An overview of recent progress on $d^*(2380)$

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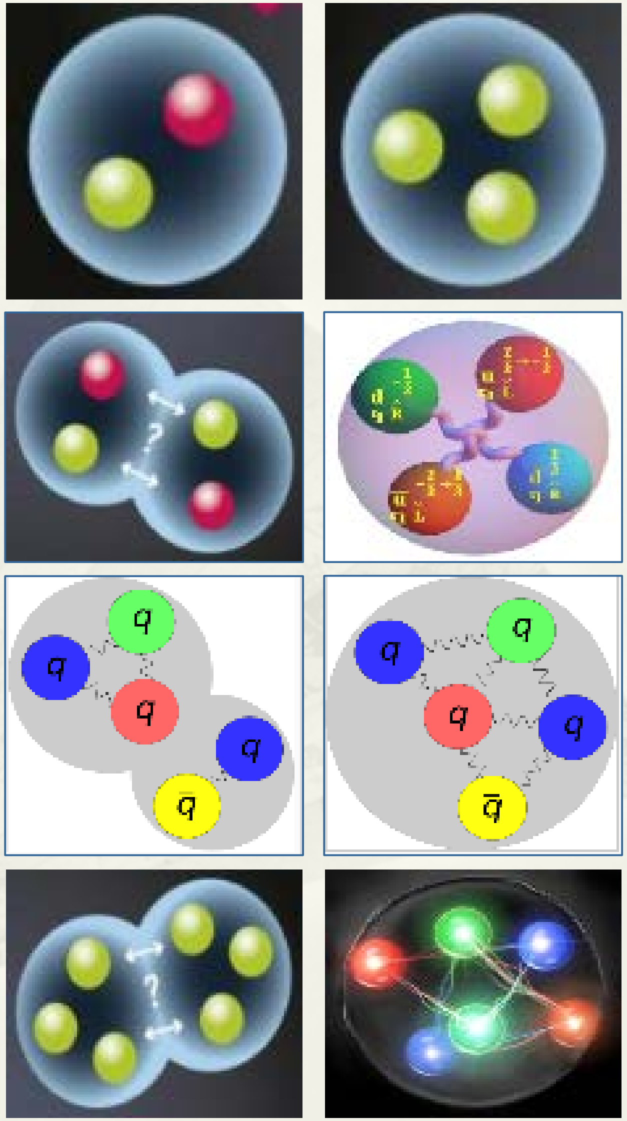
Outline

- Motivation
- Experimental status
- Theoretical predictions
- Theoretical explanations
- Summary

Motivation

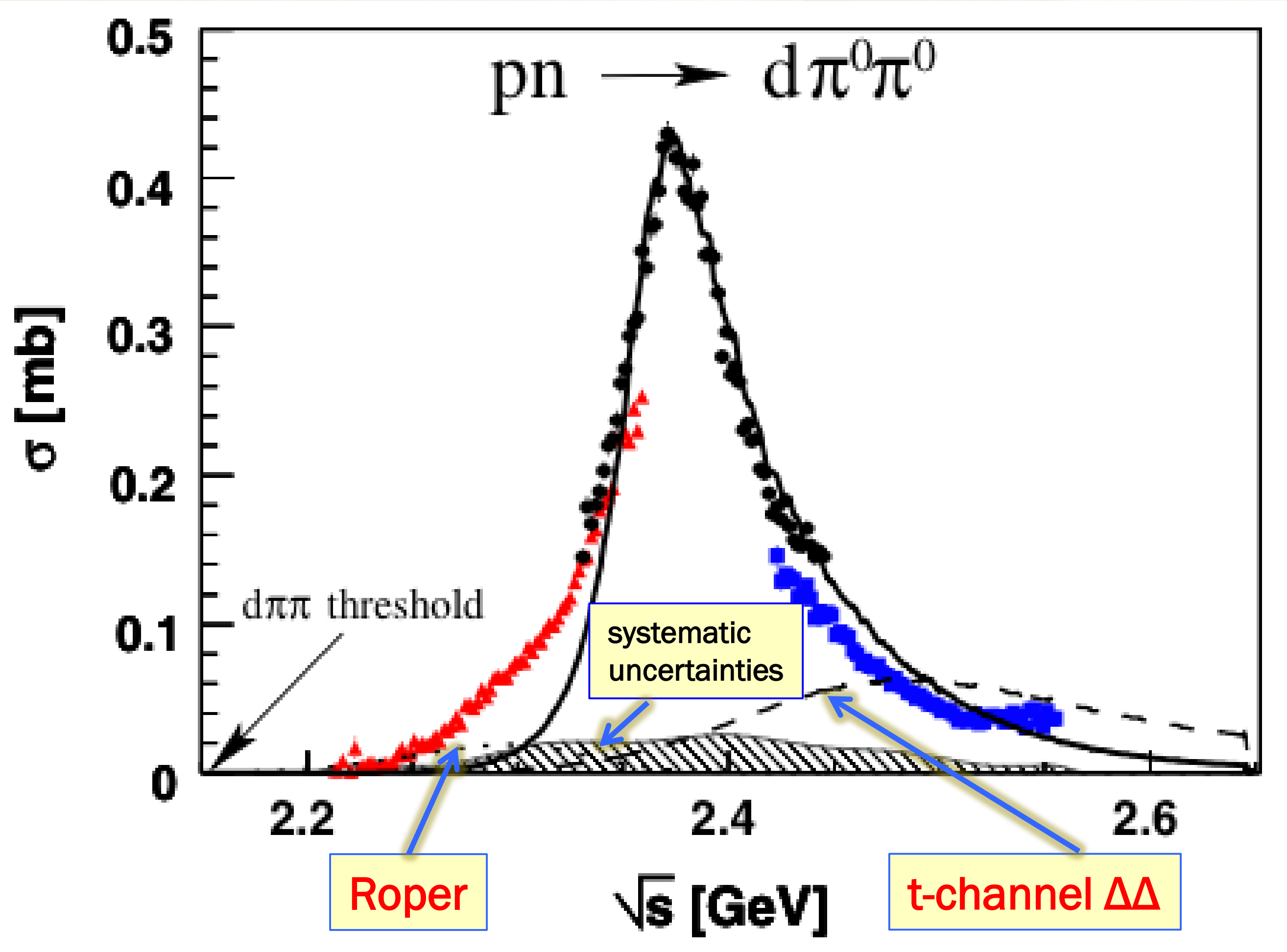
- Quarks are confined into hadrons instead of being “bare” & “alone”
- Most hadron states are categorized into mesons ($q\bar{q}$) and baryons (qqq)
- QCD does not exclude Exotics
- Many 4-, 5-quark configurations have been claimed in heavy flavor physics
- In 6-quark systems, deuteron is the only one confirmed by experiments
- Any other BB molecules? Hexaquark states? Other 6-quark exotic states?

