# Understanding d*(2380) in a chiral quark model

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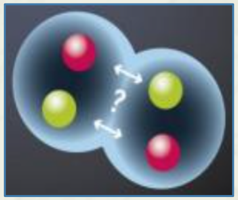
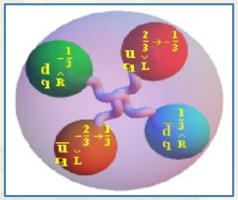
# Outline

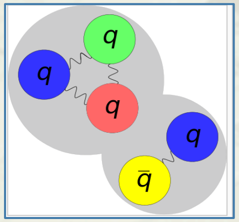
- Motivation
- Experimental observation
- Status of theoretical investigations
- Results from chiral SU(3) quark model calculations
  - Mass & structure
  - Decay widths
  - Charge distribution
- Summary

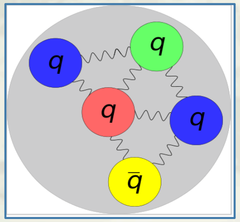
# Motivation

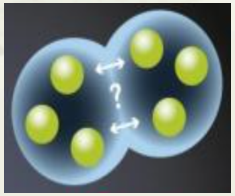
- Quarks are confined into hadrons instead of being "bare" & "alone"
- Most hadron states are categorized into mesons ($q\bar{q}$) and baryons ($qqq$)
- Exotics not excluded by QCD
- 4- or 5-quark configurations claimed in heavy flavor physics
- Possible 6-quark systems: deuteron is the only confirmed one
- Any other BB molecules? Hexaquark states?

