A study of d*(2380)

------a chiral quark model

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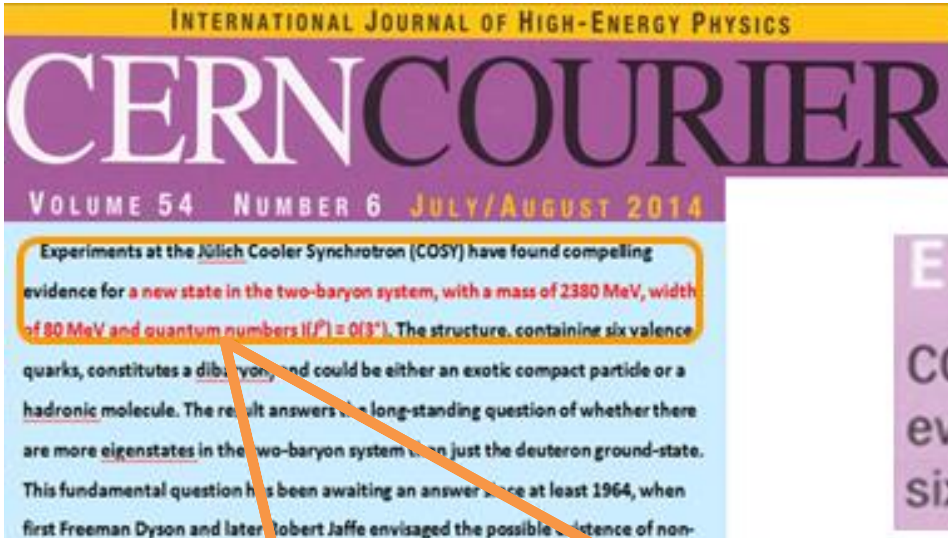
I、Observation of d*(2380)



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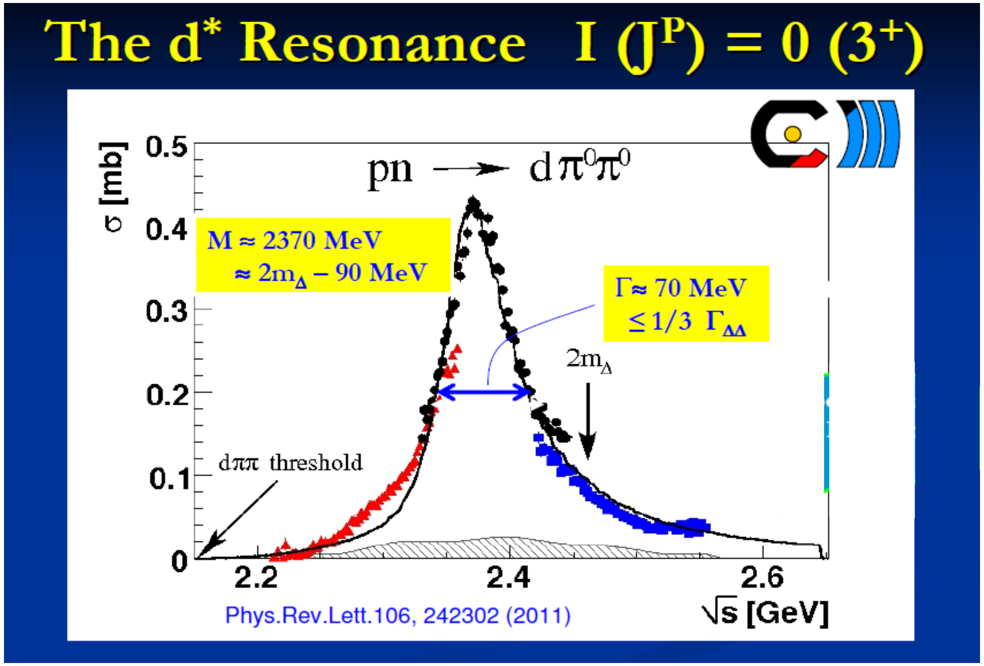
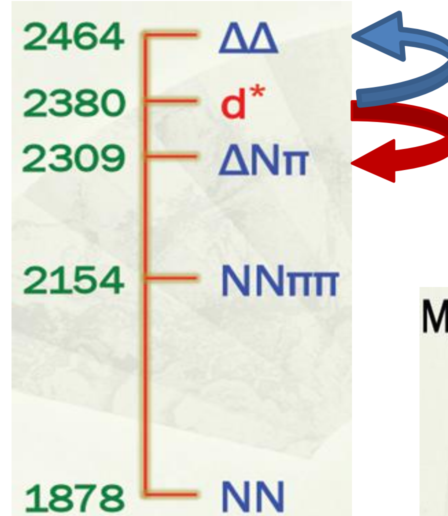
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum numbers $I(J^P) = 0(3^+)$. The structure, containing six valence quarks, constitutes a dibaryon, and could be either an exotic 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 80 MeV and quantum numbers $I(J^P) = 0(3^+)$…Since 2009



Baryon number=2



84MeV

71MeV

Unusual narrow width

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

$\approx 2M_\Delta - 84$ MeV

$> M_{\Delta N\pi}$

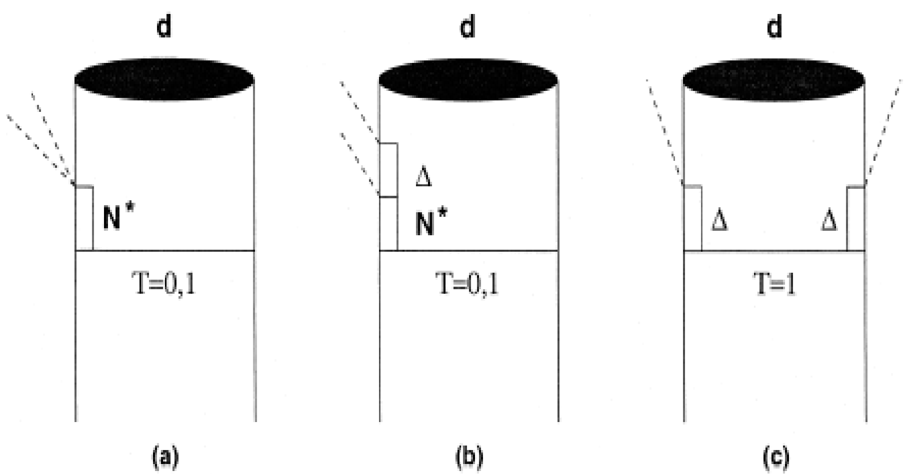
$> M_{NN\pi\pi}$

$> M_{NN}$

$2\Gamma_\Delta \approx 230$ MeV

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

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



Neither NN (Roper),
nor ΔΔ
Intermediate state

d*(2380)