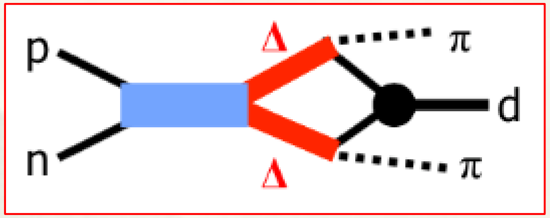


Experimental status

Experiments @ COSY

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





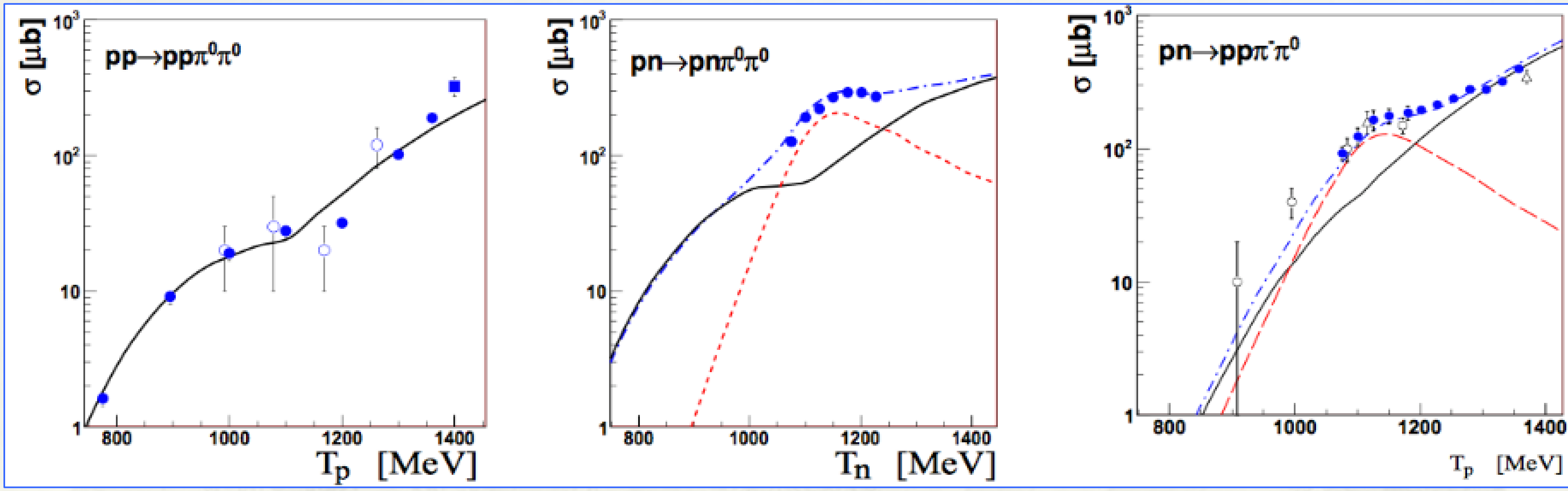
$I(J^p) = 0(3^+)$

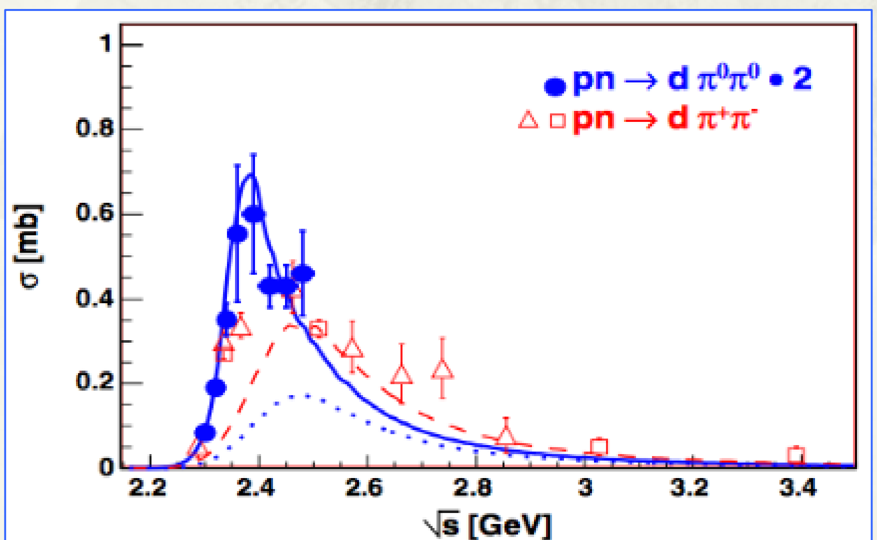
$M \approx 2380$ MeV

$\Gamma \approx 70$ MeV

$d^*(2380)$

Signals in other reactions @ COSY





Also been Measured in fusion reactions to helium isotopes:

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

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

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

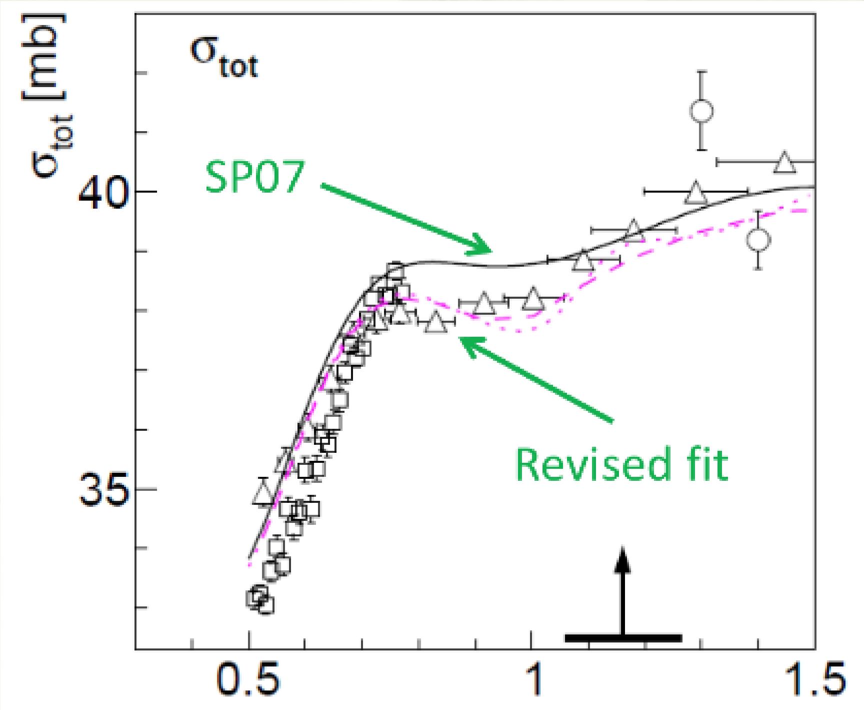
$d + d \longrightarrow {}^4He + \pi^+ + \pi^-$