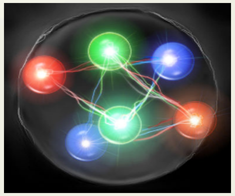






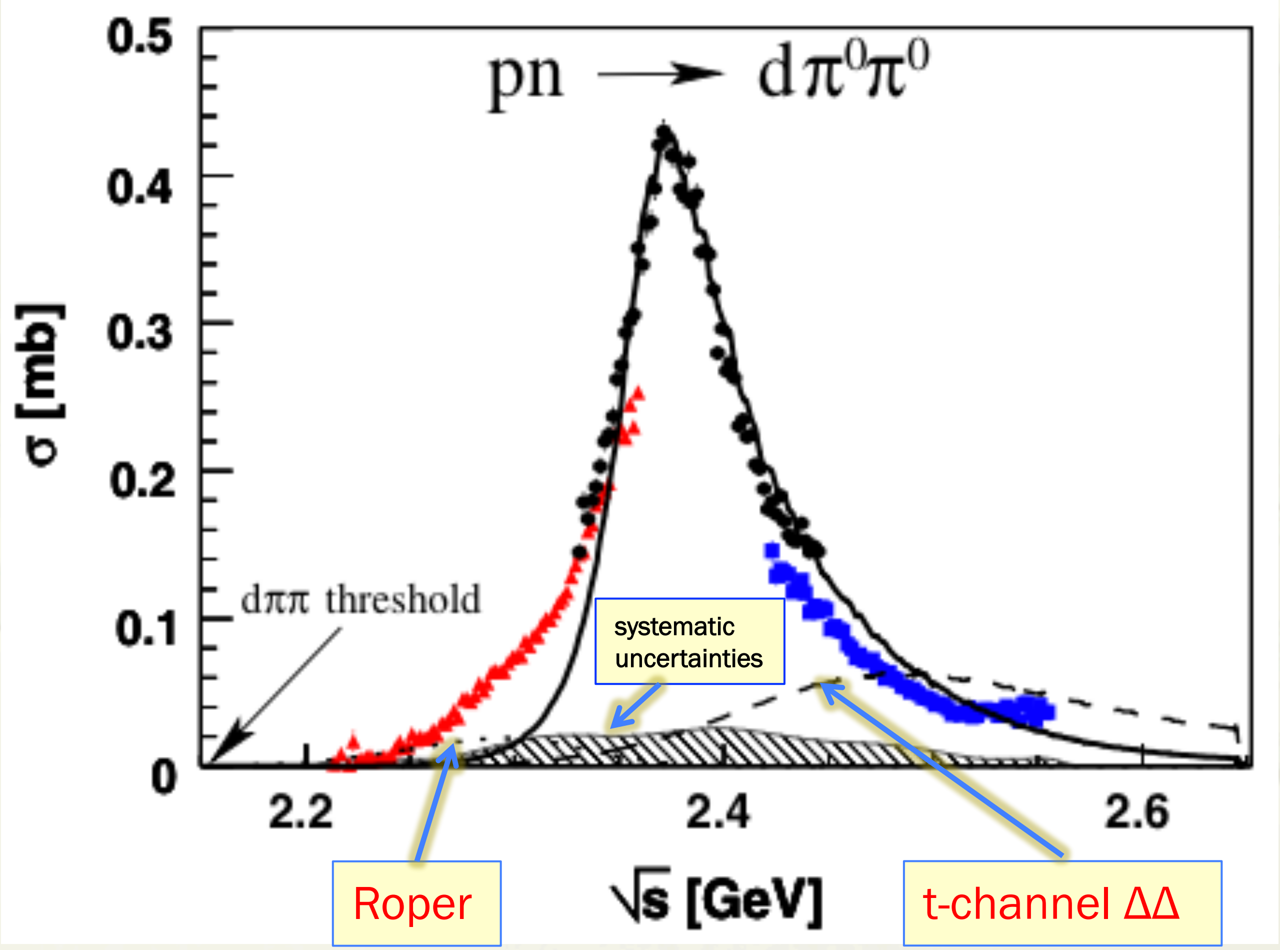



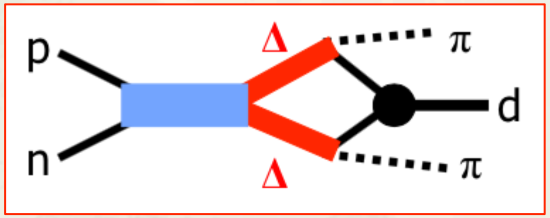


# Experiments @ COSY

WASA-at-COSY, PRL106(2011)242302




- ✧ Exclusive
- ✧ Kinematically complete



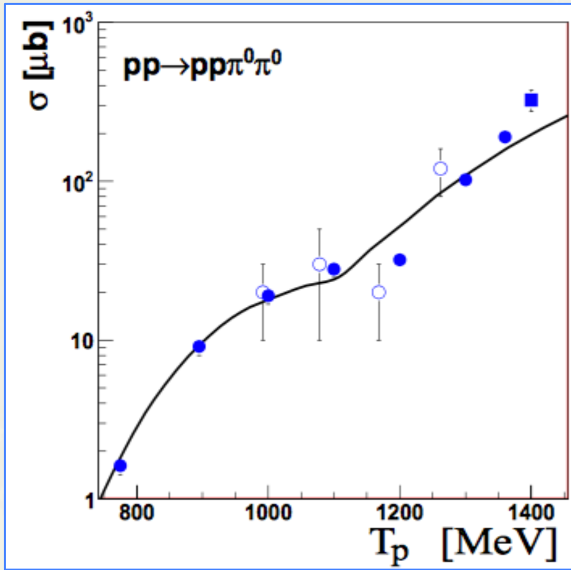

$I(J^p) = 0(3^+)$

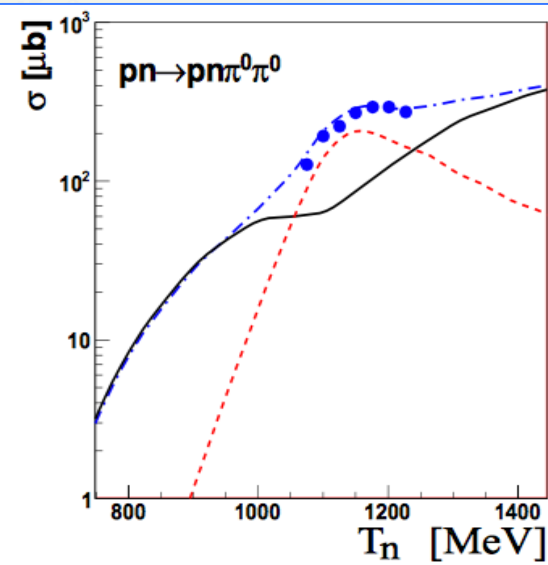
$M \approx 2380$ MeV

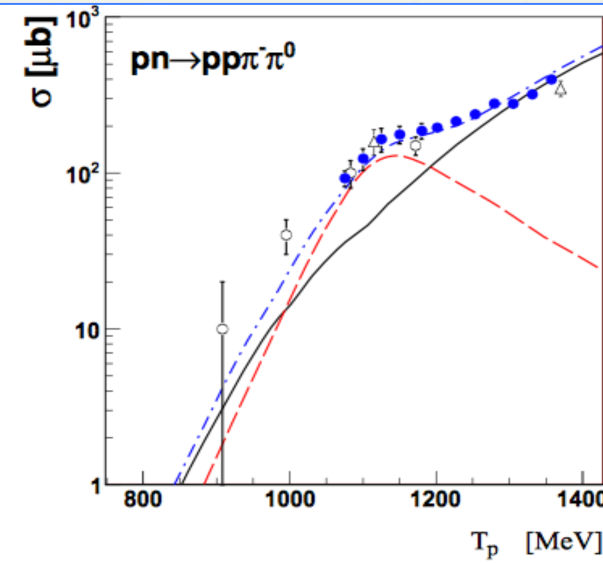
$\Gamma \approx 70$ MeV

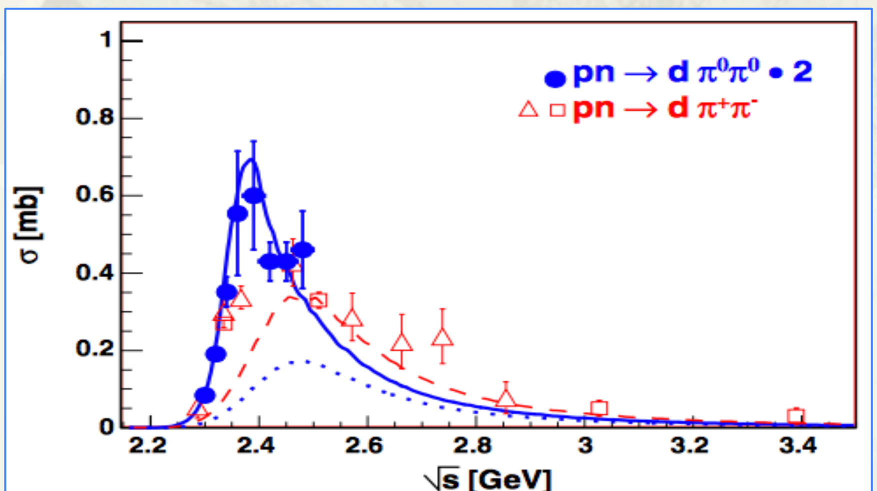
$d^*(2380)$

# Signals in other reactions @ COSY




Measured also in fusion reactions to helium isotopes:

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

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

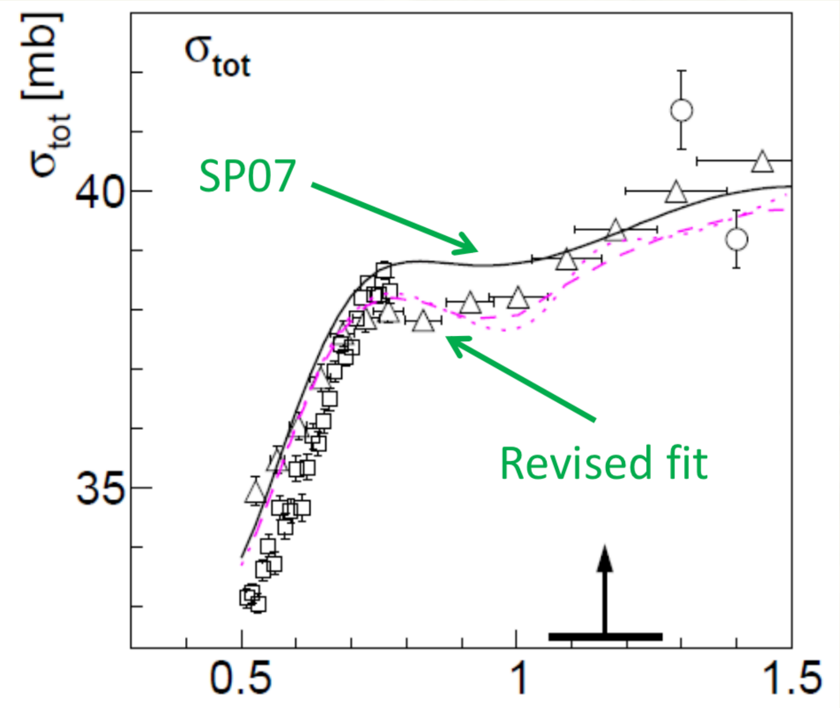
$d + d \rightarrow {}^4He + \pi^0 + \pi^0$

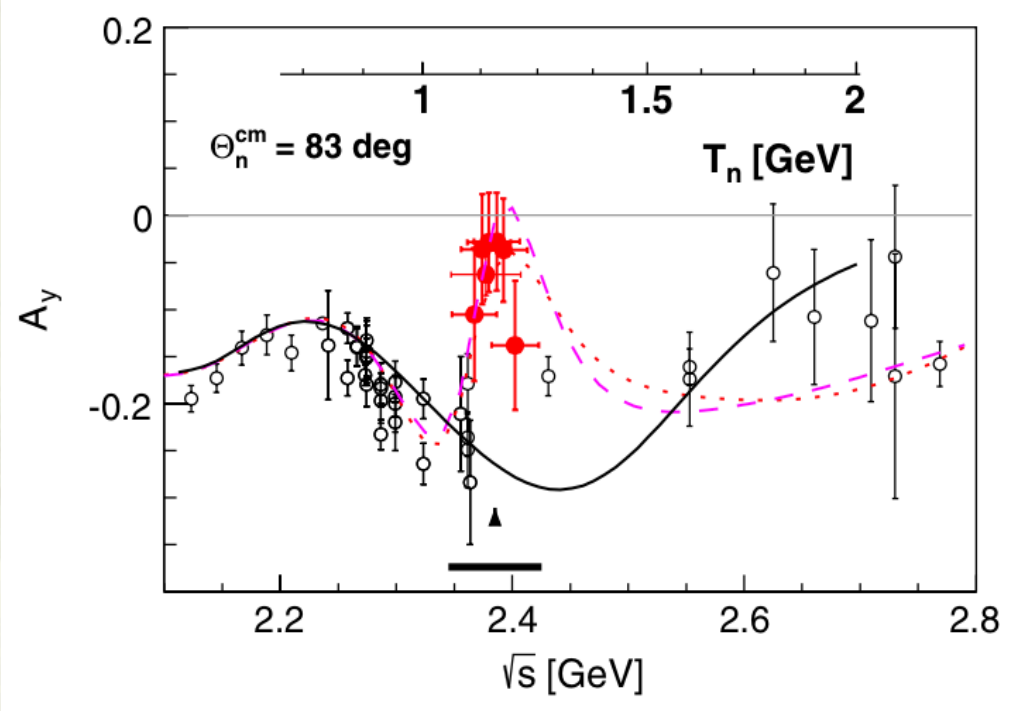
$d + d \rightarrow {}^4He + \pi^+ + \pi^-$

