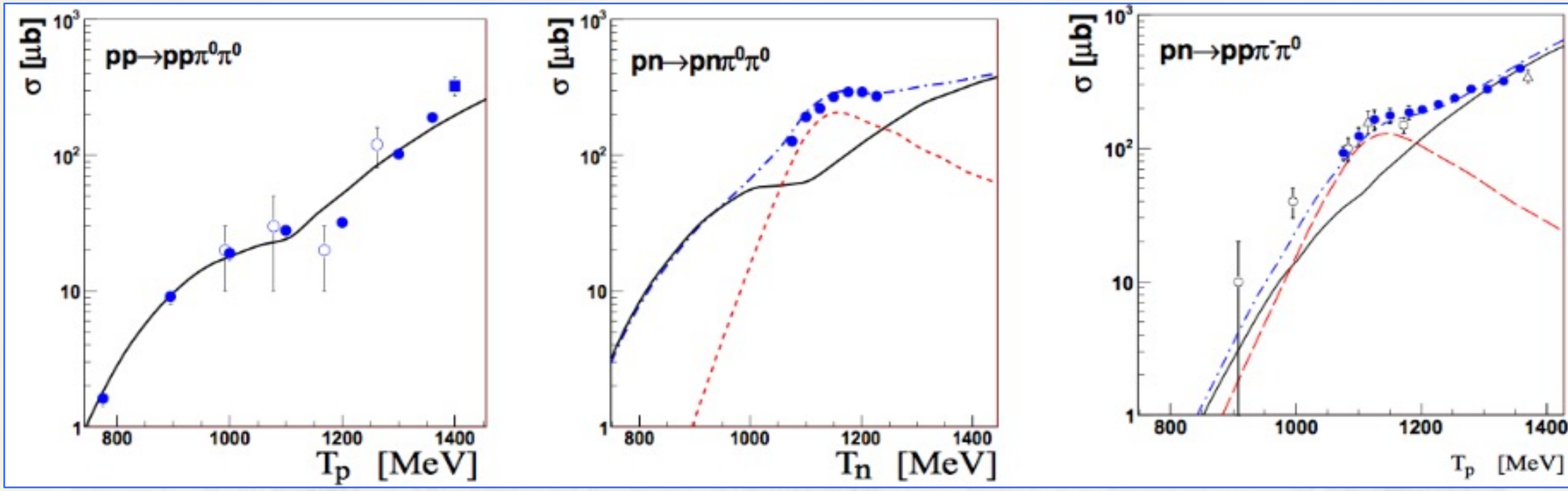

$I(J^p) = 0(3^+)$

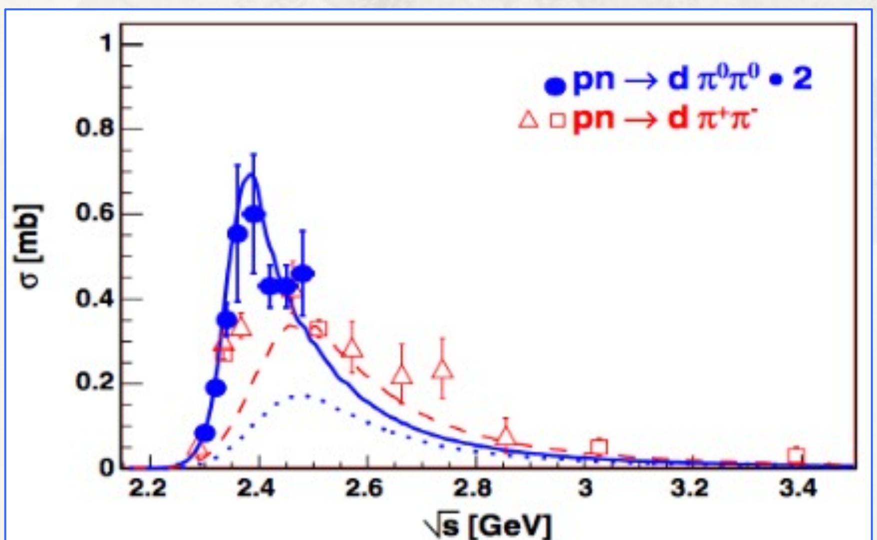
$M \approx 2380$ MeV

$\Gamma \approx 70$ MeV

$d^*(2380)$

# Signals in other reactions @ COSY




Also been Measured in fusion reactions to helium isotopes:

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

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

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

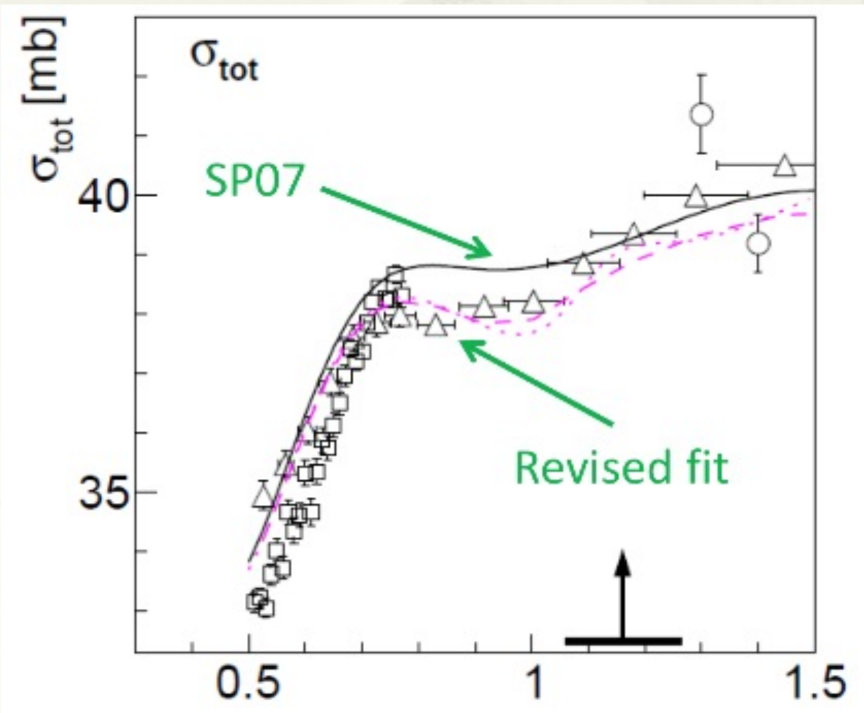
$d + d \longrightarrow {}^4He + \pi^+ + \pi^-$