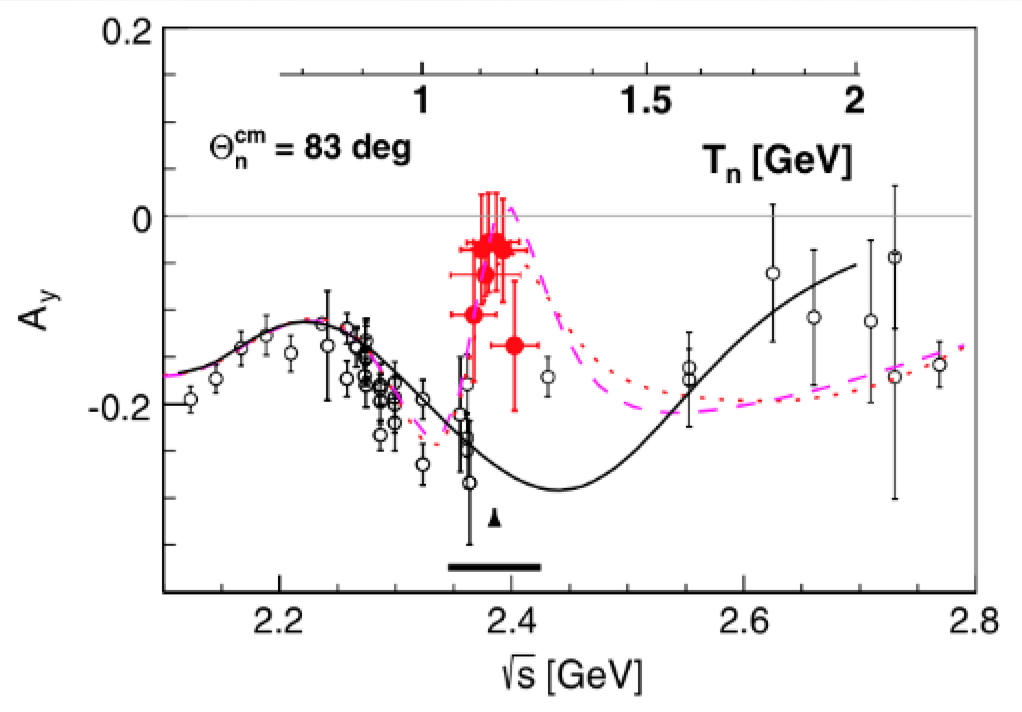
Evidence from $\vec{n}p$ scattering

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

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

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

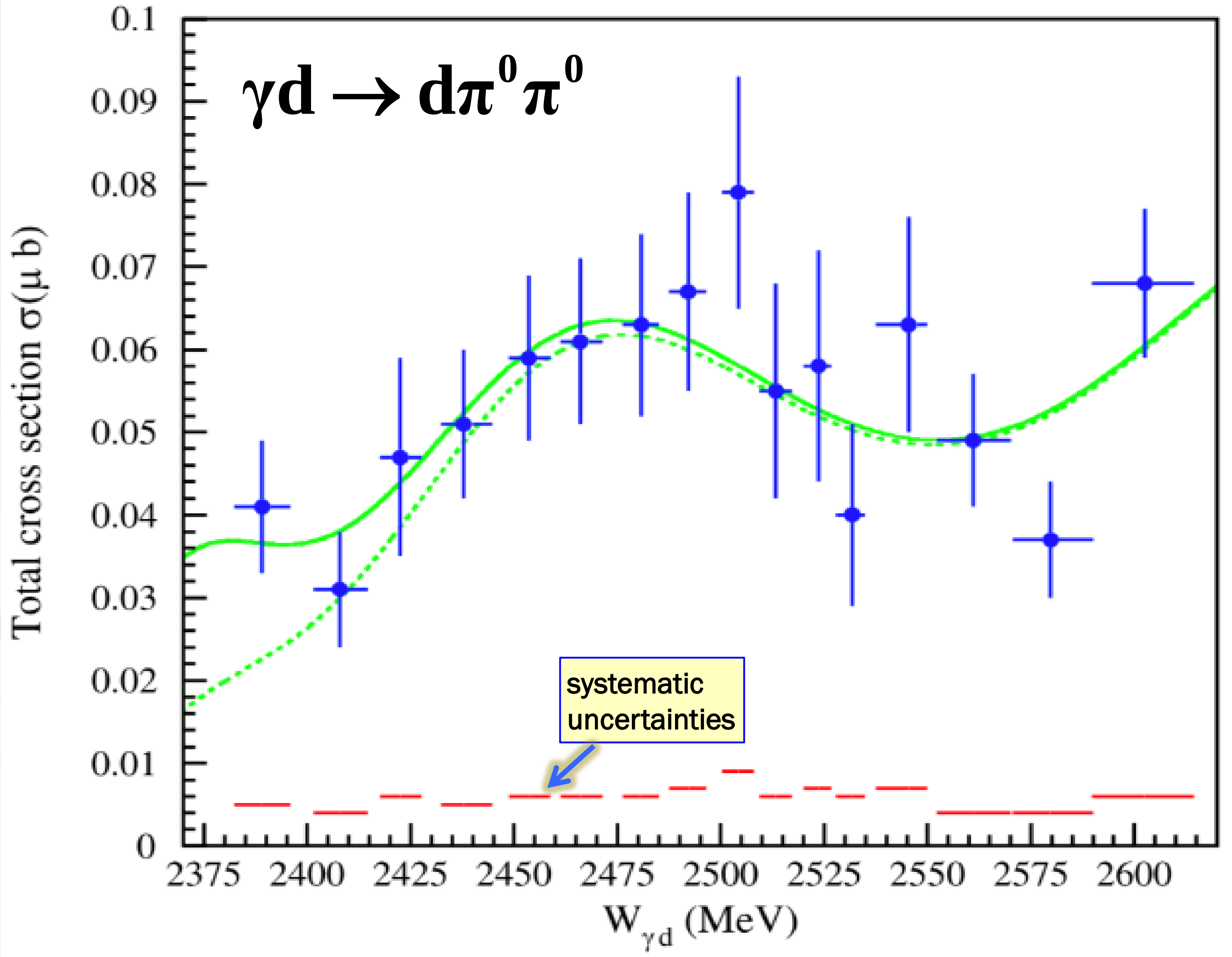




Colored lines: new fits with inclusion of new data (red symbols)