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

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

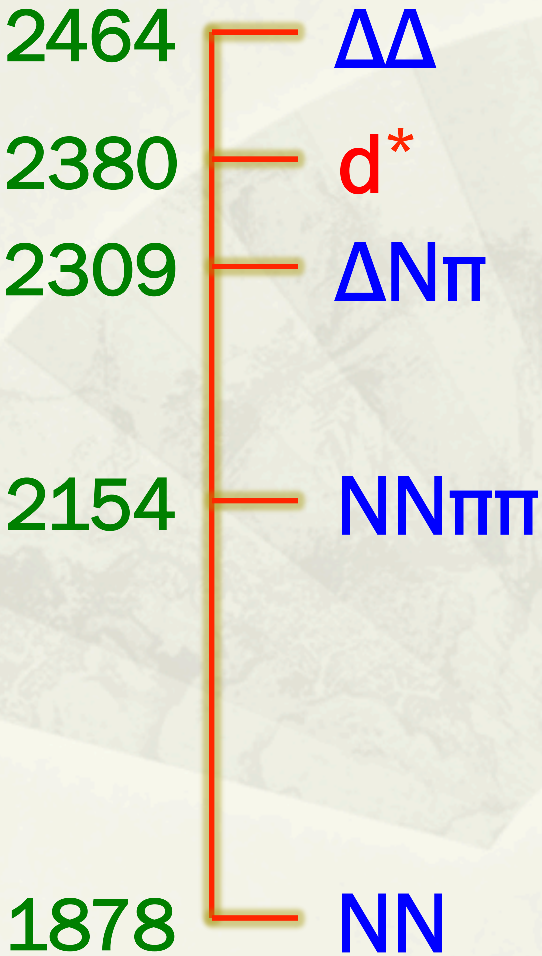
M = (2380±10) – *i* (40±5)