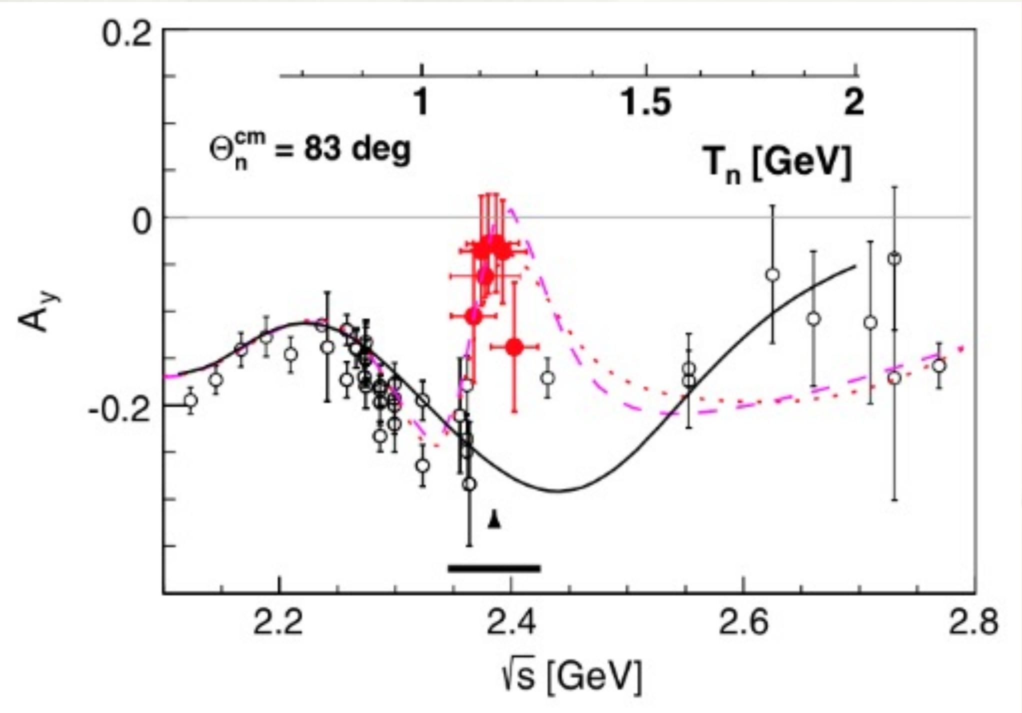
# Evidence from $\vec{n}p$ scattering

**WASA-at-COSY & SAID DAC, PRL 112 (2014) 202301**

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

**M = (2380±10) – *i* (40±5)**

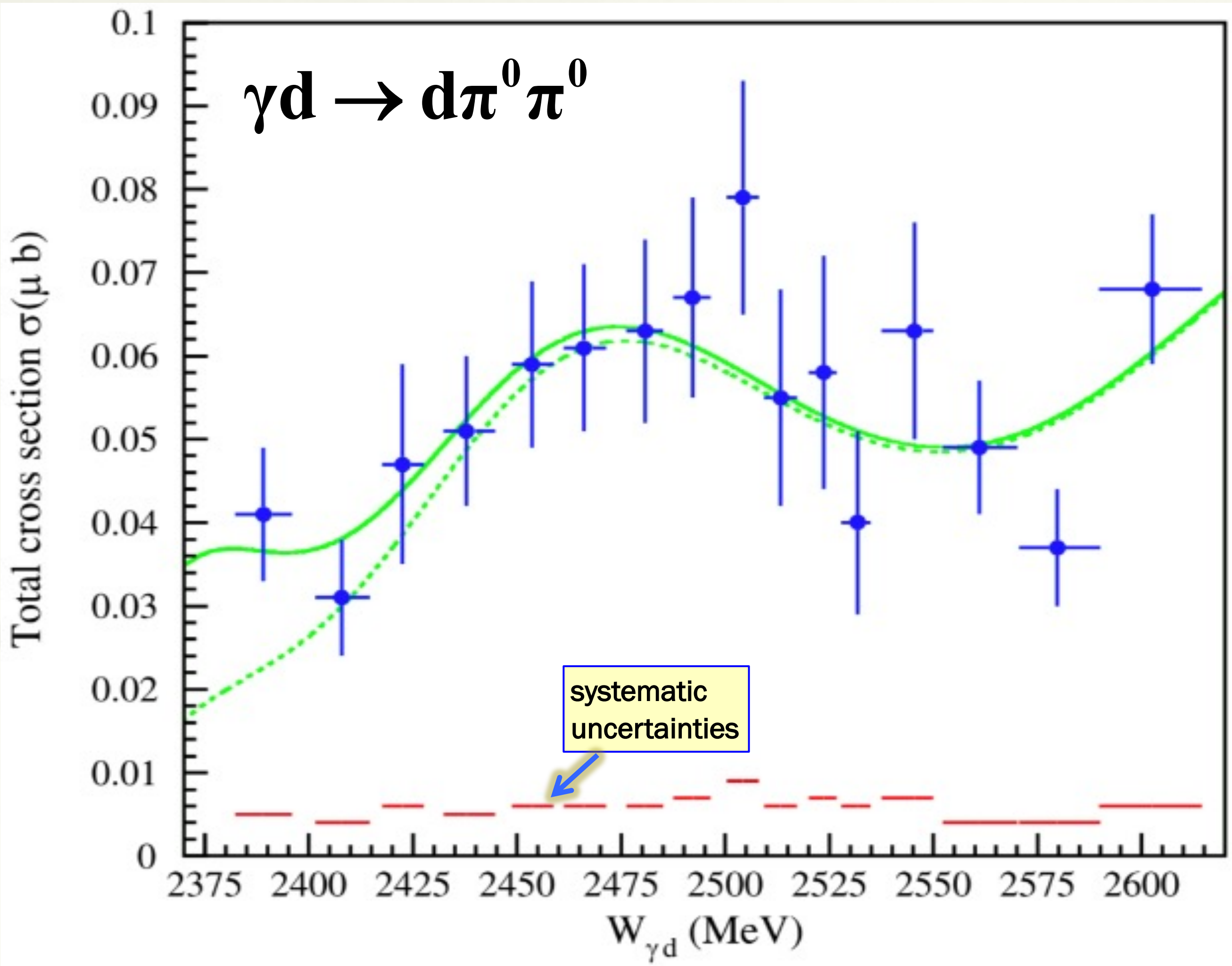



**Colored lines: new fits with the inclusion of new data (red symbols)**

# Experiment @ ELPH

**FOREST-at-ELPH, PLB 772 (2017) 398**




--- W/o d*(2380)