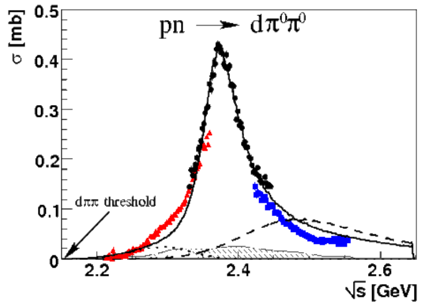
Signals in np processess @ COSY

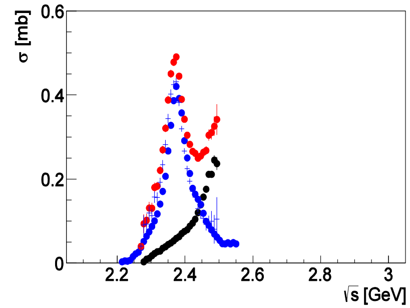
2π production processes

PRL 106 (2011) 242302

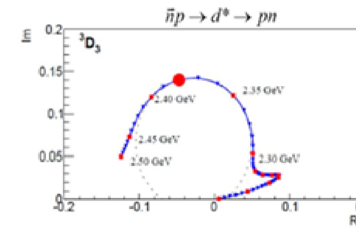
PLB 721 (2013) 229

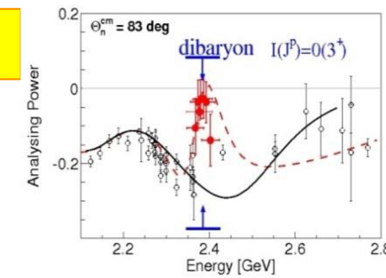
● ● ● WASA data





np scattering process





PRL 112 (2014) 202301

Fusion

$d\pi^0\pi^0$

$d\pi^+\pi^-$

pn → d*(2380)

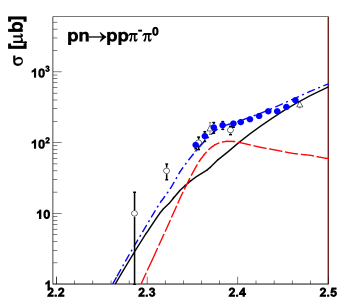
pn

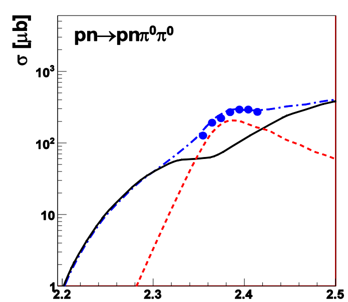
Non-fusion

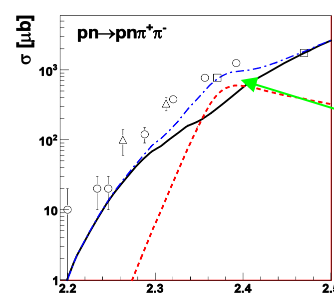
$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

$pn\pi^+\pi^-$







HADES

PRC 88 (2013) 055208

PLB 743 (2015) 325

Proc. STORI 2015

Signals in other reactions @ COSY

fusion 2π processes

Measured also in fusion reactions to helium isotopes:

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

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

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

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

Character of d*

- d* mass locates between ΔΔ and ΔNπ thresholds

  Effect from threshold is expected small

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

$M_{\Delta N\pi} = 2310\mathrm{MeV}$ $M_{d^*} \approx 2380\mathrm{MeV}$ $M_{\Delta\Delta} = 2464\mathrm{MeV}$

71MeV 84MeV

- d* narrow width → Possible 6q structure

  <u>might be different from normal hadrons</u>

Review article: by Heinz Clement,

Progress in Particle and Nuclear Physics,

93 (2017), 195-142

II、Possible interpretations

▲ Before COSY's observation

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

d*(2380)

- Prediction consists with COSY's measurement

  Dyson(64) ------- symmetry analysis

  Thomas(83) ------ bag model

  Yuan(99) -------- $\Delta\Delta$+CC quark cluster model

- Other predictions

  Jaffe(77)

  Swart(78)

  Oka(80)

  Maltman(85)

  Goldman(89)

  Wang(95)...

▲ After COSY's observation

- **Quark model**

J.Ping (09,14) ---------10 coupled channel quark cluster model

F.Huang,Y.B.Dong (14,15)---------ΔΔ+CC quark cluster model

Bashkanov, Brodsky, H.Clement (13) -- ΔΔ+CC argument

S.L.Zhu (15) ------QCD Sum Rule

- **Hadronic model**

Gal (14) --------- $\Delta N\pi$ model

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

→ A. Compact 6q dominated exotic state

B. $\Delta N\pi$ (or $D_{12}\pi$) resonant state

A. Compact 6q dominated exotic state

(a) In 1999, proposed d* with ΔΔ+CC structure

X.Q.Yuan, Z.Y.Zhang, Y.W.Yu, P.N.Shen, PRC 60 (1999) 045203

- **d* binding energy: 40-80 MeV**
- **CC enhances binding energy by 20 MeV**

(b) In 2013, proposed narrow d* width due to Harvey formula

$$|\Psi_{d^*}\rangle = \sqrt{\frac{1}{5}}|\Delta\Delta\rangle + \sqrt{\frac{4}{5}}|6Q\rangle$$

Bashkanov, Brodsky, H.Clement, Phys.Lett.B727 (2013)438

(c) In 2014, gave CC fraction of 68% in d*(ΔΔ+CC)

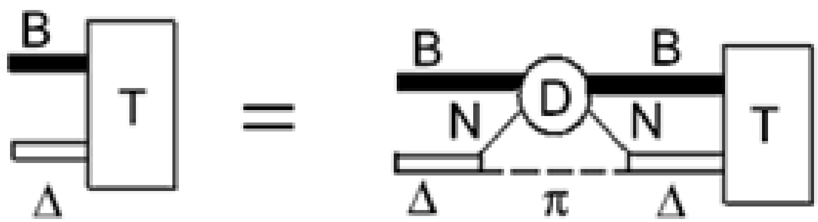
F.Huang, Z.Y.Zhang, P.N.Shen, W.L.Wang, CPC 39 (2015) 071001

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

A. Gal et al. NPA 928 (2014) 73

ΔN interaction

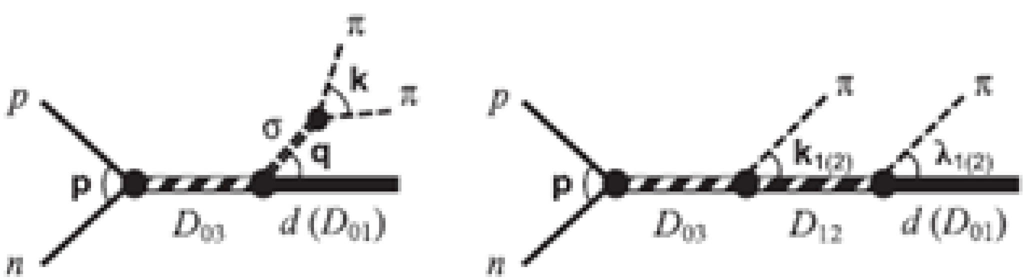
ΔNπ interaction



$$M_{\Delta' N\pi} \approx 2363 \pm 20\text{MeV}$$

$$\Gamma \approx 65 \pm 17\text{MeV}$$

V. Kukulin et al. PRC87(2013) 025202, NPA 946 (2016) 117



D12

III、Compact 6q dominated d* in chiral constituent quark model

(A) Mass and wave function

SU(3) chiral QM + RGM approach

▲ **Interaction:**

q-q potential $$\mathbf{V_{ij} = V_{ij}^{conf} + V_{ij}^{OGE} + V_{ij}^{ch} + V_{ij}^{chv}}$$

$$\mathbf{V_{ij}^{ch} = \sum_{a} (V_{ij}^{s(a)} + V_{ij}^{ps(a)})}$$

Interactive Lagrangian

$$\mathcal{L}_I = -g_{ch}\bar{\Psi}(\sum_{a=0}^{8}\sigma_a\lambda_a + i\sum_{a=0}^{8}\pi_a\lambda_a\gamma_5)\Psi$$