Experiments @ ELPH

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



--- W/o d*(2380)

Fix & Arenhovel, EPJA25(2005)115

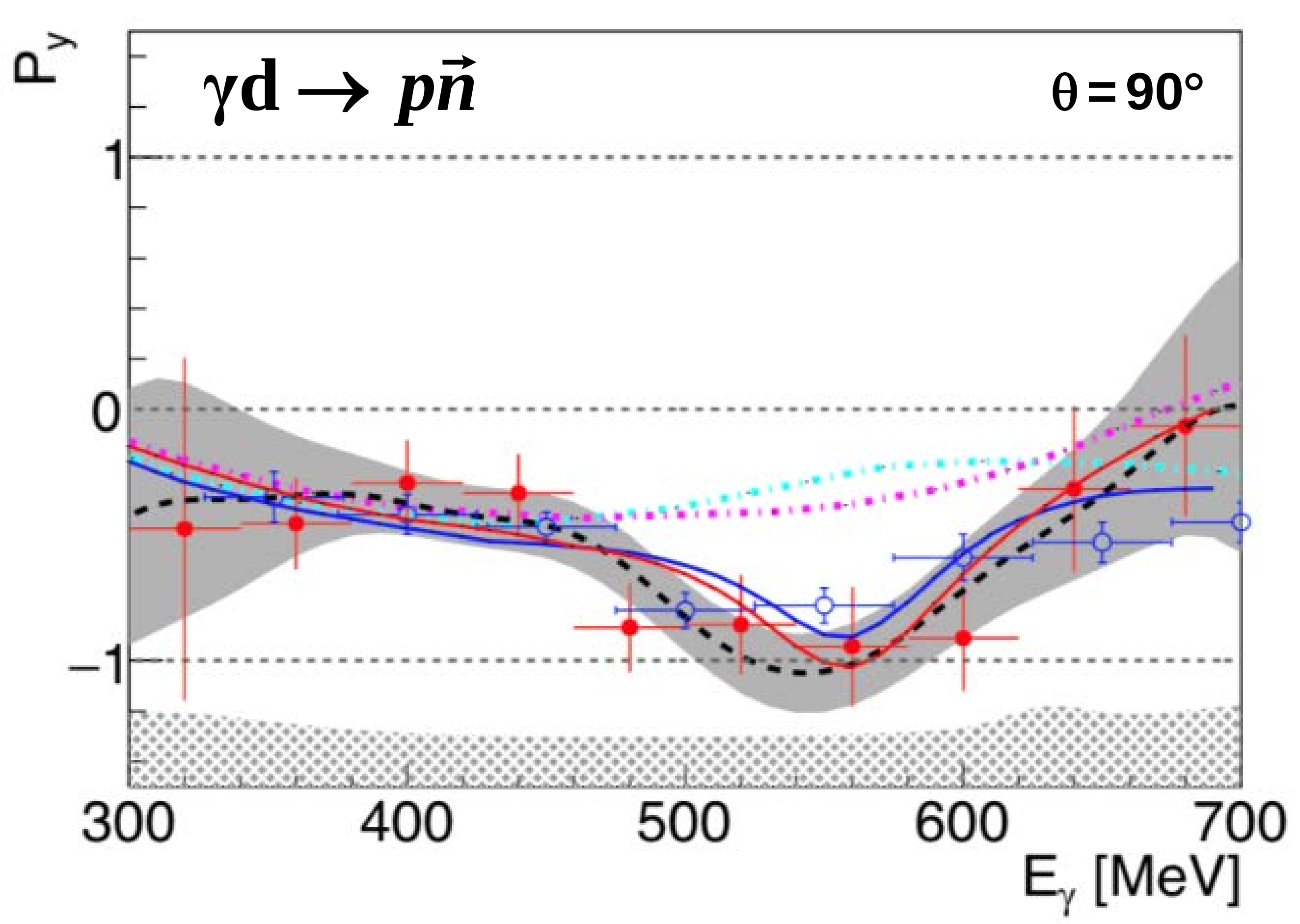
— With d*(2380)

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

A2-at-MAMI, arXiv:1911.08309



- o Old data on P_y^p (1979)
- ● New data on P_y^n

Grey band: unbinned analysis

-·-·- W/o d*(2380)

—— With d*(2380)

Theoretical Predications

There are tens of theoretical predications of ΔΔ bound states in literature.

Due to the time limits, I only show works that exactly predicated the mass of $d^*(2380)$.

Prediction by Dyson in 1964

Y=2 states in SU(6) theory, F. J. Dyson & N. H. Xuong, PRL 13 (1964) 815

$[3]\times[3]=[6]\oplus[51]\oplus[42]\oplus[33]$

SU(6) classification of BB: $\underline{56}\otimes\underline{56}=\underline{462}\oplus\underline{1050}\oplus\underline{1134}\oplus\underline{490}$

$\mathcal{S}$ $\mathcal{A}$ $\mathcal{S}$ $\mathcal{A}$

$(NN)_{IS=11}$

For Y=2, SU(6) → SU(4): $\underline{1050}\to\underline{140}=(7,5)\oplus(5,3+5+7)\oplus(3,1+3+5)\oplus(1,3)$

$\underline{490}\to\underline{50}=(7,1)\oplus(5,3)\oplus(3,1+5)\oplus(1,3+7)$

Mass formula for SU(4) 50: $M=A+B[T(T+1)+J(J+1)-2]$

Table I. $Y=2$ states with zero strangeness predicted by the $\underline{490}$ multiplet.