Fix & Arenhovel, EPJA25(2005)115

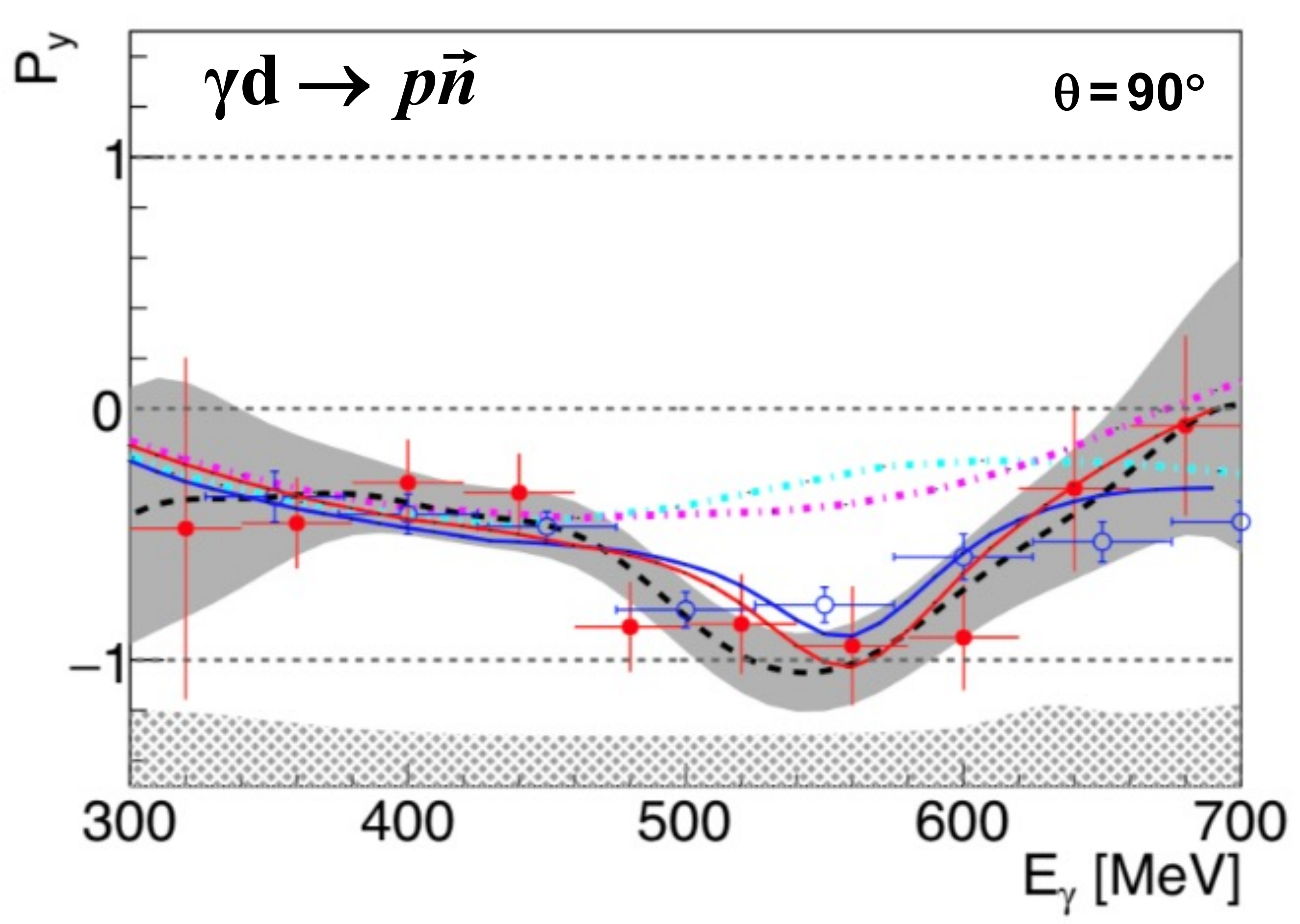
— With d*(2380)

ELPH: Research Center for Electron Photon Science @ Tohoku Univ.

# Experiments @ MAMI

Observation of an anomalous structure in proton polarization from Deuteron Photodisintegration, T. Kamae et al, PRL 38 (1977) 468

Signatures of the d*(2380) hexaquark in $d(\gamma, p\vec{n})$, A2-at-MAMI, PRL 124 (2020) 132001




o Old data on $P_y^p$

• New data on $P_y^n$

Grey band: unbinned analysis

W/o d*(2380)

With d*(2380)

# d*(2380) from lattice QCD

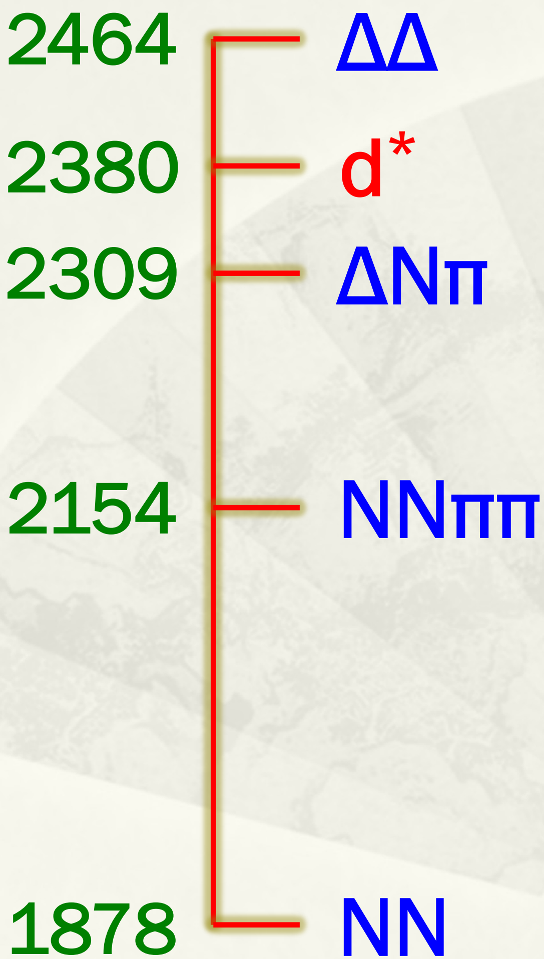
d*(2380) dibaryon from lattice QCD,
HAL QCD Collaboration, Phys. Lett. B 811, 135935 (2020).