Model parameters: reproduce experimental data for NN systems---NN phase shifts, $\mathrm{BE}_d^{exp't} = 2.22\,\mathrm{MeV}$

▲ Trial wavefunction: $\mathbf{I(J^P) = 0(3^+)}$

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

$$\boxed{\begin{array}{ll} \Delta: & (0s)^3\,[3]_{\rm orb}, S=3/2, I=3/2, C=(00), \\ C: & (0s)^3\,[3]_{\rm orb}, S=3/2, I=1/2, C=(11), \end{array}}$$

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

▲ Hadronization----Channel wave function:

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

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

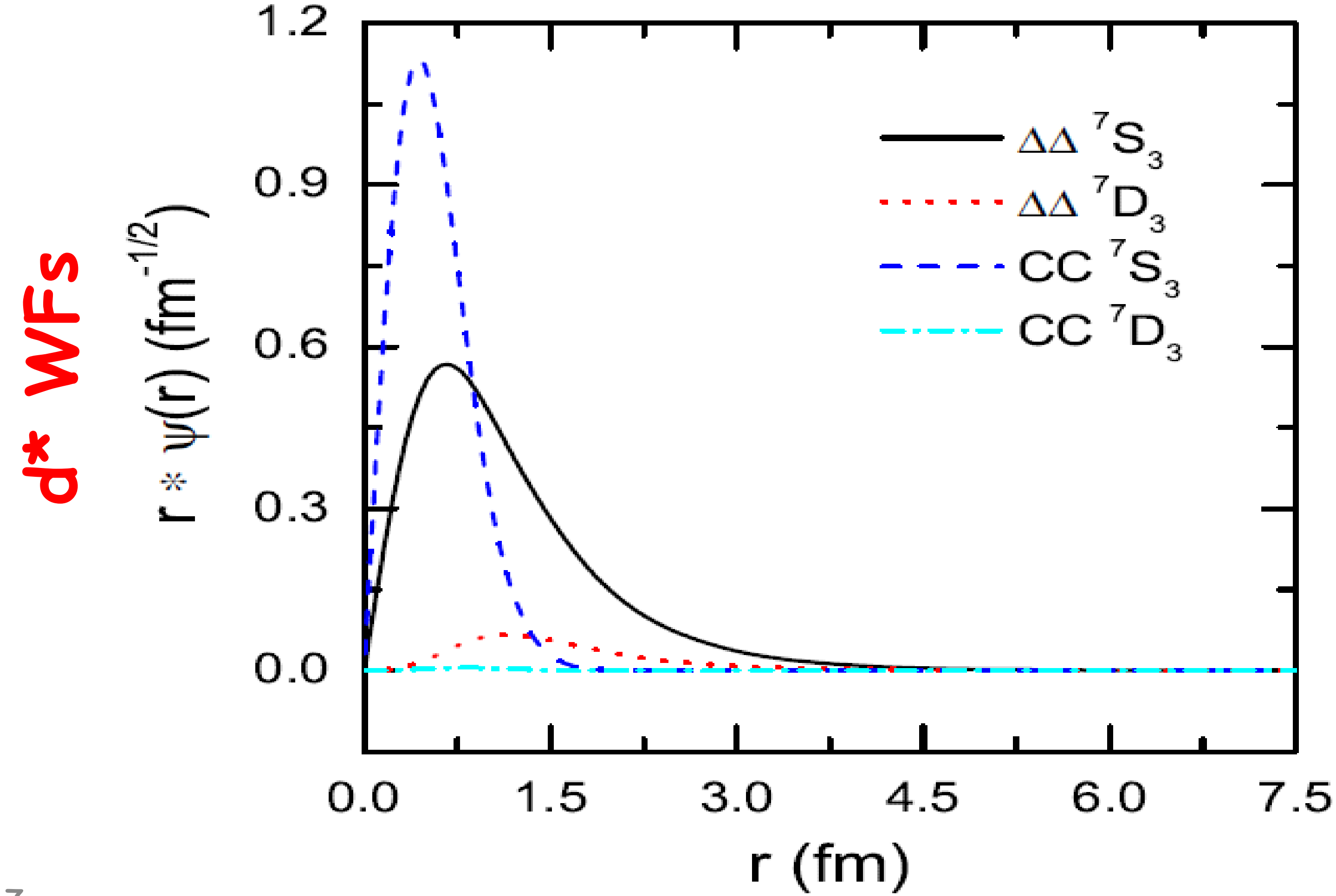
$$\chi_{\Delta\Delta}(\boldsymbol{r}) \equiv \langle\phi_\Delta(\xi_1,\xi_2)\,\phi_\Delta(\xi_4,\xi_5)\,|\,\Psi_{6q}\rangle\,,$$

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

The two components are orthogonal due to the quark exchange effect

▲ Results

- **Wave function**



- **Binding energy**

$$\mathrm{BE}_{\mathrm{d}^*}^{\mathrm{th}} = 84\mathrm{MeV} \qquad \mathrm{BE}_{\mathrm{d}^*}^{\mathrm{exp't}} = 84\mathrm{MeV}$$

		Ext. SU(3) (f/g=0)	
		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

Reason for the large component of CC (68%)

$P_{36} = P^{r}_{36}\ P^{sfc}_{36}$

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

1). Intrinsic character of d* ----- $<P^{sfc}_{36}>$

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

2). Dynamical effect-----

(SI=30) , OGE and vector meson exchange induced Δ-Δ short range interaction is attractive

Two cluster closer $\longrightarrow$ large CC component

$\longrightarrow$ d* deep bound and narrow width

d* might be a 6q dominant state!

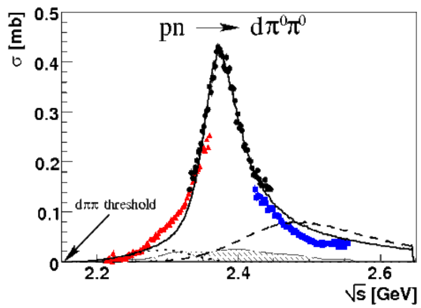
(B) Strong decays

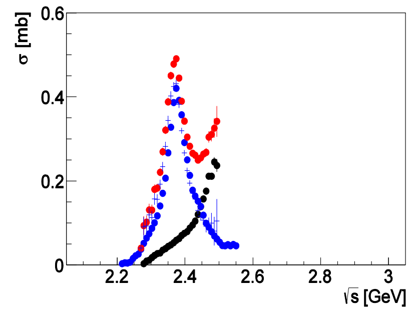
2π production processes

PRL 106 (2011) 242302

PLB 721 (2013) 229

WASA data





$d\pi^0\pi^0$

$d\pi^+\pi^-$

Fusion

$$\boxed{pn \to d^*(2380)}$$

pn

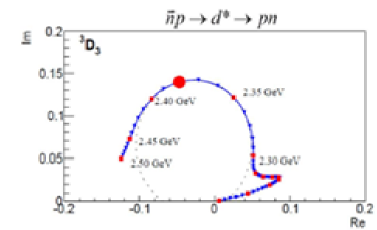
Non-fusion

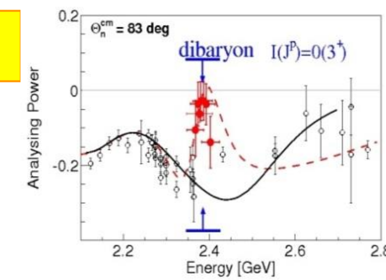
$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