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

# Unusual narrow width of d*




$M_{d*} \approx 2380$ MeV

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

$> M_{\Delta N\pi}$

$> M_{NN\pi\pi}$

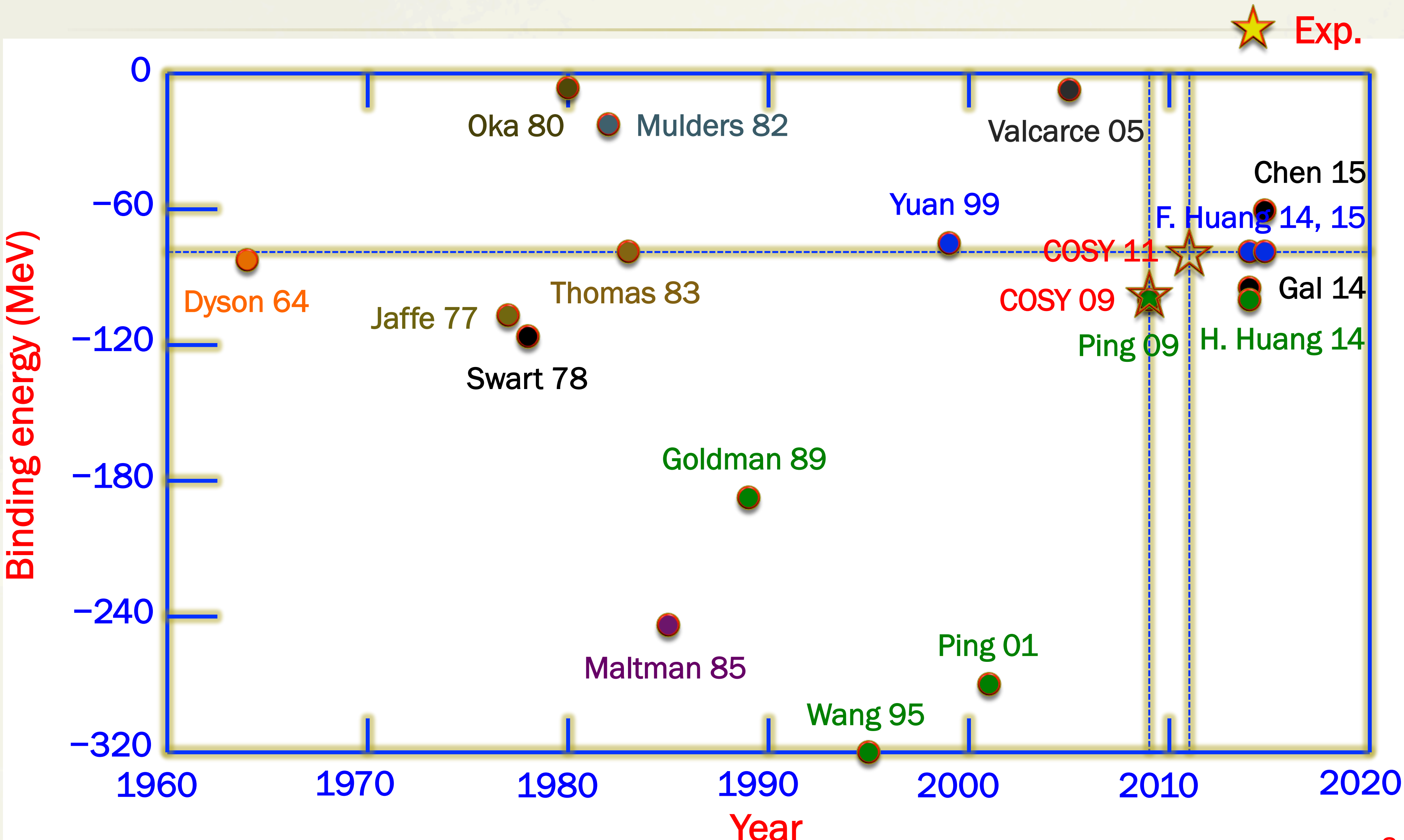
$> M_{NN}$

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

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

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

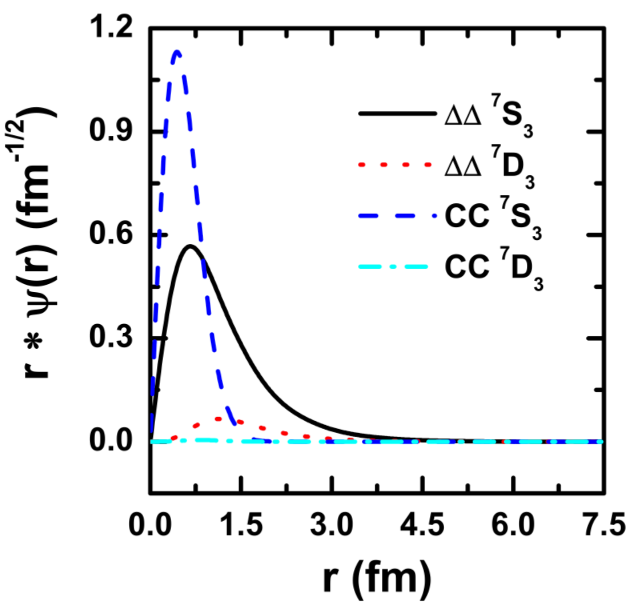
# Theoretical ΔΔ binding energies



# Chiral SU(3) QM study, revisited

## Structures & wave functions

- F. Huang, Z.Y. Zhang, P.N. Shen, W.L. Wang, Chin. Phys. C 39 (2015) 071001
- F. Huang, P.N. Shen, Y.B. Dong, Z.Y. Zhang, Sci. China-Phys. Mech. Astron. 59 (2016) 622002




## Decay widths & charge distributions

- Y.B. Dong, P.N. Shen, F. Huang, Z.Y. Zhang, Phys. Rev. C 91 (2015) 064002
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Phys. Rev. C 94 (2015) 014003
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Phys. Lett. B 769 (2017) 223
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Phys. Rev. D 96 (2017) 094001

# Other explanations in literature

- A. Gal & H. Garcilazo, NPA928(2014)73
  - Dynamically generated ΔNπ 3-body resonance
  - Binding energy: 101 MeV
  - Width: 66 MeV

$$B_{exp} \approx 84 \text{ MeV}$$
$$\Gamma_{exp} \approx 70 \text{ MeV}$$

- H.X. Huang, J.L. Ping, & F. Wang, PRC89(2014)034001
  - ΔΔ bound state
  - Binding energy: 71 MeV (ChQM), 107 MeV (QDCSM)
  - Width: 150 MeV (ChQM), 110 MeV (QDCSM)
- H.X. Chen, E.L. Cui, & W. Chen et al., PRC91(2015)025204
  - QCD sum rule analysis
  - Mass: 2.4±0.2 GeV

# The Chiral SU(3) quark model

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

- 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

# Hamiltonian of Chiral QM

Total Hamiltonian for 6q systems:

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

Ch. SU(3) QM:

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

Ext. Ch. SU(3) QM:

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

Note: OGE almost completely reduced by including VMEs.

# 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 $m_\sigma$
- Coupling constant for OGE: $g_u \propto m_\Delta - m_N$
- Confinement strength & zero point energy:

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

# RGM study of ΔΔ-CC

RGM wave functions for ΔΔ-CC system:

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

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

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

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

| | $\Delta\Delta$ $(L = 0, 2)$ | | |
|---|---|---|---|
| | 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 ≈ 47 – 84 MeV

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

- d*: a deeply bound & compact ΔΔ-CC state
- Coupling to CC plays a significant role
- Predicted binding energy close to experimental value

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

# Distinctive features of ΔΔ: why

## Quark-exchange effect:

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

- For 6 identical quarks: $\mathcal{A} = 1 - 9P_{36}$
- Quark-exchange effect: $\left\langle \mathcal{A}^{sfc} \right\rangle \in [0,\ 2]$
- $(\Delta\Delta)_{S=3,I=0}$: $\left\langle \Delta\Delta \middle| \mathcal{A}^{sfc} \middle| \Delta\Delta \right\rangle_{S=3,\,I=0} = 2$ 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: $\left\langle NN \middle| \mathcal{A}^{sfc} \middle| NN \right\rangle_{S=1,\,I=0} = 10/9 \sim 1$

OGE: repulsive + VMEs: repulsive

# Channel wave functions

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

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

$$= \left\langle \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5) \middle| (1-9P_{36})\left[\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5)\, \eta_{\Delta\Delta}(\vec{r})\right] \right\rangle$$

$$-9\left\langle \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5) \middle| P_{36}\left[\hat{\phi}_{C}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5)\, \eta_{CC}(\vec{r})\right] \right\rangle$$

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

$$= \left\langle \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5) \middle| (1-9P_{36})\left[\hat{\phi}_{C}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5)\, \eta_{CC}(\vec{r})\right] \right\rangle$$

$$-9\left\langle \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{C}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5) \middle| P_{36}\left[\hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_1,\vec{\xi}_2)\, \hat{\phi}_{\Delta}^{\text{int}}(\vec{\xi}_4,\vec{\xi}_5)\, \eta_{\Delta\Delta}(\vec{r})\right] \right\rangle$$

# Wave function of d*

Reorganize the wave function of d*:

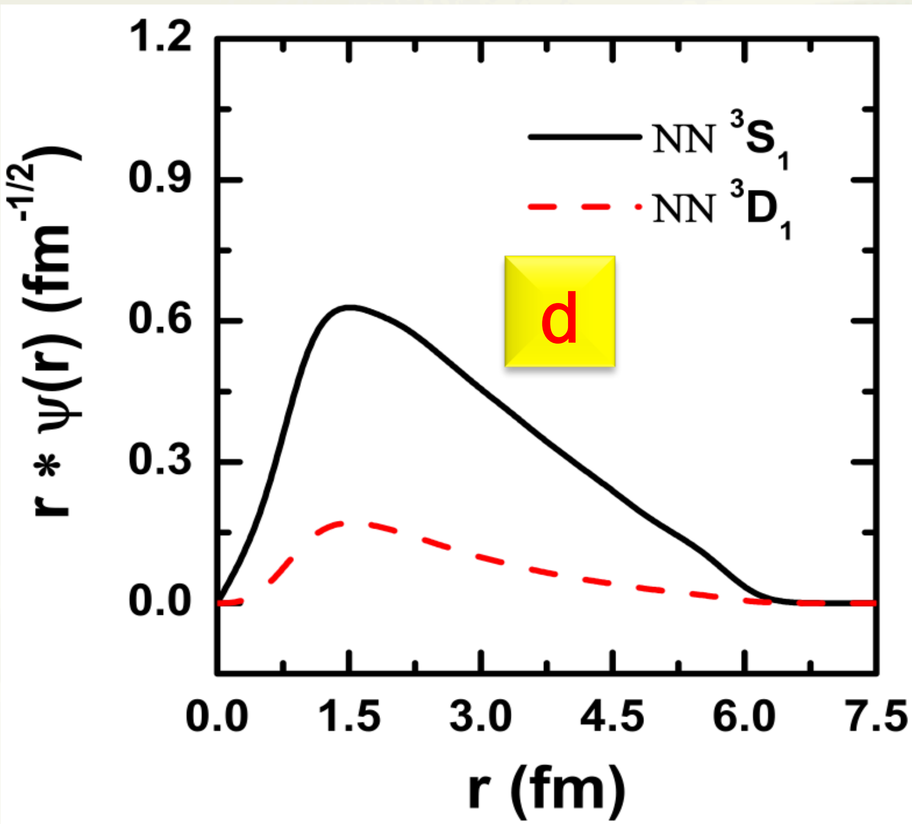
$$\psi_{d^*} = |\Delta\Delta\rangle \chi_{\Delta\Delta}(\vec{r}) + |CC\rangle \chi_{CC}(\vec{r})$$
$$= \sum_{L=0,2} \left[ |\Delta\Delta\rangle \frac{\chi^{L}_{\Delta\Delta}(r)}{r} + |CC\rangle \frac{\chi^{L}_{CC}(r)}{r} \right] Y_{L0}(\hat{r})$$