**Abstract**

The $\Delta\Delta$ dibaryon resonance $d^*(2380)$ with $(J^P, I) = (3^+, 0)$ is studied theoretically on the basis of the 3-flavor lattice QCD simulation with heavy pion masses ($m_\pi$ = 679, 841 and 1018 MeV). By using the HAL QCD method, the central $\Delta$-$\Delta$ potential in the $^7S_3$ channel is obtained from the lattice data with the lattice spacing $a \simeq 0.121$ fm and the lattice size $L \simeq 3.87$ fm. The resultant potential shows a strong short-range attraction, so that a quasi-bound state corresponding to $d^*(2380)$ is formed with the binding energy 25-40 MeV below the $\Delta\Delta$ threshold for the heavy pion masses. The tensor part of the transition potential from $\Delta\Delta$ to $NN$ is also extracted to investigate the coupling strength between the $S$-wave $\Delta\Delta$ system with $J^P = 3^+$ and the $D$-wave $NN$ system. Although the transition potential is strong at short distances, the decay width of $d^*(2380)$ to $NN$ in the $D$-wave is kinematically suppressed, which justifies our single-channel analysis at the range of the pion mass explored in this study.

*Keywords:* Lattice QCD, Decuplet baryons, ABC effect, $d^*(2380)$

# Unusual narrow width of d*




$M_{d*} \approx 2380$ MeV

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

$> M_{\Delta N\pi}$

$> M_{NN\pi\pi}$

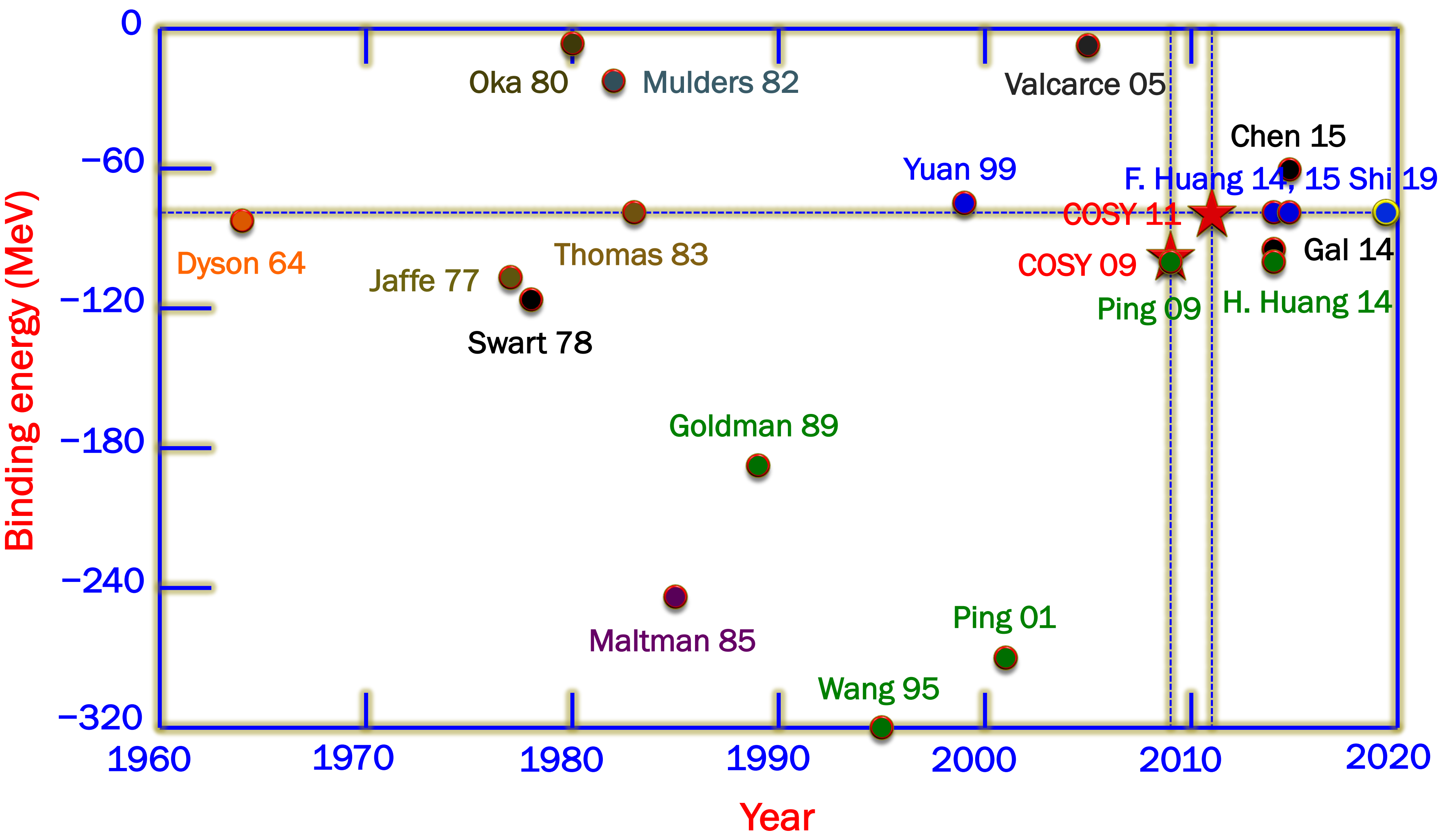
$> M_{NN}$

$\Gamma_{\Delta} \approx 115$ MeV

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

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

# Theoretical ΔΔ binding energies



# The Chiral SU(3) quark model

| SU(2) linear σ model | Chiral SU(3) quark model |
|---|---|
| $\Sigma = \sigma + i\sum_{a=1}^{3}\tau_a\pi_a$ | $\Sigma = \sum_{a=0}^{8}\lambda_a\sigma_a + i\sum_{a=0}^{8}\lambda_a\pi_a$ |
| $\mathcal{L}_I^{\mathrm{ch}} = -g\left(\bar{\psi}_L\Sigma\psi_R + \bar{\psi}_R\Sigma^\dagger\psi_L\right) = -g\,\bar{\psi}\left(\sigma + i\gamma_5\sum_{a=1}^{3}\tau_a\pi_a\right)\psi$ | $\mathcal{L}_I^{\mathrm{ch}} = -g\left(\bar{\psi}_L\Sigma\psi_R + \bar{\psi}_R\Sigma^\dagger\psi_L\right) = -g\,\bar{\psi}\left(\sum_{a=0}^{8}\lambda_a\sigma_a + i\gamma_5\sum_{a=0}^{8}\lambda_a\pi_a\right)\psi$ |