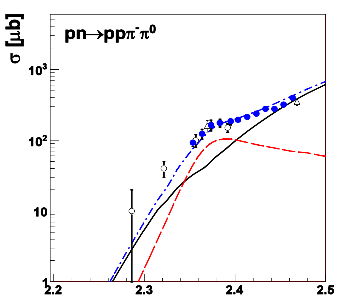
$pn\pi^+\pi^-$

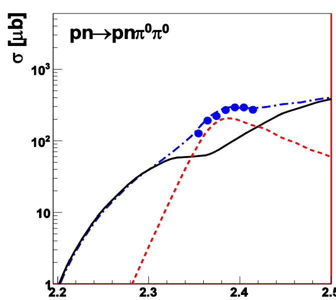
np scattering process

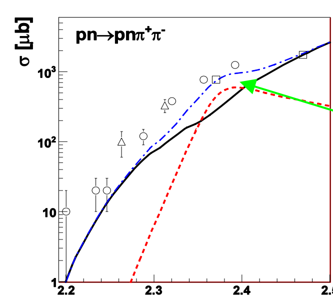




PRL 112 (2014) 202301







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PRC 88 (2013) 055208

PLB 743 (2015) 325

Proc. STORI 2015

▲ 2π decay widths

Three-body decay

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

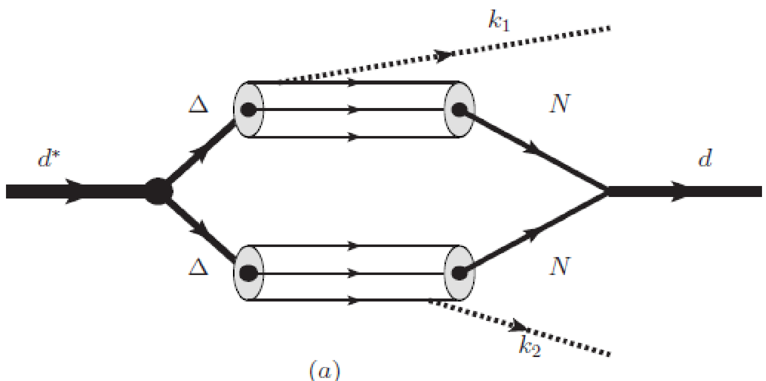
$d^* \to pp\pi^-\pi^0$

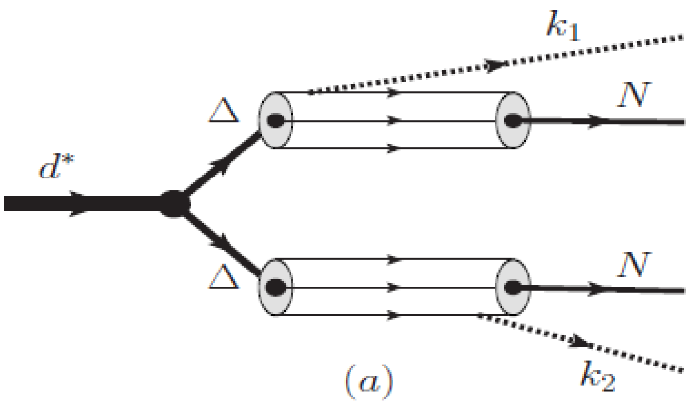
Typical diagrams

Four-body decay

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

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





Parameter:

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

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

decay widths

Three-body decay

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

$$\mathcal{M}_{if}^{\pi^0\pi^0} = \frac{1}{\sqrt{3}}\sum F_1F_2k_{1,\mu}k_{2,\nu}I_S^0 I_I^0 C_{1\nu,1\mu}^{jm_j}C_{3m_{d^*},jm_j}^{1m_d}$$
$$\times\int d^3q\Bigg[\frac{\chi_d^*(\vec{q}-\frac{1}{2}\vec{k}_{12})}{E_\Delta(q)-E_N(q-k_1)-\omega_1}$$
$$+\frac{\chi_d^*(\vec{q}+\frac{1}{2}\vec{k}_{12})}{E_\Delta(q)-E_N(q-k_2)-\omega_2}$$
$$+\frac{\chi_d^*(\vec{q}+\frac{1}{2}\vec{k}_{12})}{E_\Delta(-q)-E_N(-q-k_1)-\omega_1}$$
$$+\frac{\chi_d^*(\vec{q}-\frac{1}{2}\vec{k}_{12})}{E_\Delta(-q)-E_N(-q-k_2)-\omega_2}\Bigg]\chi_{d^*}(\vec{q})$$

Four-body decay

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

$$\mathcal{M}(k_1,k_2;p_1) = \mathcal{M}^{\text{bare}}(k_1,k_2;p_1)\times\mathcal{I}$$ $\Leftrightarrow$ **FSI**

$$\mathcal{I} = \mathcal{J}^{-1}(k) = C(k^2)\frac{\sin\delta e^{i\delta}}{k}$$

$$\mathcal{M}^a(k_1,k_2;p_1) = \int d^3p_2d^3q[\mathcal{H}\mathcal{S}_f\mathcal{H}]\Psi_{d^*}(q)$$
$$\times\,\delta^3(\vec{p}_1+\vec{k}_1-\vec{q})\delta(\vec{p}_2+\vec{k}_2+\vec{q})$$
$$= \int d^3p_2\delta^3(\vec{p}_1+\vec{p}_2+\vec{k}_1+\vec{k}_2)[\mathcal{H}\mathcal{S}_f\mathcal{H}]$$
$$\times\,\Psi_{d^*}(-\vec{p}_2-\vec{k}_2)$$

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

	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

* Too large width for (ΔΔ) component only

M_{d^*}(MeV)	(100%)ΔΔ 2374	Expt 2375
Decay channel	Γ(MeV)	Γ(MeV)
$d^* \to d\pi^0\pi^0$	17.0	10.2
$d^* \to d\pi^+\pi^-$	30.8	16.7
Total	132.8	74.9

Discussions:

* FSI is about 26~30%

* Isospin breaking factor

$$\frac{\Gamma(d^* \to d\pi^+\pi^-)}{\Gamma(d^* \to d\pi^0\pi^0)} \sim 1.8 \quad (1.6, \quad 2.0)$$

$$\frac{\Gamma(d^* \to pn\pi^+\pi^-)}{\Gamma(d^* \to pn\pi^0\pi^0)} \sim 2.2 \quad (2.5, \quad 2.5)$$