Particle	T	J	SU(3) multiplet	Comment	Predicted mass	
D_{01}	0	1	$\underline{10}^*$	Deuteron	A	**1876**
D_{10}	1	0	$\underline{27}$	Deuteron singlet state	A	
D_{12}	1	2	$\underline{27}$	S-wave N-N^* resonance	$A+6B$	**2160**
D_{21}	2	1	$\underline{35}$	Charge-3 resonance	$A+6B$	
D_{03}	0	3	$\underline{10}^*$	S-wave N^*-N^* resonance	$A+10B$	**2346**
D_{30}	3	0	$\underline{28}$	Charge-4 resonance	$A+10B$	

$B=(2160-1876)/6\simeq 47$ $\Longrightarrow$ $A+10B=1876+470=2346$

Prediction by Thomas in 1983

Pionic corrections and multiquark bags,
P. J. Mulders & A. W. Thomas, J. Phys. G 9, 1159 (1983).

Table 2. Masses of the non-strange ($Y=2$) dibaryons in the original MIT bag-model calculation (Jaffe 1977, Aerts *et al* 1978) (A) and in the present calculation including pionic corrections (B).

				A		B	
I	S	Δ	Σ	$R(\mathrm{GeV}^{-1})$	$M(\mathrm{GeV})$	$R(\mathrm{GeV}^{-1})$	$M(\mathrm{GeV})$
0	1	$\frac{2}{3}$	−76	6.60	2.16	6.41	2.18
1	0	2	−76	6.68	2.23	6.45	2.24
1	2	4	−52	6.79	2.35	6.52	2.36
0	3	4	−36	6.79	2.35	6.52	2.38
2	1	$\frac{20}{3}$	−52	6.93	2.50	6.61	2.46
3	0	12	−36	7.19	2.79	6.78	2.69

Prediction by Yuan et al. in 1999

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

		$\Delta\Delta(L=0)$	$\Delta\Delta\binom{L=0}{+2}$	$\Delta\Delta$ CC $(L=0)$	$\Delta\Delta$ 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+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

30-60   40-80

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

Theoretical Explanations

I am sorry if I overlooked your work.

Unusual narrow width of d*

2464 — ΔΔ

2380 — d*

2309 — ΔNπ

2154 — NNππ

1878 — NN

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

$\Gamma_\Delta \approx 115$ MeV

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

$d^*(2380)$ as ΔΔ bound state?

$2\Gamma_\Delta \approx 230$ MeV $\Gamma_{d^*} \approx 70$ MeV $M_{d^*} - 2M_\Delta \approx 84$ MeV

Phase space effects:

$$\Gamma_\Delta = \gamma_{N\pi} \frac{R^2 q_{N\pi}^2}{1 + R^2 q_{N\pi}^2} q_{N\pi}$$

$$\gamma_{N\pi} = 0.76,\ R = 6.3\ (\mathrm{GeV}/c)^{-1}$$

$$\Gamma_{\Delta\Delta}:\ 230\ \mathrm{MeV} \to 168\ \mathrm{MeV}$$

Effects from dynamics:

$$\Gamma_{\Delta\Delta}:\ 168\ \mathrm{MeV} \to\ 110 \sim 120\ \mathrm{MeV}$$

Confirmed by:

H.X. Huang, J.L. Ping, F. Wang, PRC 89 (2014) 034001

Y.B. Dong, P.N. Shen, F. Huang, Z.Y. Zhang, PRC 91 (2015) 064002

ΔΔ bound state?

Dynamical calculation of the ΔΔ dibaryon candidates,
H. X. Huang, J. L. Ping, F. Wang, Phys. Rev. C 89, 034001 (2014).

TABLE III. ΔΔ or resonance mass M and decay width Γ, in MeV, in two quark models for the $IJ^P = 03^+$ state.

	QDCSM		ChQM		
	sc	4 cc	sc	4 cc	10 cc
M	2365	2357	2425	2413	2393
Γ_{NN}	–	14	–	14	14
Γ_{inel}	103	96	177	161	136
Γ	103	110	177	175	150

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

QCD sum rule for d*(2380)

QCD sum rule study of the d*(2380)
H. X. Chen, E. L. Cui, W. Chen, T. G. Steele, S. L. Zhu
PRC 91 (2015) 025204

We systematically construct $I\left(J^P\right)=0\left(3^+\right)$ six-quark local interpolating currents without derivative operators. We discuss the best choice of operator and select three Δ–Δ-like operators to perform QCD sum rule analyses to calculate the mass of the $d^*\left(2380\right)$. The mass extracted from this analysis is $M_{d^*}=2.4\pm0.2$ GeV, consistent with the $d^*\left(2380\right)$ mass observed by the WASA detector at COSY. We also obtain a sum rule lower mass bound $M_{d^*}>2.25$ GeV. We also consider the effect of mixing of singlet dibaryon fields with the same quantum numbers, and perform the QCD sum rule analysis of the mixed interpolating current and extract the mass of the $d^*\left(2380\right)$ and its lower mass bound. With optimized mixing parameters, we find that the mixed current does not change the numerical result significantly.

Single 6q cluster?

Investigations on the I(J^P)=0(3$^+$) hexaquark states
C. S. An and H. Chen, EPJA 52 (2016) 2

Here we investigate the energies of hidden color hexaquark states with quantum numbers $I(J^p) = 0(3^+)$ within the framework of the constituent quark model. The hyperfine interaction between quarks is taken to be the instanton-induced interaction, and mixing between different hexaquark configurations caused by hyperfine interaction between quarks is considered. Numerical results show that energies of several obtained hexaquark states are very close to the mass of the experimentally observed d^* resonance, it indicates that these states may be the dominant components of d^* baryon resonance, if d^* is a genuine hexaquark dominated baryon state.

M_{d*} & Γ_{d*}: 3 possible explanations

- $\Delta\Delta + \Delta N\pi$

  A. Gal & H. Garcilazo, PRL 111 (2013) 172301
  A. Gal & H. Garcilazo, NPA 928 (2014) 73
  A. Gal, Phys. Lett. B 769, 436 (2017)