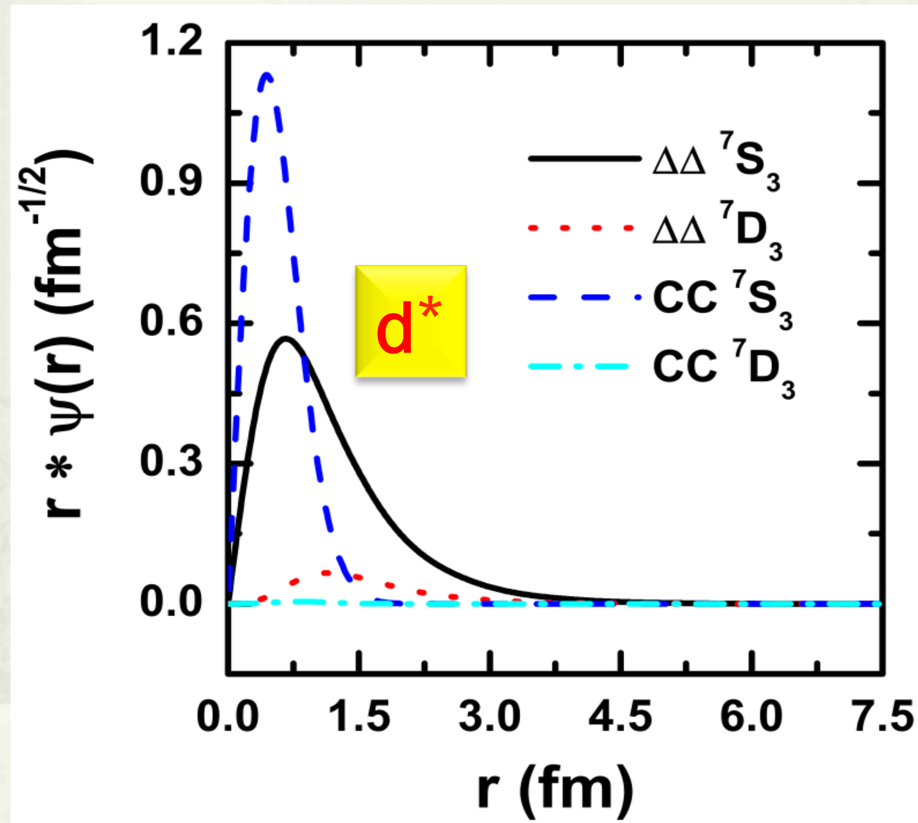
ΔΔ & CC parts are now orthogonal to each other:

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

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

# Relative wave function




Unlike deuteron, d* is rather narrowly distributed!

# CC component

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

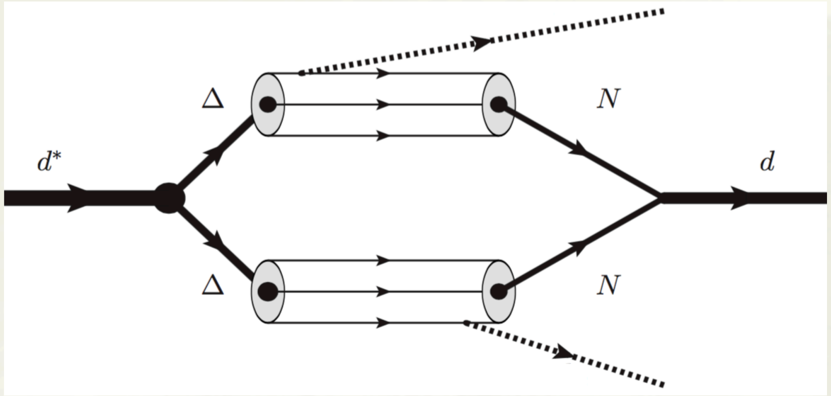
| | $\Delta\Delta - CC\ (L=0,2)$ | | |
|---|---|---|---|
| | SU(3) | Ext. SU(3) (f/g=0) | Ext. SU(3) (f/g=2/3) |
| B (MeV) | 47.27 | 83.95 | 70.25 |
| RMS (fm) | 0.88 | 0.76 | 0.78 |
| $(\Delta\Delta)_{L=0}$ (%) | 33.11 | 31.22 | 32.51 |
| $(\Delta\Delta)_{L=2}$ (%) | 0.62 | 0.45 | 0.51 |
| $(CC)_{L=0}$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

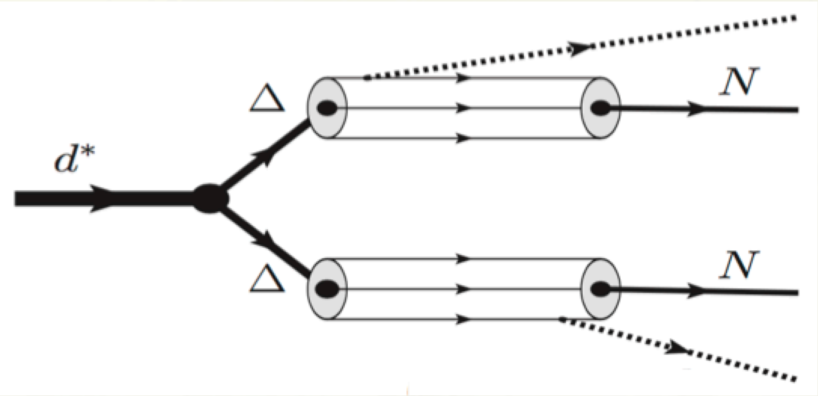
- A pure hexaquark state of ΔΔ system has 4/5 CC fraction

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

- d* is a hexaquark-dominated exotic state!

# 2π-decay




Given the qqπ vertex & wave functions of N, Δ, d* & d, the amplitudes & further decay widths can be calculated explicitly.