Ideal

* All partial and total widths agree with data

$$\Gamma^{exp't} = 70 \sim 75\, MeV$$

$$\Gamma^{th} \approx 72\, MeV$$

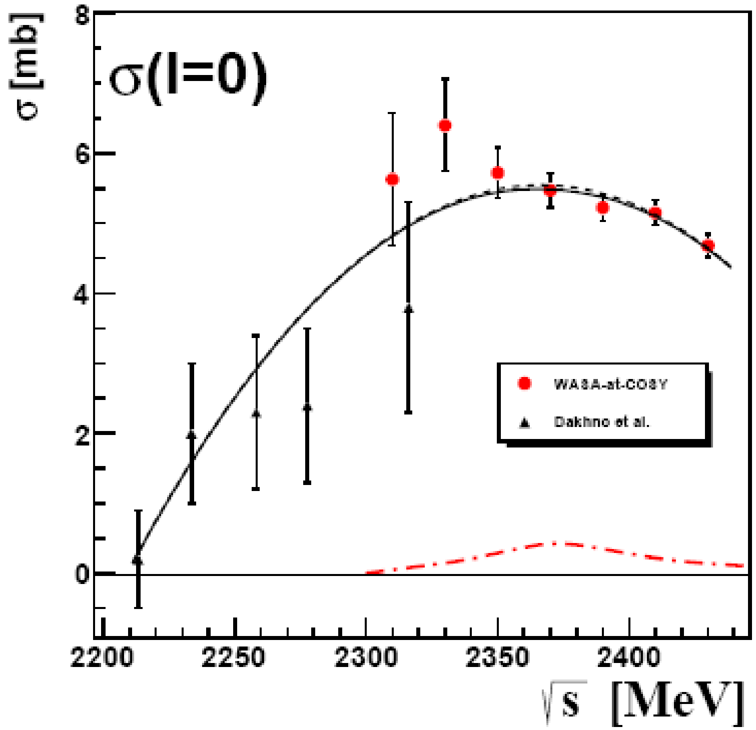
The narrow width is due to large CC component

▲ single-π decay

- Experimental status

The WASA-@-COSY Collaborations, arXiv:1702.07212v1 [nucl-ex]

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



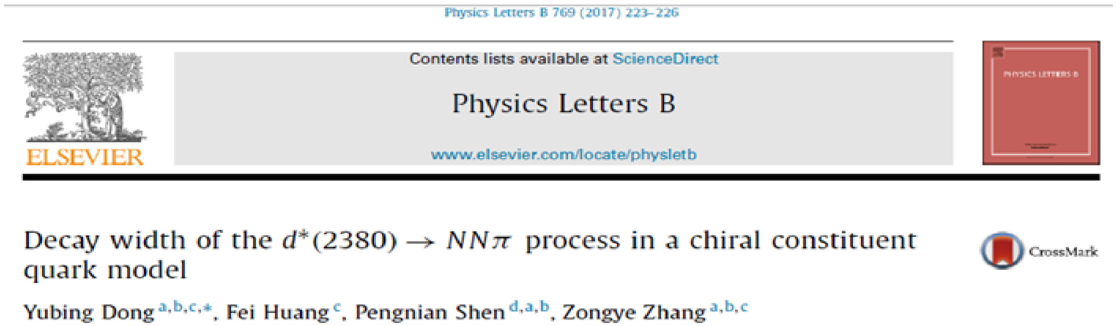
Dash-dotted line illustrates a 10% d*(2380) resonance contribution

Upper limit of branching ratio for $d^*(2380) \to NN\pi$ is 9%.

This channel might serve as a test for different interpretations, since the result of the ΔπN (or $D_{12}\pi$) is about 18%.

• Theoretical status

- compact 6q dominated case



Physics Letters B 769 (2017) 223–226

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Decay width of the $d^*(2380) \to NN\pi$ process in a chiral constituent quark model

Yubing Dong [a,b,c,*], Fei Huang [c], Pengnian Shen [d,a,b], Zongye Zhang [a,b,c]

Typical diagrams: pion emitted from cluster II

Dong, Huang, Shen, Zhang, PLB769 (2017) 223-226

Very recently

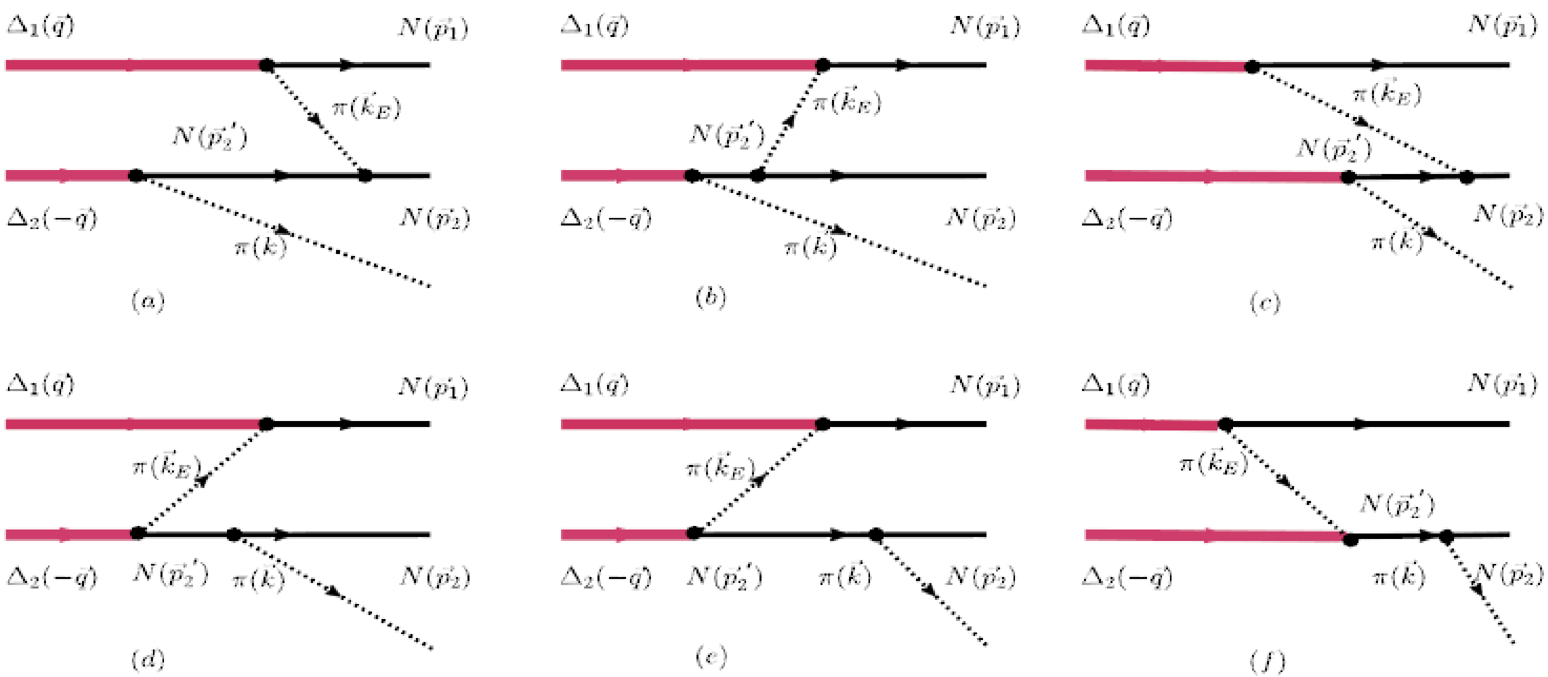
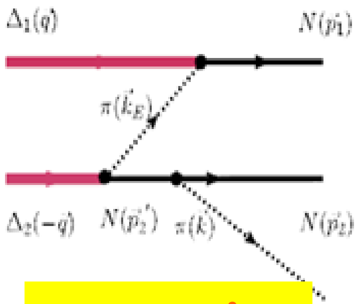


Fig. 1. Six possible ways to emit pion only from the $\Delta\Delta$ component of d^* in the $d^* \to NN\pi$ decay process. The outgoing pion with momenta $\vec{k}$ is emitted from Δ_2. The other six sub-diagrams with pion emitted from Δ_1 are similar, and then are not shown here for reducing the size of the figure.