- CC + $\Delta\Delta$

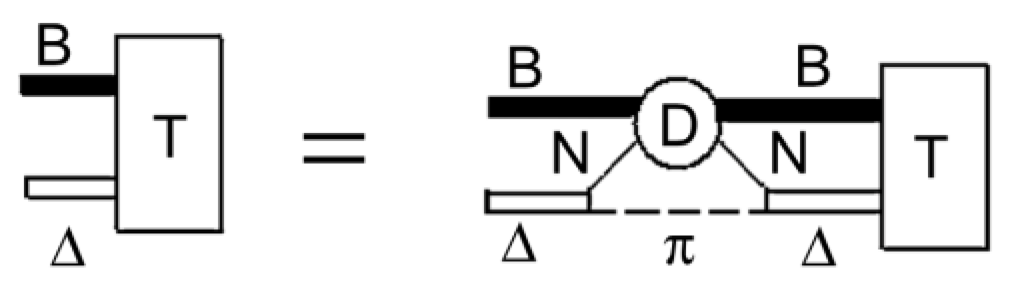
  F. Huang, Z.Y. Zhang, P.N. Shen, W.L. Wang, CPC 39 (2015) 071001
  Y.B. Dong, P.N. Shen, F. Huang, Z.Y. Zhang, PRC 91 (2015) 064002
  Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, PRC 94 (2015) 014003
  Q.F. Lv, F. H., Y.B. Dong, P.N. Shen, Z.Y. Zhang, PRD 96 (2017) 014036
  Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, PLB 769 (2017) 223
  Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, PRD 96 (2017) 094001

- 3-diquark

  P.P. Shi, F. Huang, W.L. Wang, EPJC 79 (2019) 314

ΔNπ model for d*(2380)

A. Gal & H. Garcilazo, PRL 111 (2013) 172301
A. Gal & H. Garcilazo, NPA 928 (2014) 73



Dynamically generated
ΔNπ 3-body resonance

$\mathcal{D}_{IJ}$ pole positions (in MeV) found by solving Eqs. (28) for the best-fit baryon–baryon interaction V_1 with Type I g_1 form factors (25) and $A_1^j = 1$, $j = 1, 2, 3$, using width-suppression fractions x_{IJ} from Table 6 and Types I, II g_3 πN form factors, with averaged results denoted W in the last line. Note: $\mathcal{D}_{23}$ is numerically unstable.

g_3	$\mathcal{D}_{03}$	$\mathcal{D}_{30}$	$\mathcal{D}^*_{12}$	$\mathcal{D}^*_{21}$	$\mathcal{D}_{23}$	$\mathcal{D}_{32}$
I	2383 − i41	2411 − i41	2431 − i76	2449 − i94	2431 − i72	2444 − i89
II	2343 − i24	2370 − i22	2428 − i67	2436 − i72	2429 − i72	2439 − i66
W	2363 − i33	2391 − i32	2430 − i72	2443 − i83	2430 − i72	2442 − i78

binding energy 101, width 66

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

Partial widths in Gal's ΔNπ model

The d*(2380) dibaryon resonance width and decay branching ratios, A. Gal, Phys. Lett. B 769, 436 (2017).

ΔNπ → ΔΔ + ΔNπ : **d* is a mixture of ΔΔ & ΔNπ**

final state	ΔΔ ($\alpha = 1$)		$\pi\mathcal{D}_{12}$ ($\alpha = 0$)		mixed ($\alpha = \frac{5}{7}$)		exp. [14]
	$\Gamma_f^{d^*}$	BR	$\Gamma_f^{d^*}$	BR	$\Gamma_f^{d^*}$	BR	BR
$d\pi^0\pi^0$	9.3	12.4	7.6	10.1	8.4	11.2	14(1)
$d\pi^+\pi^-$	17.0	22.7	14.0	18.6	15.3	20.4	23(2)
$pn\pi^0\pi^0$	9.7	12.9	7.9	10.5	8.7	11.6	12(2)
$pn\pi^+\pi^-$	21.7	28.9	17.2	22.9	19.3	25.8	30(5)
$pp\pi^-\pi^0$	4.15	5.55	2.9	3.9	3.55	4.7	6(1)
$nn\pi^+\pi^0$	4.15	5.55	2.9	3.9	3.55	4.7	6(1)
$NN\pi$	–	–	11.5	15.4	6.2	8.3	– (<9%)
NN	9	12	11	14.7	10	13.3	12(3)
total	75	100	75	100	75	100	103(15)

CC+ΔΔ model for d*(2380)

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
- Q.F. Lv, F. Huang, Y.B. Dong, P.N. Shen, Z.Y. Zhang, PRD 96 (2017) 014036

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
- Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang, Chin. Phys. C 41 (2017) 101001

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 & wave functions

Total Hamiltonian for 6q systems:

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

RGM wave functions for ΔΔ-CC system:

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

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

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

RGM equation for a bound state problem:

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

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:

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

- 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:

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

No free parameters for ΔΔ

d* mass & structure in chiral QM

ΔΔ only: BE ≈ 29 − 62 MeV

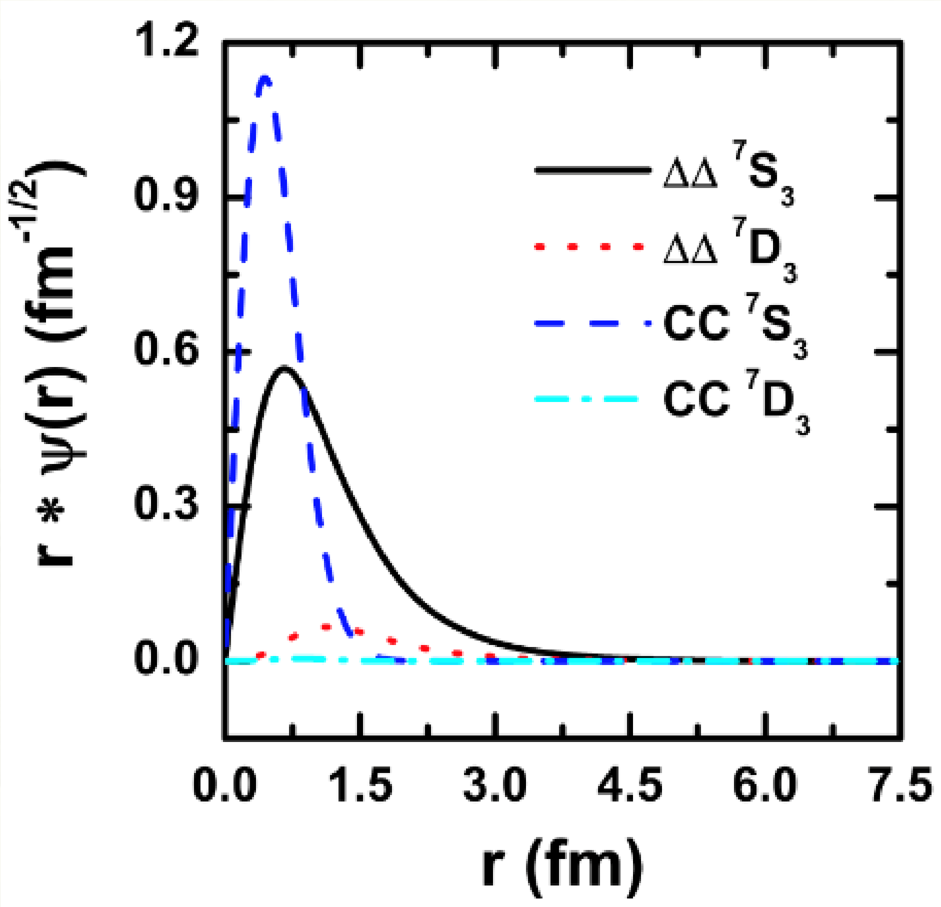
ΔΔ + CC: BE ≈ 47 − 84 MeV

CC component:

$$\frac{|\chi_{CC}|^2}{|\chi_{\Delta\Delta}|^2 + |\chi_{CC}|^2} \approx \frac{2}{3}$$