- Chiral symmetry restored by introducing S & PS fields
- CQ obtains constituent mass via spontaneous CSB
- GB gets mass via explicit CSB caused by tiny current quark mass

# Chiral SU(3) QM: Hamiltonian

$$H=\sum_i\left(m_i+\frac{\vec{P}_i^2}{2m_i}\right)-T_{\rm cm}+\sum_{i<j}\left[V_{ij}^{\rm conf}+V_{ij}^{\rm OGE}+\sum_{a=0}^{8}\left(V_{ij}^{\sigma_a}+V_{ij}^{\pi_a}\right)\right]$$

$$V_{ij}^{\rm OGE}=\frac{g_ig_j}{4}\left(\lambda_i^c\cdot\lambda_j^c\right)\left\{\frac{1}{r_{ij}}-\frac{\pi}{2}\delta\left(r_{ij}\right)\left[\frac{1}{m_i^2}+\frac{1}{m_j^2}+\frac{4}{3}\frac{\sigma_i\cdot\sigma_j}{m_im_j}\right]\right\}+V_{\rm ls}^{\rm OGE}+V_{\rm ten}^{\rm OGE}$$

$$V_{ij}^{\rm conf}=\begin{cases}-\left(\lambda_i^c\cdot\lambda_j^c\right)\left(a_{ij}^c r_{ij}^2+a_{ij}^{c0}\right)\\-\left(\lambda_i^c\cdot\lambda_j^c\right)\left(a_{ij}^c r_{ij}+a_{ij}^{c0}\right)\end{cases}\qquad Y(x)=\frac{e^{-x}}{x}$$

$$V_{ij}^{\sigma_a}=-\frac{g_{\rm ch}^2}{4\pi}\frac{\Lambda^2 m_a}{\Lambda^2-m_a^2}\left[Y\left(m_ar_{ij}\right)-\frac{\Lambda}{m_a}Y\left(\Lambda r_{ij}\right)\right]\left(\lambda_i^a\lambda_j^a\right)+V_{\rm ls}^{\sigma_a}$$

$$V_{ij}^{\pi_a}=\frac{g_{\rm ch}^2}{4\pi}\frac{\Lambda^2}{\Lambda^2-m_a^2}\frac{m_a^3}{12m_im_j}\left[Y\left(m_ar_{ij}\right)-\left(\frac{\Lambda}{m_a}\right)^3Y\left(\Lambda r_{ij}\right)\right]\left(\sigma_i\cdot\sigma_j\lambda_i^a\lambda_j^a\right)+V_{\rm ten}^{\pi_a}$$

# Chiral SU(3) QM: Wave functions

Spatial wave function for a single baryon:

$$\psi_B = \prod_{i=1}^{3} \left( \frac{1}{\pi b_i^2} \right)^{3/4} \exp\left[ -\frac{r_i^2}{2b_i^2} \right] = \psi_{\text{int}}(\xi_1, \xi_2)\, \psi_{3q}(R_{\text{cm}})$$

Wave function for a two-baryon system:

$$\psi_{BB} = \mathcal{A}\left[ \hat{\phi}_{\text{int}}(\xi_1, \xi_2)\; \hat{\phi}_{\text{int}}(\xi_3, \xi_4)\; \chi(r)\; \psi_{6q}(R_{\text{cm}}) \right]_{ST}$$

$$\mathcal{A} = 1 - 9P_{36}$$

$$\langle \delta\psi_{BB} | H - E | \psi_{BB} \rangle = 0 \quad \rightarrow \quad \begin{cases} \chi(r) \\ \textbf{binding energy / phase shifts} \end{cases}$$

# Model parameters

- **Input:** $m_u = m_d = 313$ MeV, $b_u = 0.5$ fm
- **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 $m_\sigma$
- **Coupling constant for OGE:** $g_u \propto m_\Delta - m_N$
- **Confinement strength & zero point energy:**

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

No free parameters when study ΔΔ interaction!

# Results from previous calculations

ΔΔ dibaryon structure in chiral SU(3) quark model,
X. Q. Yuan, Z. Y. Zhang, Y. W. Yu, & P. N. Shen, Phys. Rev. C 60, 045203 (1999).

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

| | | $\Delta\Delta(L=0)$ | $\Delta\Delta\binom{L=0}{+2}$ | $\frac{\Delta\Delta}{CC}(L=0)$ | $\frac{\Delta\Delta}{CC}\binom{L=0}{+2}$ |
|---|---|---|---|---|---|
| OGE | $B$ (MeV) | 29.8 | 29.9 | 41.0 | 42.0 |
| | $\bar{R}$ (fm) | 0.92 | 0.92 | 0.87 | 0.87 |
| OGE+$\pi,\sigma$ | $B$ (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 |

30-60

40-80

$\Delta: I=3/2,\ C=(00)$

$\mathrm{C}: I=1/2,\ C=(11)$

- $E_{\text{bind}}$: 40 ~ 80 MeV
- CC: 10 ~ 20 MeV increase in $E_{\text{bind}}$

# Components of CC in d*

Analysis of the wave functions based on: Phys. Rev. C 60, 045203 (1999)

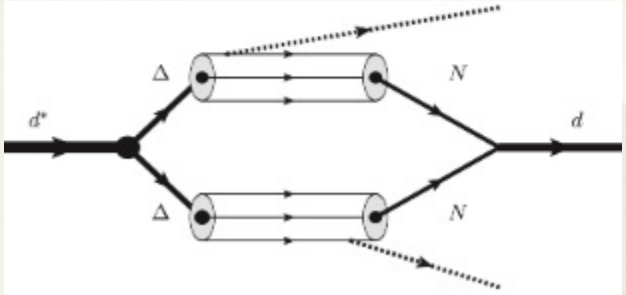
| | $\Delta\Delta - CC$ $(L = 0, 2)$ | | |
|---|---|---|---|
| | SU(3) | Ext. SU(3) (f/g=0) | Ext. SU(3) (f/g=2/3) |
| B (MeV) | 47.27 | 83.95 | 70.25 |
| RMS (fm) | 0.88 | 0.76 | 0.78 |
| $(\Delta\Delta)_{L=0}$ (%) | 33.11 | 31.22 | 32.51 |
| $(\Delta\Delta)_{L=2}$ (%) | 0.62 | 0.45 | 0.51 |
| $(CC)_{L=0}$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