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

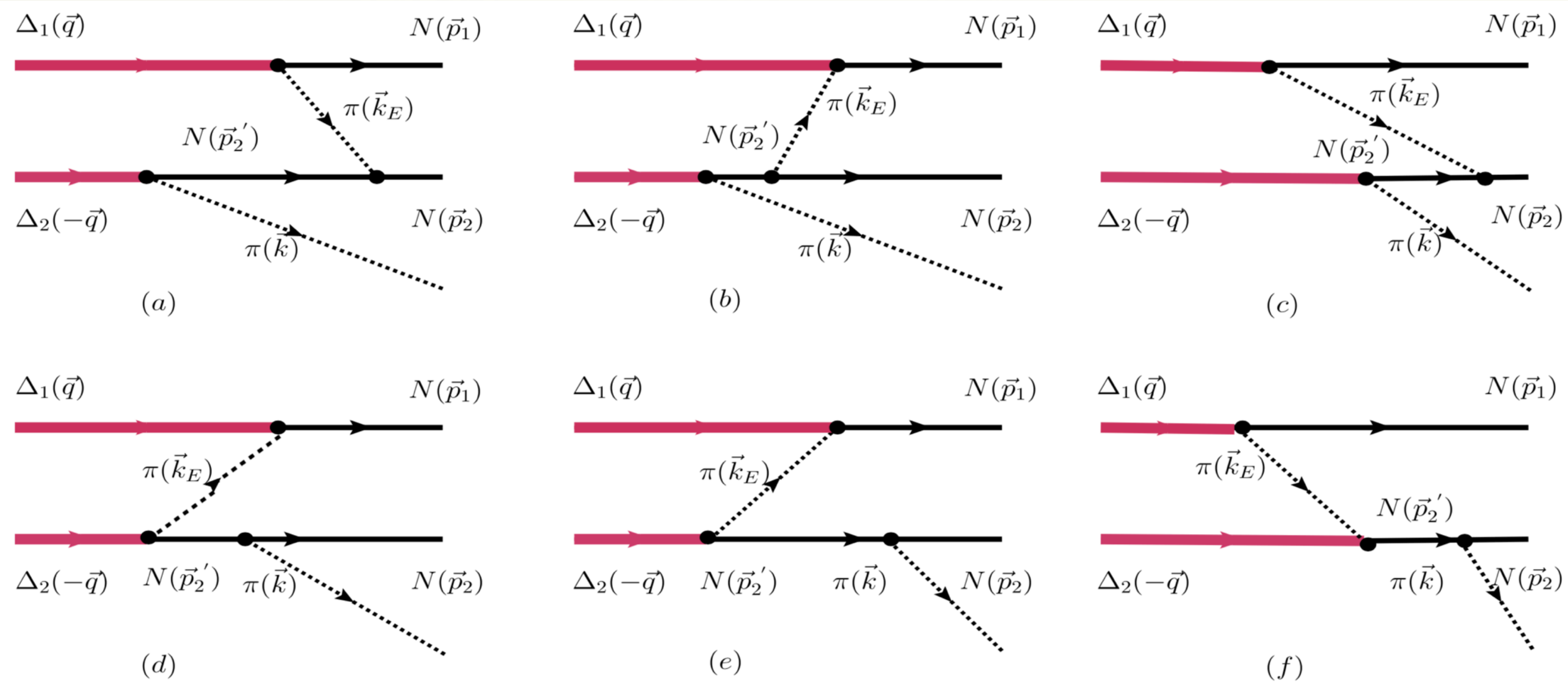
$$\Gamma_{d^* \to d\pi^0\pi^0} = \frac{1}{2!}\int d^3k_1 d^3k_2 d^3p_d (2\pi)\delta^3(\vec{k}_1 + \vec{k}_2 + \vec{p}_d)\delta(\omega_{k_1} + \omega_{k_2} + E_{p_d} - M_{d^*}) \mid \overline{\mathcal{M}_{if}^{\pi^0\pi^0}} \mid^2$$

$$\Gamma_{d^* \to pn\pi^0\pi^0} = \frac{1}{2!2!}\int d^3k_1 d^3k_2 d^3p_1 (2\pi)\delta(\Delta E) \mid \overline{\mathcal{M}(k_1, k_2; p_1)} \mid^2,$$

# Widths for 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 |

# Single π decay




$$\mathcal{M}^{(a)}_{d^*\to NN\pi} = \int d^3q \frac{\Psi_{d^*}(q)}{2\omega_{k_E}\sqrt{2\omega_k}(2\pi)^6}\delta^3\left(p_{N_2'} + p_{N_1'} + k - p_{\Delta_1} - p_{\Delta_2}\right) \times \tilde{\mathcal{M}}_{\pi(k_E)N(p_2')\to N(p_2)}\mathcal{D}_{af}\tilde{\mathcal{M}}_{\Delta_1\to\pi(k_E)N(p_1)}\mathcal{D}_{ai}\tilde{\mathcal{M}}_{\Delta_2\to\pi(k)N(p_2')}$$

$$\mathcal{D}_{af} = \frac{1}{M_{d^*} - \omega(\vec{k}) - \omega(\vec{k}_E) - E_N(\vec{p}_1) - E_N(\vec{p}_2')}$$

$$\mathcal{D}_{ai} = \frac{1}{M_{d^*} - \omega(\vec{k}) - E_{\Delta_1}(\vec{q}) - E_N(\vec{p}_2')}.$$

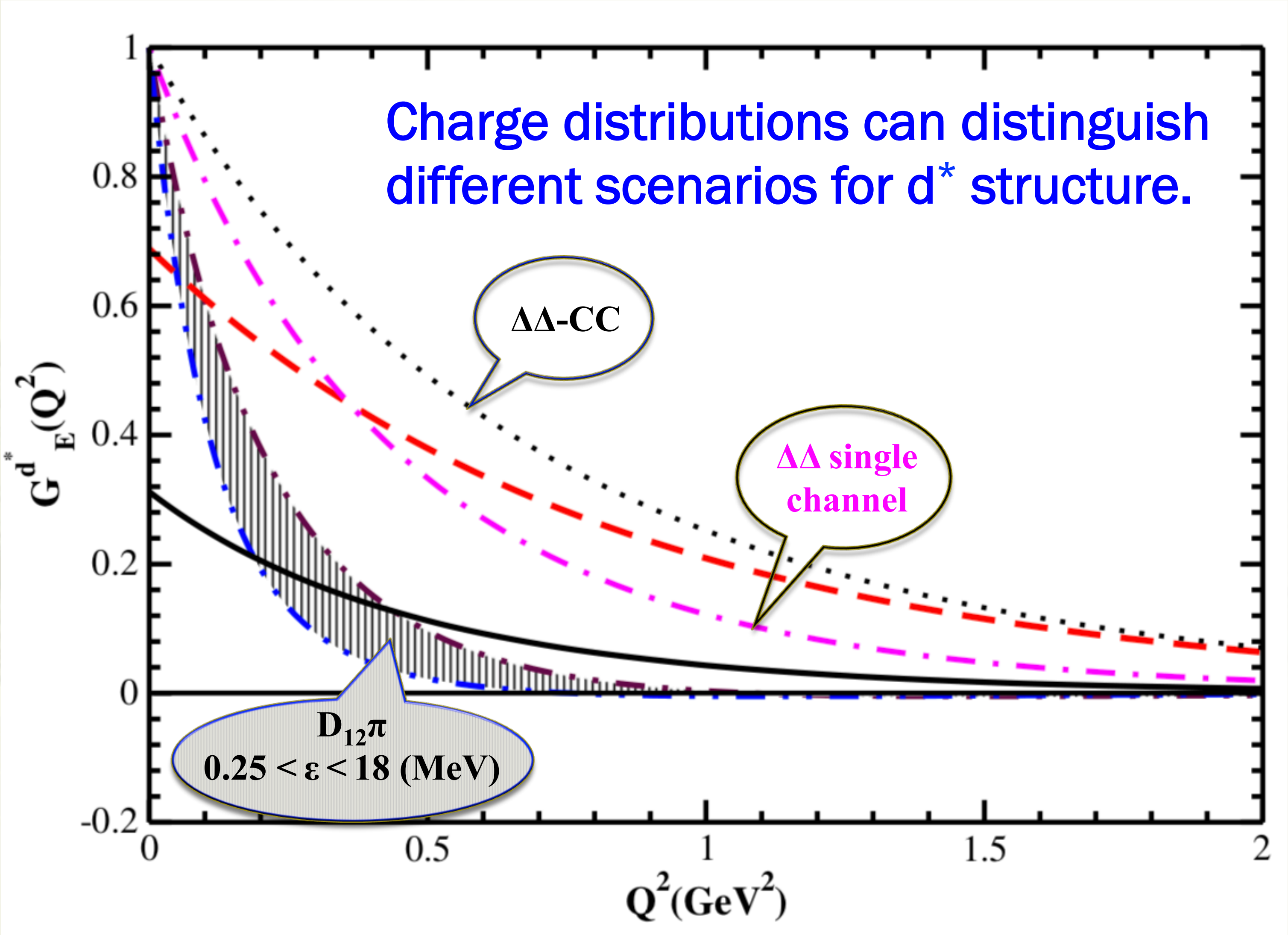
# Results for single π decay

$$\Gamma_{d^* \to NN\pi} \approx 0.67\ \text{MeV} \qquad \frac{\Gamma_{d^* \to NN\pi}}{\Gamma} \approx 0.9\%$$