Sample

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

$$\boxed{\begin{array}{ll} \Delta: & (0s)^3\,[3]_{\rm orb}, S=3/2, I=3/2, C=(00), \\ C: & (0s)^3\,[3]_{\rm orb}, S=3/2, I=1/2, C=(11), \end{array}}$$

$$L = L_{\pi NN} + L_{\Delta N\pi}$$

Intermediate states: (N,N*,Δ,Δ*)
Low-lying resonances are considered

From quark model

$$\frac{g^2_{\pi\Delta\Delta}}{4\pi} = \frac{1}{25}\frac{M^2_{\Delta}}{M^2_{N}}\frac{g^2_{\pi NN}}{4\pi}, \quad g_{\pi\Delta\Delta} \quad small$$

1, C→Δ, interaction should be color and isospin-dependent

2, CC(SI=3,0)→NN*(1400), D-wave of OGE is required

The suppressions enable to ignore the contribution from the CC component in d*

Our prediction of 1% is compatible with the exp't upper-limits

(C) Charge distribution of d*(2380)

Dong, Huang, Shen, Zhang, arXiv:1704.01253v1 [nucl-th]

For a spin=3 system:

2S+1=7 form factors (related to the size of system)

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

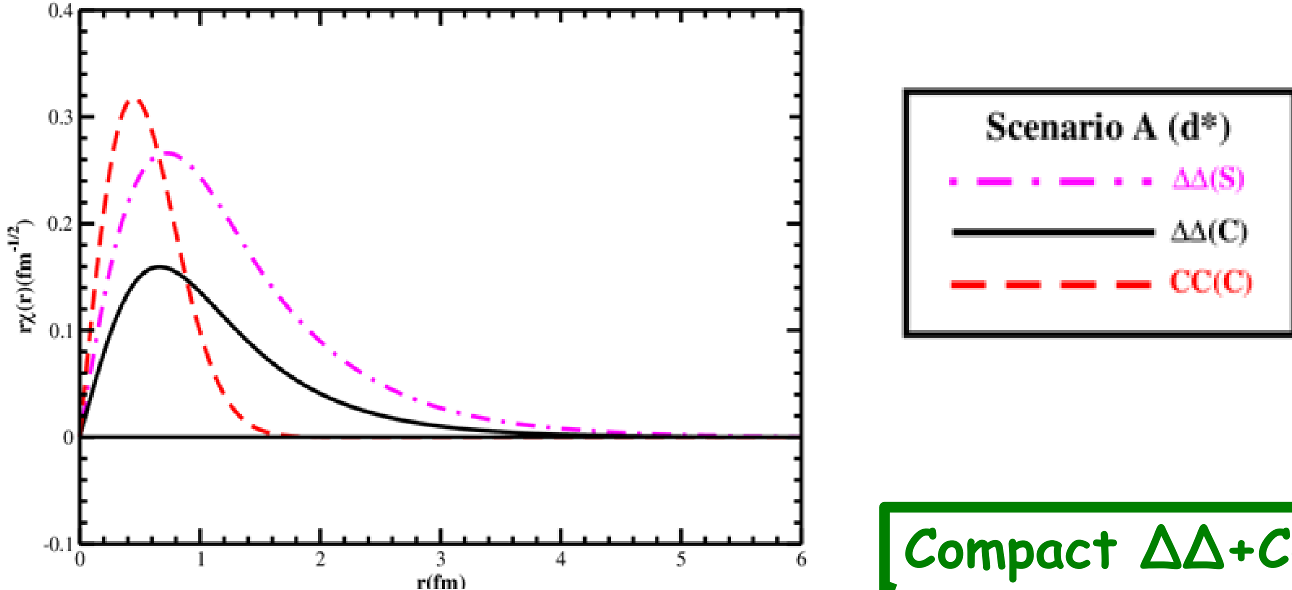
Both Channels

$$\begin{aligned}
\mathcal{M}^\mu_{\alpha'\beta'\gamma',\alpha\beta\gamma} = \Big[& G_1(Q^2)\mathcal{P}^\mu\Big[g_{\alpha'\alpha}\Big(g_{\beta'\beta}g_{\gamma'\gamma}+g_{\beta'\gamma}g_{\gamma'\beta}\Big)+permutations\Big] \\
& +G_2(Q^2)\mathcal{P}^\mu\Big[q_{\alpha'}q_\alpha\big[g_{\beta'\beta}g_{\gamma'\gamma}+g_{\beta'\gamma}g_{\gamma'\beta}\big]+permutations\Big]/(2M^2) \\
& +G_3(Q^2)\mathcal{P}^\mu\Big[q_{\alpha'}q_\alpha q_{\beta'}q_\beta g_{\gamma'\gamma}+permutations\Big]/(4M^4) \\
& +G_4(Q^2)\mathcal{P}^\mu q_{\alpha'}q_\alpha q_{\beta'}q_\beta q_{\gamma'}q_\gamma/(8M^6) \\
& +G_5(Q^2)\Big[\Big(g^\mu_{\alpha'}q_\alpha-g^\mu_\alpha q_{\alpha'}\Big)\Big(g_{\beta'\beta}g_{\gamma'\gamma}+g_{\beta'\gamma}g_{\beta'\gamma}\Big)+permutations\Big] \\
& +G_6(Q^2)\Big[\Big(g^\mu_{\alpha'}q_\alpha-g^\mu_\alpha q_{\alpha'}\Big)\Big(q_{\beta'}q_\beta g_{\gamma'\gamma}+q_{\gamma'}q_\gamma g_{\beta'\beta}+q_{\beta'}q_\gamma g_{\gamma'\beta}+q_{\gamma'}q_\beta g_{\gamma\beta'}\Big) \\
& \qquad +permutations\Big]/(2M^2) \\
& +G_7(Q^2)\Big[\Big(g^\mu_{\alpha'}q_\alpha-g^\mu_\alpha q_{\alpha'}\Big)q_{\beta'}q_\beta q_{\gamma'}q_\gamma+permutations\Big]/(4M^4)\Big]
\end{aligned}$$