Pure hexaquark state:

$$[6]_o[33]_{IS} = \sqrt{\frac{1}{5}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|CC\rangle$$



Conclusion: d* is a hexaquark-dominated exotic state!

d^* width in chiral QM

ΔΔ component: ~1/3

Rough estimate of Γ_{d^*}: 1/3 × 2Γ_Δ ≈ 77 MeV

Detailed Calculations:

Y.B. Dong, F. Huang, P.N. Shen, Z.Y. Zhang,

PRC 91 (2015) 064002

PRC 94 (2015) 014003

PLB 769 (2017) 223

PRD 96 (2017) 094001

	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
$d^* \to NN\pi$	0.7	---
Total	72.6	74.9

Diquark model for d*(2380)

d*(2380) and its partners in a diquark model,
P.P. Shi, F. Huang, W.L. Wang, Eur. Phys. J. C 79, 314 (2019).

Width is naturally narrow if accommodated in diquark model!

Table 1 Possible two-quark configurations

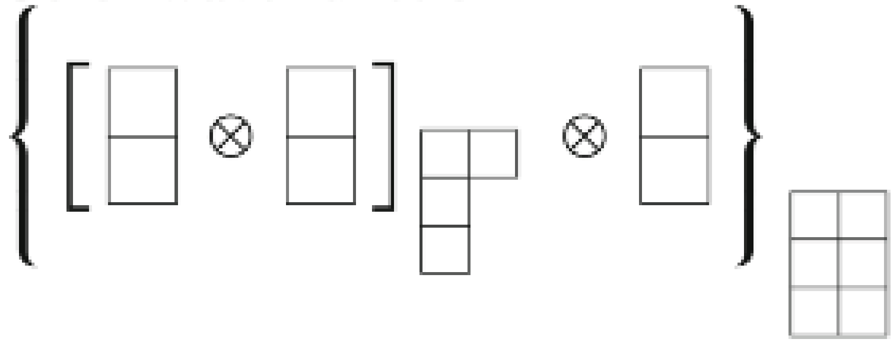
	Spin	Flavor	Color
$(0, \mathbf{6}_f, \mathbf{6}_c)$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\square\square$	$\square\square$
$(1, \bar{\mathbf{3}}_f, \mathbf{6}_c)$	$\square\square$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\square\square$
$(0, \bar{\mathbf{3}}_f, \bar{\mathbf{3}}_c)$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$
$(1, \mathbf{6}_f, \bar{\mathbf{3}}_c)$ ✓	$\square\square$	$\square\square$	$\begin{smallmatrix}\square\\\square\end{smallmatrix}$

First two configurations: $\lambda_i^c \cdot \lambda_j^c > 0$

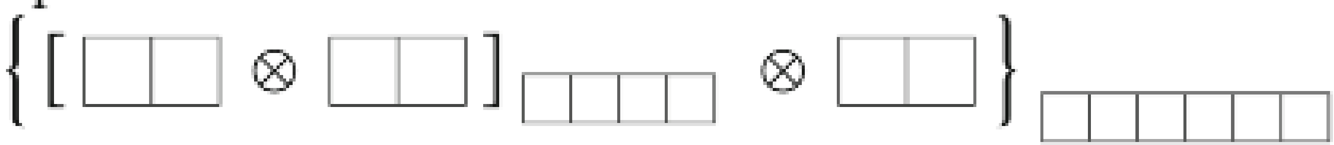
Last two configurations: $\lambda_i^c \cdot \lambda_j^c < 0$

Wave functions in diquark model

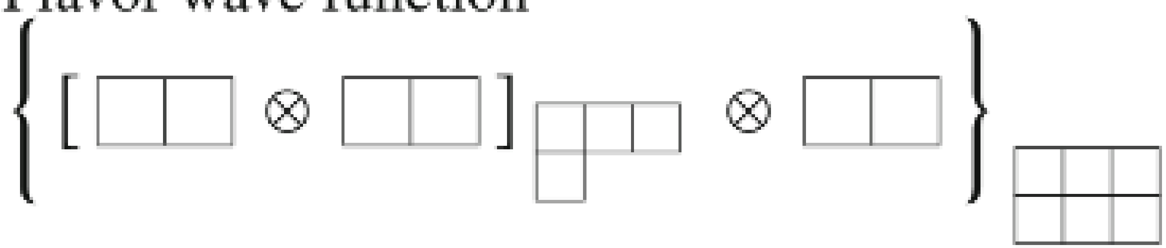
1. Color wave function



2. Spin wave function



3. Flavor wave function



Mass formula for d* & its partners

$$H = \sum_n M_n + 2\sum_{i>j}\left[\alpha_{ij}\left(\boldsymbol{\lambda}_i \cdot \boldsymbol{\lambda}_j S_i \cdot S_j\right) + \frac{\beta}{m_i m_j}\left(\boldsymbol{\lambda}_i \cdot \boldsymbol{\lambda}_j\right)\right]$$

Following Jaffe [Phys. Rept. 409 (2005) 1] to fix parameters:

$\Lambda_c,\ \Sigma_c,\ \Sigma_c^*,\ \Xi_c,\ \Xi_c',\ \Xi_c^*,\ \Omega_c^0$ — **quark-diquark**