The WASA-at-COSY Collaboration / Physics Letters B 774 (2017) 599–607

Exclusive measurements of the quasi-free $pn \to pp\pi^-$ and $pp \to pp\pi^0$ reactions have been performed by means of $pd$ collisions at $T_p = 1.2$ GeV using the WASA detector setup at COSY. Total and differential cross sections have been obtained covering the energy region $T_p = 0.95$–$1.3$ GeV ($\sqrt{s} = 2.3$–$2.46$ GeV), which includes the regions of $\Delta(1232)$, $N^*(1440)$ and $d^*(2380)$ resonance excitations. From these measurements the isoscalar single-pion production has been extracted, for which data existed so far only below $T_p = 1$ GeV. We observe a substantial increase of this cross section around 1 GeV, which can be related to the Roper resonance $N^*(1440)$, the strength of which shows up isolated from the $\Delta$ resonance in the isoscalar $(N\pi)_{I=0}$ invariant-mass spectrum. No evidence for a decay of the dibaryon resonance $d^*(2380)$ into the isoscalar $(NN\pi)_{I=0}$ channel is found. An upper limit of 180 μb (90% C.L.) corresponding to a branching ratio of 9% has been deduced.

# d* charge distribution results



# 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 → it is a hexaquark-dominated exotic state
- Our calculated binding energy & decay widths consistent with the data
- Charge distributions can be used to test different scenarios for the structure of $d^*(2380)$
- More experiments & theoretical works needed

# THANK YOU FOR YOUR PATIENCE!

# 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 $B=-(E_{\mathrm{deltaron}}-2M_{\Delta})$, $\bar{R}=\sqrt{\langle r^2\rangle}$.

| | | $\Delta\Delta(L=0)$ | $\Delta\Delta\binom{L=0}{+2}$ | | $\Delta\Delta$ $CC$ $(L=0)$ | | $\Delta\Delta$ $CC$ $\binom{L=0}{+2}$ |
|---|---|---|---|---|---|---|---|
| | $B$ (MeV) | 29.8 | 29.9 | | 41.0 | | 42.0 |
| OGE | $\bar{R}$ (fm) | 0.92 | 0.92 | | 0.87 | | 0.87 |
| | $B$ (MeV) | 50.2 | 62.6 | 30-60 | 68.6 | 40-80 | 79.7 |
| OGE+$\pi$,$\sigma$ | $\bar{R}$ (fm) | 0.87 | 0.86 | | 0.84 | | 0.83 |
| | $B$ (MeV) | 18.4 | 22.5 | | 31.7 | | 37.3 |
| OGE+SU(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

# Argument of Bashkanov et al.

M. Bashkanov, S. J. Brodsky, and H. Clement, Phys. Lett. B 727, 438 (2013).

- $Br(d^* \to \Delta\Delta)/Br(d^* \to pn) = 9:1$, but a deltaron with binding energy 90 MeV would have width ~160 MeV
- $d^*$ must be of an unconventional origin, possibly indicating a genuine six-quark nature
- Two possible six-quark structures for $I(J^P)=0(3^+)$:

$$\left|\psi^{[6]_{\text{orb}}[33]_{\text{IS}}}_{(0s)^6}\right\rangle = \sqrt{\frac{1}{5}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|CC\rangle$$

$$\left|\psi^{[42]_{\text{orb}}[33]_{\text{IS}}}_{(0s)^4(0p)^2}\right\rangle = \sqrt{\frac{4}{5}}|\Delta\Delta\rangle - \sqrt{\frac{1}{5}}|CC\rangle$$

- It is nature to assign $d^*$ to the former one --- six-quark predominantly "hidden color state"

# Resonating group method (RGM)

- RGM: well-established method for studying interactions between two composite particles; center of mass motion treated correctly
- Six-quark wave function in C.M. frame:

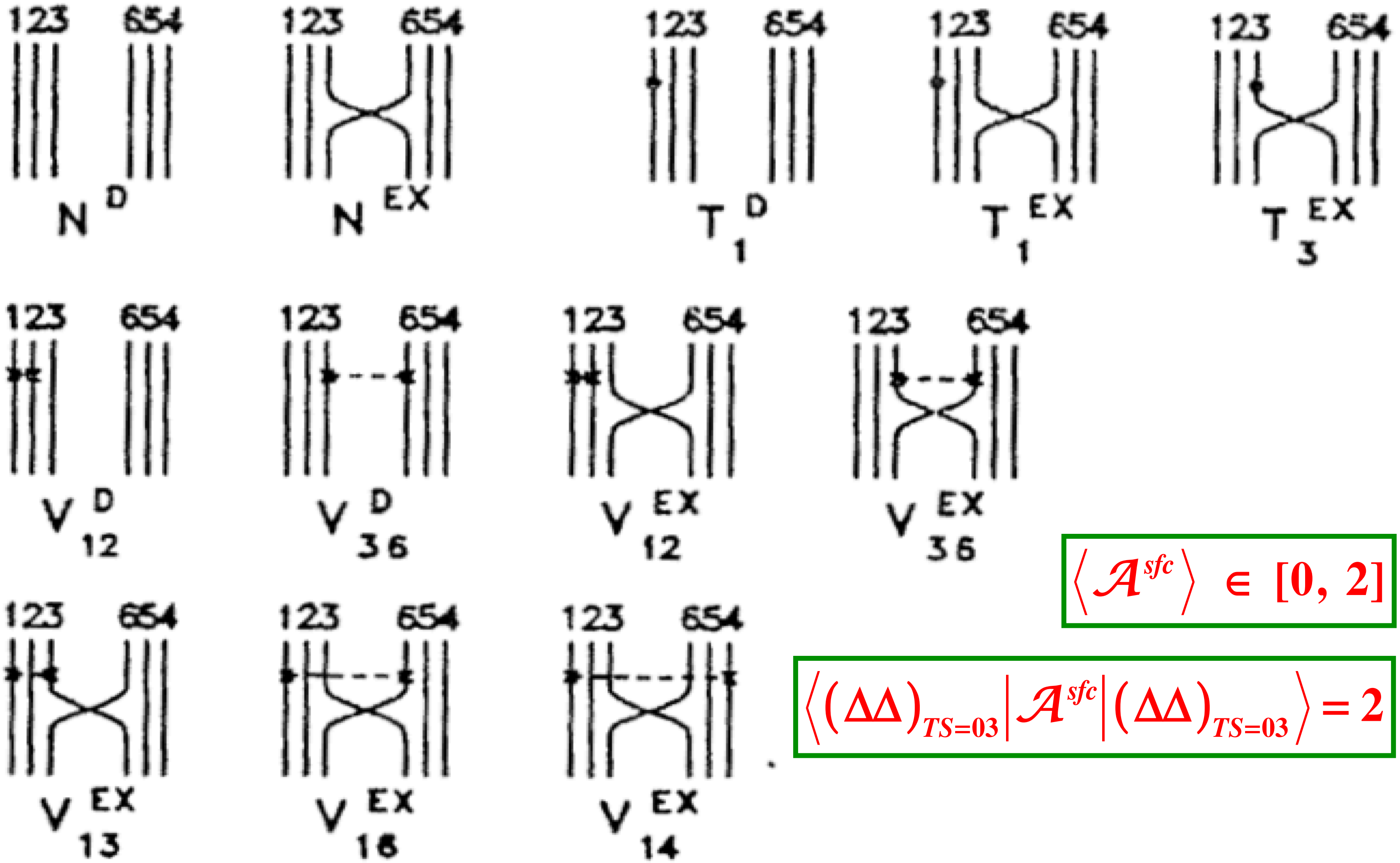
$$\Psi_{6q} = \mathcal{A}\left[\hat{\Phi}_A^{\text{int}}\left(\vec{\xi}_1,\vec{\xi}_2\right)\hat{\Phi}_B^{\text{int}}\left(\vec{\xi}_3,\vec{\xi}_4\right)\chi\left(\vec{R}_{AB}\right)\right]_{STY}$$