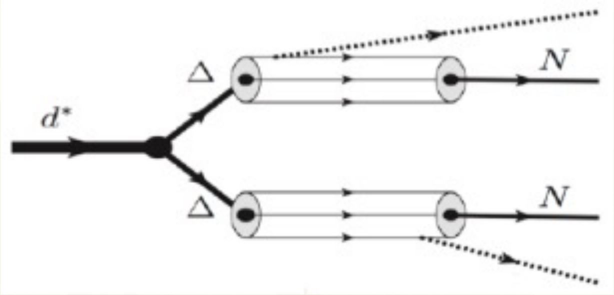
$d^*$ has a CC fraction of about 2/3!

A pure hexaquark state: $$[6]_{orb}[33]_{IS=03} = \sqrt{\frac{1}{5}}|\Delta\Delta\rangle_{IS=03} + \sqrt{\frac{4}{5}}|CC\rangle_{IS=03}$$

2/3 is close to 4/5 → $d^*$ is a hexaquark-dominated exotic state!

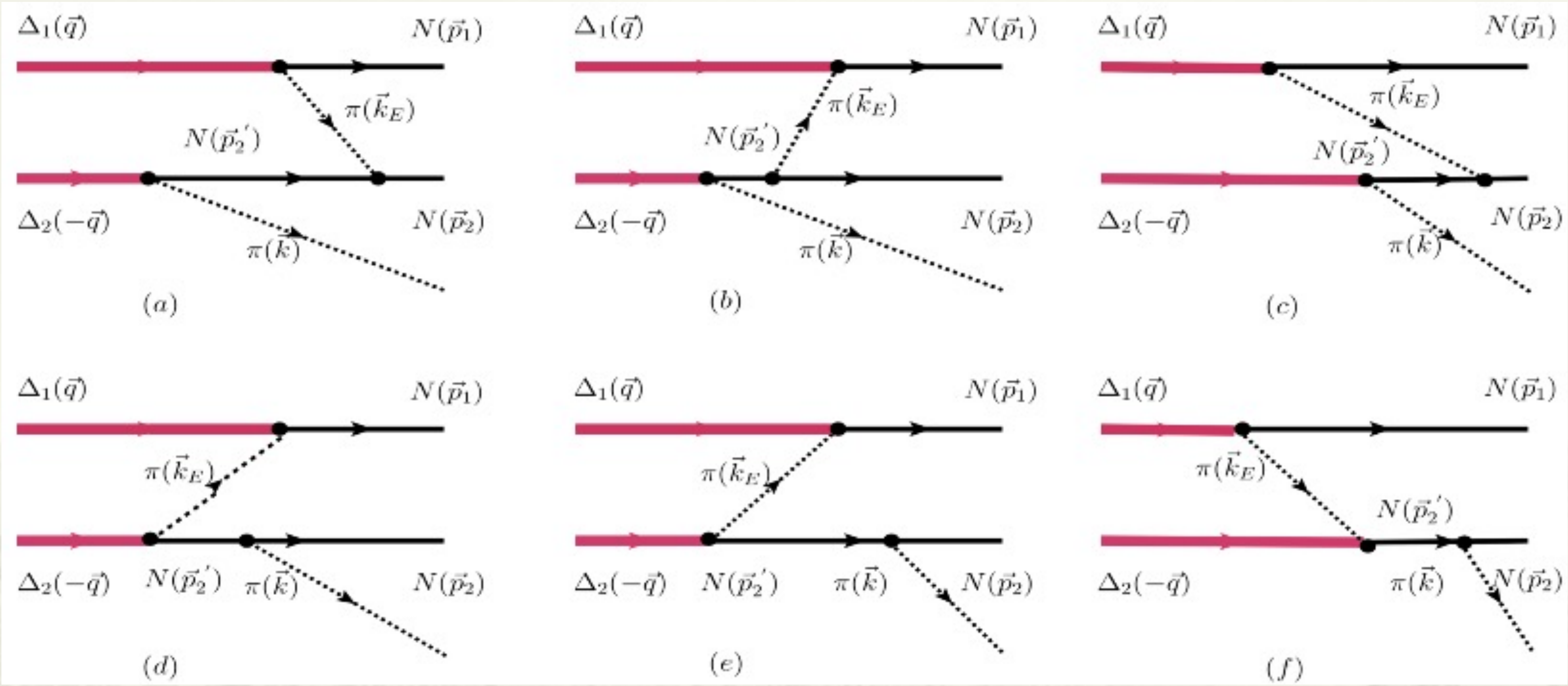
# Partial decay widths: 2π-decay




| | 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 |

# Partial decay widths: 1π decay




$\Gamma_{d^* \to NN\pi} \approx \mathbf{0.67\ MeV}$

$\frac{\Gamma_{d^* \to NN\pi}}{\Gamma} \approx \mathbf{0.9\%}$

Expt.: < 9%

# Problem in earlier QM calculations

$$\psi_B = \prod_{i=1}^{3} \left( \frac{1}{\pi b_i^2} \right)^{3/4} \exp\left[ -\frac{r_i^2}{2b_i^2} \right]$$

$b_u = 0.5$

- Problem: why different baryons have the same size?
- Consequence:
  - The wave function of a single baryon is not the solution of the given Hamiltonian
  - When study BB interactions, non-physical channels might be needed to change the internal wave functions of single baryons

  → Be careful in explaining the structure of bound BB states!

# Solving the inconsistency problem

Nucleon-nucleon interaction in a chiral SU(3) quark model revisited,
F. Huang & W.L. Wang, Phys. Rev. D 98, 074018 (2018).