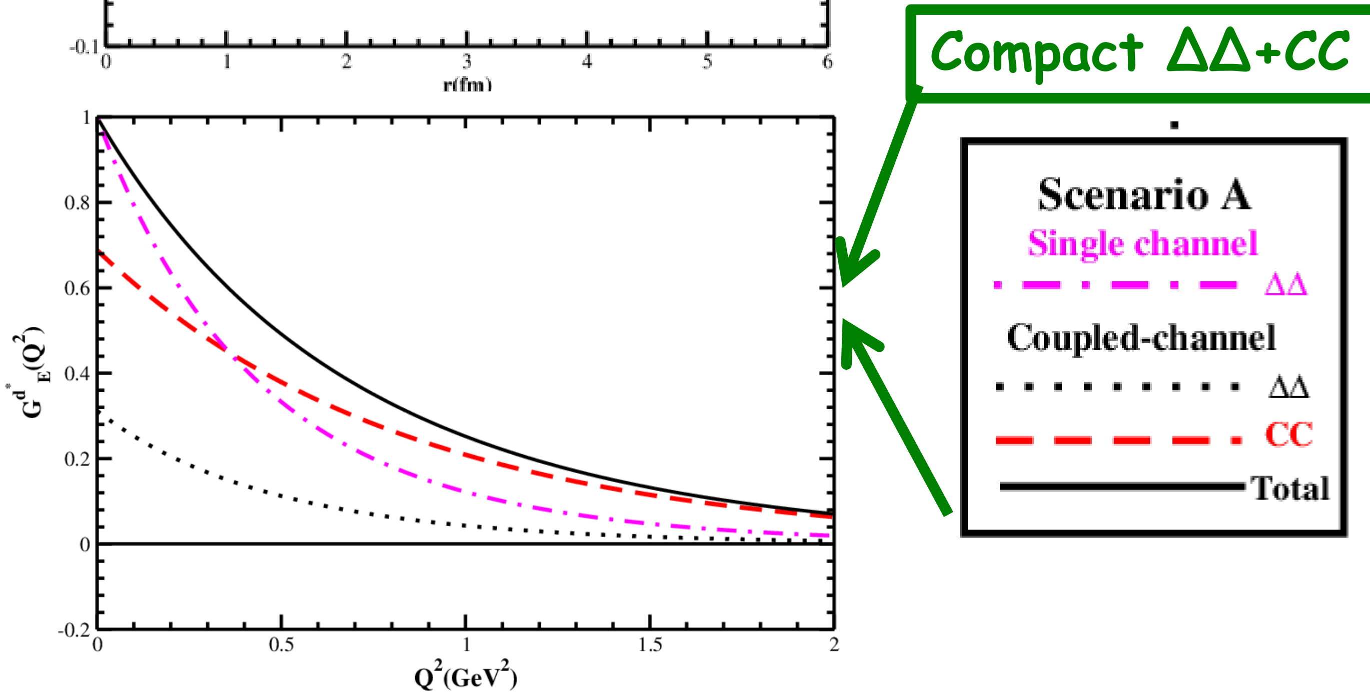
$$J^0=\sum_{i=1}^{6}e_i\bar{q}_i\gamma^0 q_i=\sum_{i=1}^{6}j_i^0.$$

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

Wave Function



Charge Distribution



rms

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

IV、 Summary and Remarks

- **Our understanding:**

  d*: Hexaquark dominated state

  (CC component ~ 66-68% in $\Delta\Delta$+CC)

$M \approx 2380$ MeV $\Gamma \approx 72$ MeV

($M^{exp't} \approx 2380$ MeV $\Gamma^{exp't} \approx 70$-$75$ MeV)

• Remarks

Compact 6q dominated

Dong, Huang, Shen, Zhang, PLB769 (2017) 223

$\Delta N\pi$ (or $D_{12}\pi$) system

A. Gal, PLB769 (2017) 436

Good ⟵ **Mass**

Double-pion strong decays ⟶ Good

d*(2380) single-π decay $d^*(2380) \to NN\pi$

Exp't BR ≤ 9%

our predicted BR of 1% is compatible with the exp't upper limit of 9%

the resultant BR for $\Delta N\pi$ (or $D_{12}\pi$) is about 18%.

in the mixing case

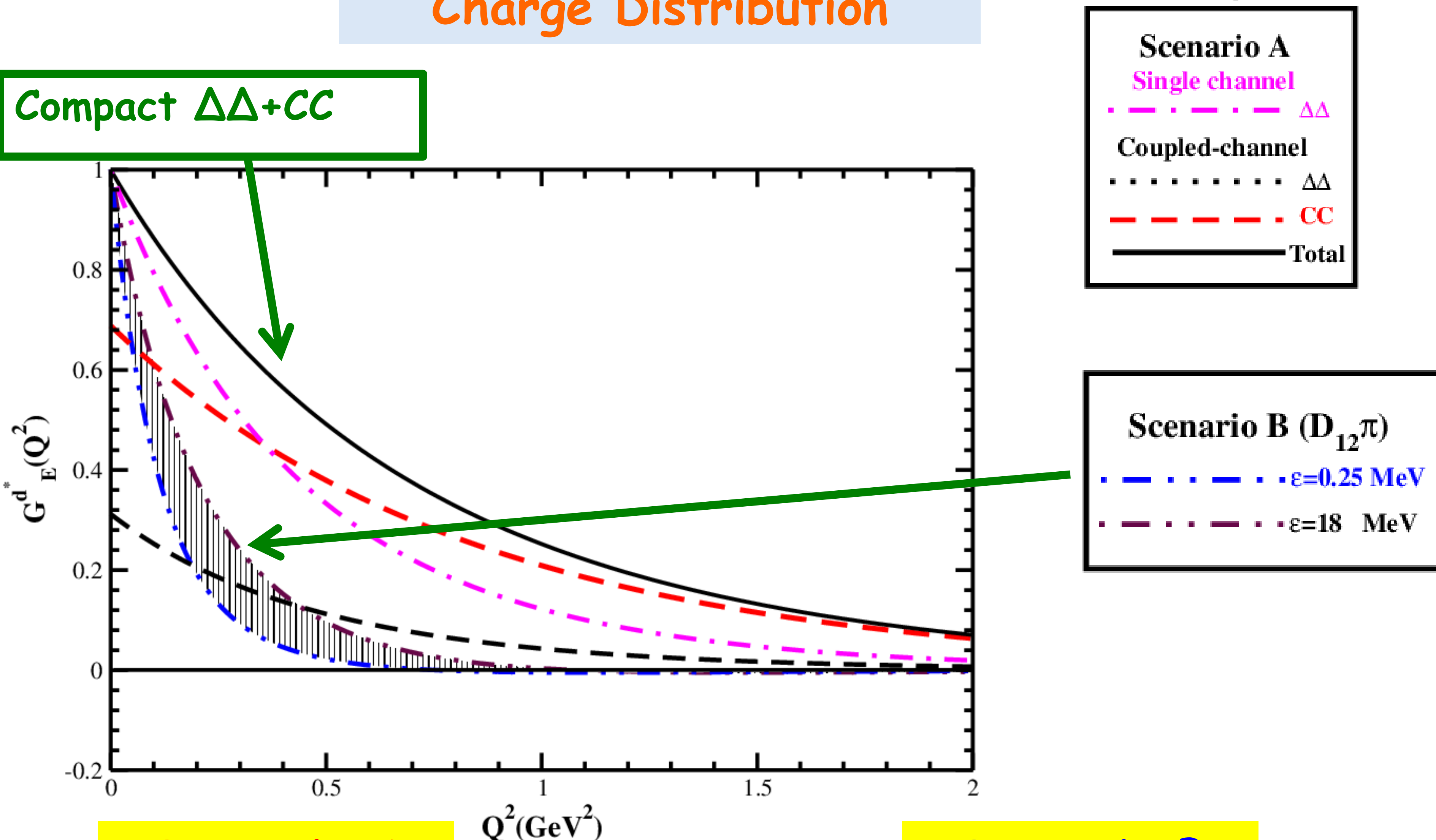
$$\alpha\Gamma_< + (1-\alpha)\Gamma_> = \Gamma^{d^*}_{NN\pi\pi}$$

$$\Gamma_> = 100 \text{ MeV} \qquad \Gamma^{d^*}_{NN\pi\pi} = 60 \text{ MeV}$$

if $\Gamma_< = 44$ MeV, $\alpha = \frac{5}{7}$

BR can be 9%

Charge Distribution



Scenario A

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

rms

Scenario B

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

Suggest other experimental searches

- $\gamma + d$ Process (Mainz, Jlab.)
- $\Upsilon \rightarrow \bar{d}^* + X$ Process (Belle)