$$\mathcal{A} \equiv \sum_{i\in A, j\in B}\left(1-P_{ij}^{OSFC}\right)$$

- Cluster wave functions in coordinate space: Gaussian
- Relative wave function determined by dynamics of the 6-quark system:

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

# Six-quark diagrams in RGM




$$\left\langle \mathcal{A}^{sfc} \right\rangle \in [0,\ 2]$$

$$\left\langle (\Delta\Delta)_{TS=03} \middle| \mathcal{A}^{sfc} \middle| (\Delta\Delta)_{TS=03} \right\rangle = 2$$

# Parameter values

All parameters fixed already in the study of NN scattering.
No additional parameters introduced for ΔΔ system.

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 |
| $m_\sigma$ (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 |

# Masses of baryons & deuteron

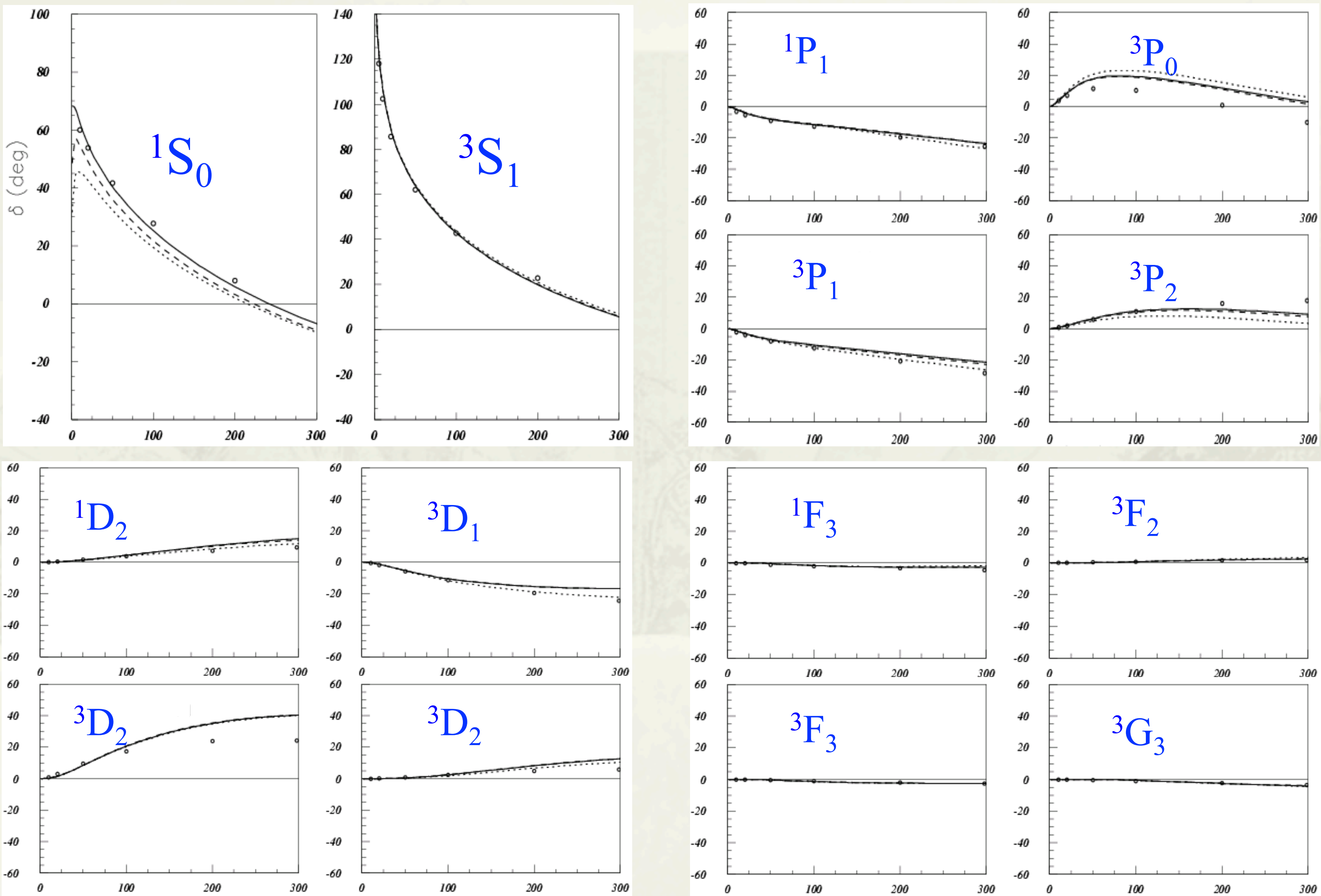
## The masses of baryons

| | $N$ | $\Sigma$ | $\Xi$ | $\Lambda$ | $\Delta$ | $\Sigma^*$ | $\Xi^*$ | $\Omega$ |
|---|---|---|---|---|---|---|---|---|
| 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 wave functions

RGM wave functions:

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

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

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

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

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

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

Not suitable for clarification of ΔΔ, CC components in d*

# d* charge distribution calculation

$$\langle N(p')|J_N^\mu|N(p)\rangle = \frac{1}{1+\eta}\bar{u}_N(p',s')\left[(1+\eta)G_M\gamma^\mu - \frac{G_M - G_E}{2M_N}P^\mu\right]u_N(p,s).$$

$$G_E^{d^*}(Q^2) = \frac{1}{7}\sum_{m_{d^*}=-3}^{3}\langle p', m_{d^*}|J^0|p, m_{d^*}\rangle$$

$$J^0 = \sum_{i=1}^{6} e_i\bar{q}_i\gamma^0 q_i = \sum_{i=1}^{6} j_i^0.$$