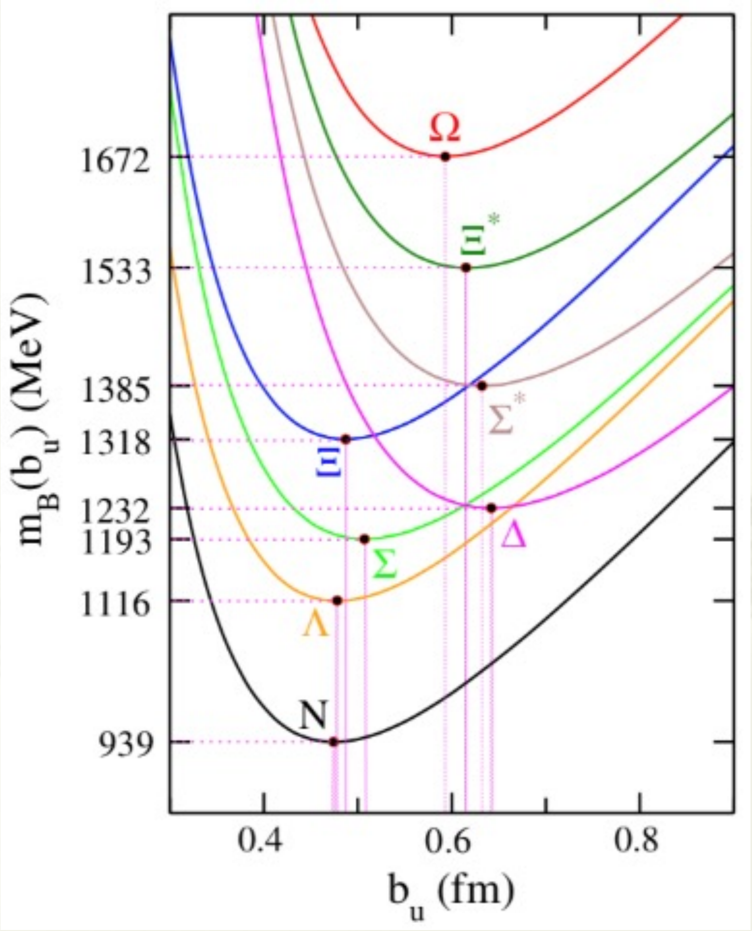
Determine $b_u$ for each baryon by variation principle:

$$\frac{\partial}{\partial b_u}\langle \psi_B | H | \psi_B \rangle = 0$$

The size parameters for decuplet baryons are much larger than those for octet baryons!

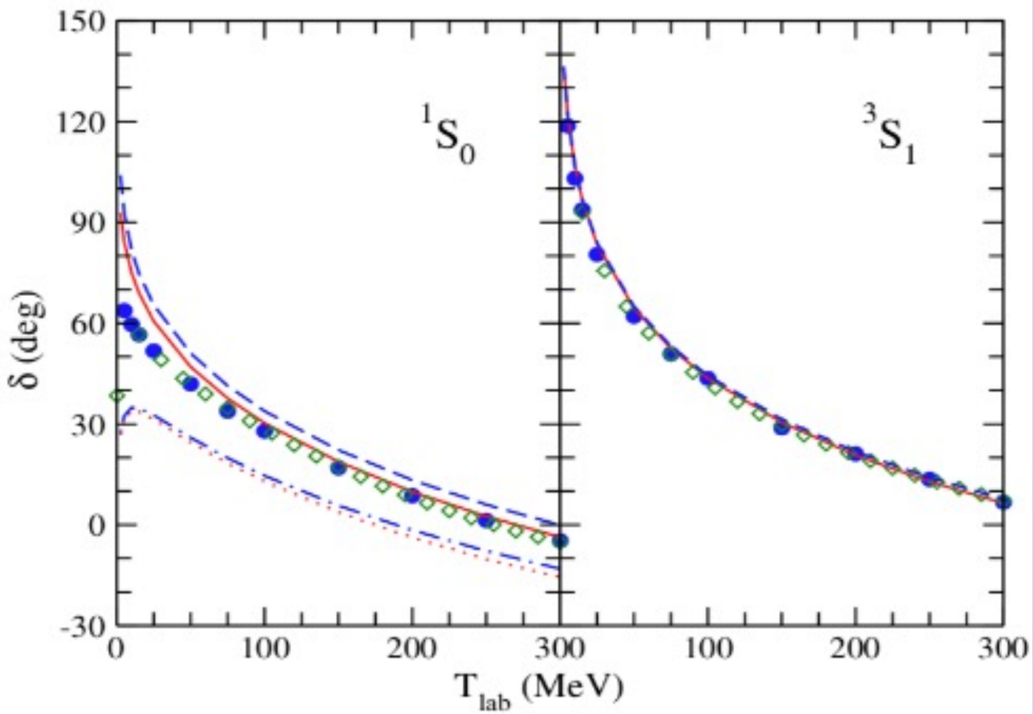
$b_u \approx 0.47$ fm for N

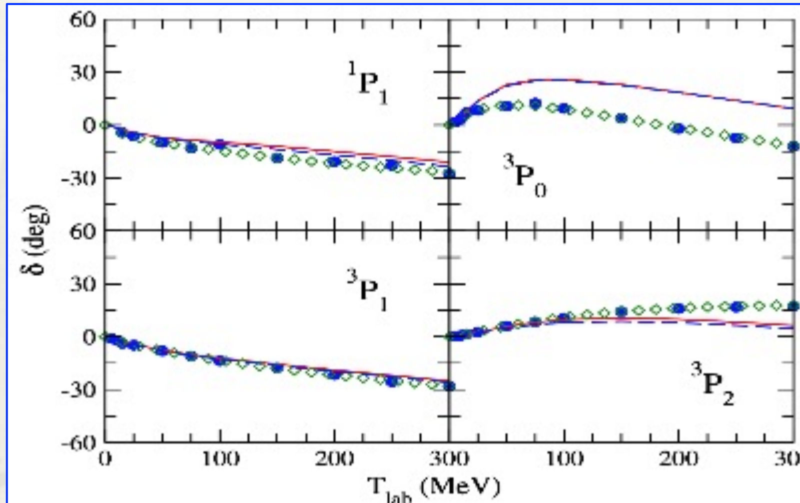
$b_u \approx 0.64$ fm for Δ



# New results for NN interaction

Nucleon-nucleon interaction in a chiral SU(3) quark model revisited, F. Huang & W.L. Wang, Phys. Rev. D 98, 074018 (2018).