$D_s,\ D_s^*$ — **quark-antiquark**

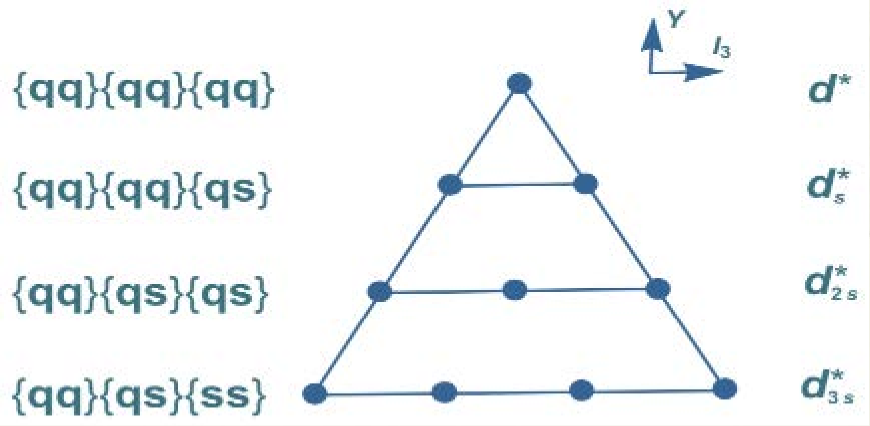
Table 2 Model parameters. The diquark masses M_{qq}, M_{qs} and the coefficients α_{qq}, α_{qs}, α_{ss} are in MeV. The coefficient β is in fm^{-3}

M_{qq}	M_{qs}	α_{qq}	α_{qs}	α_{ss}	β
1032	1103	− 39.5	− 29.1	− 3.3	0.41

Masses for d* & its partners

Table 3 Masses of $d^*(2380)$ and its flavor SU(3) partners. The masses M, the corresponding baryon-baryon thresholds $M_{\text{thr.}}$, and their differences $M_{\text{thr.}} - M$ are in MeV

	M	Channel	$M_{\text{thr.}}$	$M_{\text{thr.}} - M$
d^*	2383	$\Delta\Delta$	2464	81
d_s^*	2541	$\Delta\Sigma^*$	2617	76
d_{2s}^*	2689	$\Delta\Xi^*$	2762	73
d_{3s}^*	2797	$\Delta\Omega$	2904	107



Decay widths for d* & its partners

Quark tunneling + Bound BB decay

$$\Gamma \approx \mathcal{P}^2 \Gamma_{BB'} \approx e^{-r_0\sqrt{2m(M_{\rm thr.}-M)/3}}\,(\Gamma_B + \Gamma_{B'})$$

$$\Gamma_\Delta = \gamma_{N\pi}\frac{R^2 q_{N\pi}^2}{1+R^2 q_{N\pi}^2} q_{N\pi},$$

$$\Gamma_{\Sigma^*} = \gamma_{\Lambda\pi}\frac{R^2 q_{\Lambda\pi}^2}{1+R^2 q_{\Lambda\pi}^2} q_{\Lambda\pi} + \gamma_{\Sigma\pi}\frac{R^2 q_{\Sigma\pi}^2}{1+R^2 q_{\Sigma\pi}^2} q_{\Sigma\pi},$$

$$\Gamma_{\Xi^*} = \gamma_{\Xi\pi}\frac{R^2 q_{\Xi\pi}^2}{1+R^2 q_{\Xi\pi}^2} q_{\Xi\pi},$$

Table 4 Decay widths (in MeV) of $d^*(2380)$ and its flavor SU(3) partners at selected values for the distances (in fm) of two diquarks. $\Gamma_{BB'}$ is the decay width of a bound BB' state

	$\Gamma_{BB'}$	r_0					
		0.9	1.1	1.3	1.5	1.7	1.9
d^*	168.2	93.0	81.5	71.4	62.6	54.9	48.1
d_s^*	107.9	60.7	53.5	47.1	41.4	36.5	32.1
d_{2s}^*	88.7	50.2	44.2	39.0	34.3	30.3	26.7
d_{3s}^*	66.6	33.7	29.0	24.9	21.4	18.4	15.8

Doubts raised by Gal & Karliner

A diquark model for the d*(2380) dibaryon resonance?
A. Gal and M. Karliner, Eur. Phys. J. C 79, 538 (2019)

of about 0.4. Unfortunately these authors overlooked the rearrangement required also in color-flavor space for a $3\mathcal{D}$ system to become a $\Delta\Delta$ system. This produces another suppression factor of 1/9, as shown in some detail below, so the resulting width is less than 10 MeV.

respect, we found that the $3\mathcal{D}$ $I = 0$ $J^P = 1^+$ deuteron-like and the $I = 1$ $J^P = 0^+$ virtual-like states in the particular diquark model suggested by these authors are located some 200–250 MeV above the physical deuteron, where no

Responses to Gal & Karliner's doubts

$$\left\{\left[(12)_{1\bar{3}_c}(34)_{1\bar{3}_c}\right]_{13_c}(56)_{1\bar{3}_c}\right\}_{01_c}$$

$$= \frac{2}{3}\left\{\left[(12)_{1\bar{3}_c}5\right]_{\frac{1}{2}8_c}\left[(34)_{1\bar{3}_c}6\right]_{\frac{1}{2}8_c}\right\}_{01_c}$$

$$+\frac{\sqrt{2}}{3}\left\{\left[(12)_{1\bar{3}_c}5\right]_{\frac{1}{2}1_c}\left[(34)_{1\bar{3}_c}6\right]_{\frac{1}{2}1_c}\right\}_{01_c}$$

$$-\frac{\sqrt{2}}{3}\left\{\left[(12)_{1\bar{3}_c}5\right]_{\frac{3}{2}8_c}\left[(34)_{1\bar{3}_c}6\right]_{\frac{3}{2}8_c}\right\}_{01_c}$$

$$-\frac{1}{3}\left\{\left[(12)_{1\bar{3}_c}5\right]_{\frac{3}{2}1_c}\left[(34)_{1\bar{3}_c}6\right]_{\frac{3}{2}1_c}\right\}_{01_c}$$

Doubt 1: a factor of 1/9 is overlooked.

Only the last term is allowed! No 1/9 factor!

Doubt 2: Fails to describe deuteron.

Not supposed to describe deuteron.

Flavor-spin dependent interactions needed!

Summary

- d*(2380) reported by WASA-at-COSY with an unusual narrow width ($\Gamma \approx 70$ MeV)
- Possible theoretical explanations (M & Γ):
  - A. Gal & H. Garcilazo: |ΔΔ> + |ΔNπ>
  - F. Huang, Y.B. Dong, P.N. Shen, Z.Y. Zhang: **ΔΔ+CC,** hexaquark dominated exotic state
  - P.P. Shi, F. Huang, W.L. Wang: **3-diquark**
- More experimental & theoretical works needed