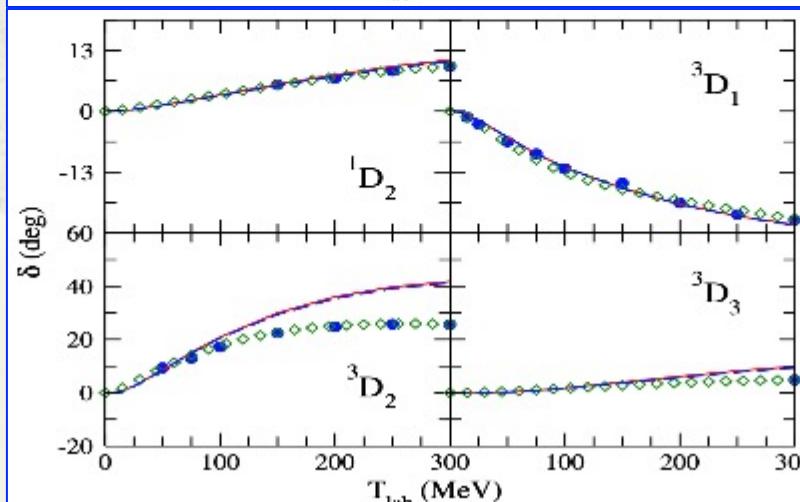
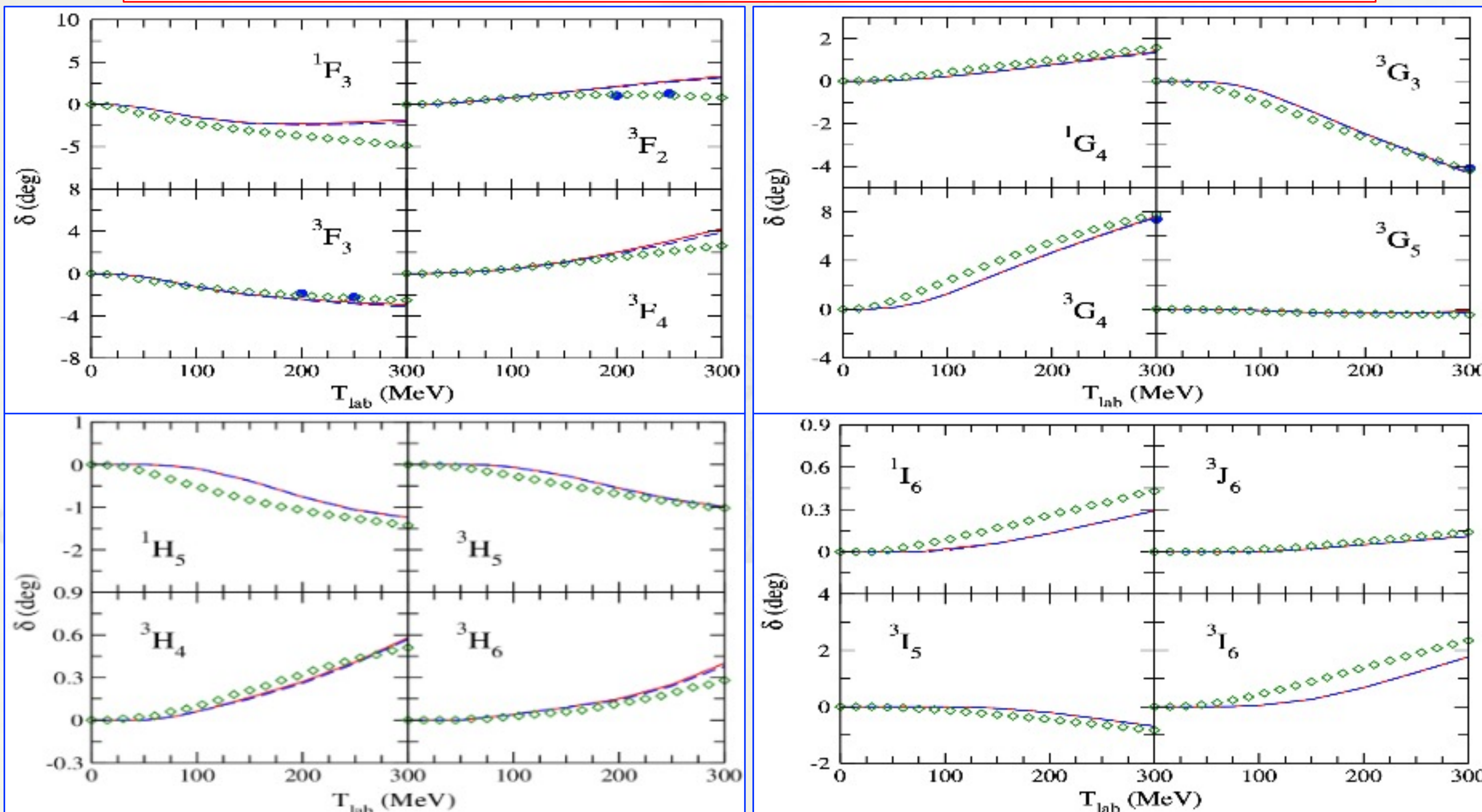




TABLE III. Binding energy of deuteron (in MeV).

| Model I ($r$ conf.) | Model II ($r^2$ conf.) | Expt. |
|---|---|---|
| −2.215 | −2.218 | −2.224 |

# New results for NN interaction

Nucleon-nucleon interaction in a chiral SU(3) quark model revisited,
F. Huang & W.L. Wang, Phys. Rev. D 98, 074018 (2018).



# New results for ΔΔ-CC

| | Previous calculation ($b_u$= 0.5 for N, Δ) | New calculation ($b_u$= 0.47, 0.64 for N, Δ) |
|---|---|---|
| ΔΔ (L = 0 + 2) | $E_{bind}$ = 23 MeV | $E_{bind}$ = 18 MeV |
| ΔΔ + CC (L = 0 + 2) | $E_{bind}$ = 37 MeV | $E_{bind}$ = 21 MeV |

Single baryons and two-baryon systems treated consistently in new calculation:

- Binding energy of ΔΔ+CC largely reduced
- Effects of CC much less important

Narrow $\Gamma_{d^*}$ not yet been understood !

# Summary

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

- Previous chiral SU(3) QM calculation: $b_u$ = 0.5 for N, Δ
  - binding energy of ΔΔ+CC qualitatively consistent with $M_{d^*}$
  - large CC components explains the narrow $\Gamma_{d^*}$

- Updated calculation: B and BB treated consistently
  - binding energy of ΔΔ+CC largely reduced
  - Effects of CC much less important $\Rightarrow$ narrow $\Gamma_{d^*}$ still difficult to understand

- $d^*$(2380) not yet been well understood in quark model!