  [BR($\Upsilon \rightarrow \bar{d} + X$) ~ 2.86 X 10^{-5}]
- $e^+ + e^- \rightarrow \bar{d}^* + p + n$ Process (BES,Belle?)

If the d* is further confirmed by experiments, we believe that our interpretation is reasonable. Thus, it is a state with 6q structure dominant and moreover, the more information about the short range interaction is expected.

Thanks !

BACKUP SLICES

Analysis: Large component of CC (67%) in d* ?

$$\Psi_{6q} = \left(\overset{(1)}{1} - \overset{(2)}{9P_{36}}\right)\left[\phi_\Delta \phi_\Delta \eta_{\Delta\Delta}(\mathbf{r})\right]_{SIC=30(00)}$$

$$+ \left(\underset{(3)}{1} - \underset{(4)}{9P_{36}}\right)\left[\phi_C \phi_C \eta_{CC}(\mathbf{r})\right]_{SIC=30(00)}$$

$$\chi_{\Delta\Delta}(r) \equiv \langle \phi_\Delta(\xi_1, \xi_2)\, \phi_\Delta(\xi_4, \xi_5) \,|\, \Psi_{6q} \rangle \,,$$ (1) (2) (4) terms

$$\chi_{CC}(r) \equiv \langle \phi_C(\xi_1, \xi_2)\, \phi_C(\xi_4, \xi_5) \,|\, \Psi_{6q} \rangle \,,$$ (3) (4) (2) terms

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

χ_{CC} contains the contri. From (2), from ΔΔ exchanged terms。

Thus P_{36} Exchange is important!

$P_{36} = P^{r}_{36}\ P^{sfc}_{36}$ d* has ΔΔ and CC components

- $\Delta\Delta$+coupled channels (in quark level)

J.L.Ping, F.Wang et al. PRC 89, 034001 (2014)

ChQM (10 channles with hidden-color ones)

	1	2	3	4		
$IJ^P = 03^+$	$\Delta\Delta(^7S_3)$	$NN(^3D_3)$	$\Delta\Delta(^3D_3)$	$\Delta\Delta(^7D_3)$		
	5	6	7	8	9	10
[redacted]	$^2\Delta_8\,^2\Delta_8(^3D_3)$	$^4N_8\,^4N_8(^3D_3)$	$^4N_8\,^2N_8(^3D_3)$	$^2N_8\,^2N_8(^3D_3)$	$^4N_8\,^4N_8(^7S_3)$	$^4N_8\,^4N_8(^7D_3)$

BE= 71 MeV Γ = 150 MeV

QDCSM (4 coupled channels)

$$\Delta\Delta^7S_3, NN^3D_3, \Delta\Delta^3D_3, \Delta\Delta^7D_3$$

BE= 107 MeV Γ = 110 MeV

TABLE III. $\Delta\Delta$ 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

Before the discovery of d*

- A pioneer discussion from symmetry: J.Dyson, PRL 13, 815 (1964)

Two baryon systems SU(6) classification :

Anti-symmetric representations:

Non-strange states

(I, J) = (3,0)(2,1)(1,0)(1,2)(0,1)(0,3) 6 states

Casmir operator reduced

a mass formula

$M = A + B' (T(T+1)) + B'' (J(J+1))$

If $B' = B'' = B$, the obtained deuteron mass 1876MeV, and then, obtain A,

Choose B = 50MeV, Then, M_{d*} = 2376MeV

$b_{\mathbf{u}},\quad m_\sigma$ are determined by fitting experimental data for NN systems

$$\mathrm{BE}_d^{exp't} = 2.22\,\mathrm{MeV}$$

		SU(3)	**Ext. SU(3) (f/g=0)**	Ext. SU(3) (f/g=2/3)
Deuteron Binding energy(MeV)		2.09	**2.24**	2.20
Fraction of Wave Function (%)	NN (L=0)	93.68	**94.66**	94.71
	NN (L=2)	6.32	**5.34**	5.29

$b_{\mathbf{u}} = 0.5\,fm$ $\qquad$ $b_{\mathbf{u}} = 0.45\,fm$

$m_\sigma = 595\,\mathrm{MeV}$ $\qquad$ $m_\sigma = 535 \sim 547\,\mathrm{MeV}$

NN Phase shifts: Good

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

Reason for the large component of CC (67%)

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

$P_{36} = P_{36}^{r}\ P_{36}^{sfc}$ if it large

$\langle P_{36}^{r} \rangle$: 1 should also large

$\langle P_{36}^{r} \rangle$ 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.

$\longrightarrow$ Two clusters ΔΔ closer, $\langle P_{36}^{r} \rangle$ is not small

1). d* special characters

spin-flavor-color spaces exchange effect :model independent

2). ΔΔ (SI=30) , Δ-Δ short range interaction is attractive

Dynamical effect —— Model dependent

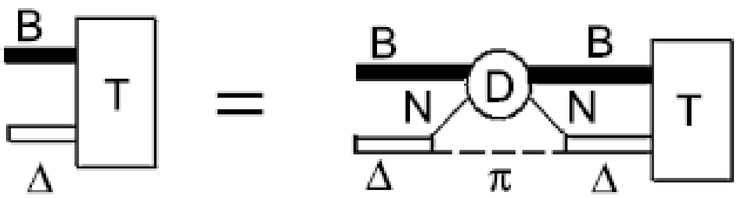
P_{36} Effect large, large CC componet

d* might be a 6q dominant state

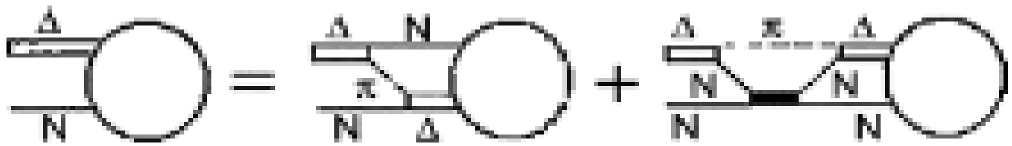
$\longrightarrow$ d* deep bounded and narrow width

- $\Delta N\pi$ 3-body bound state（π induced $D_{12}\pi$ scenario）

B =Δ' (Δ (Γ=0)) A. Gal et al. NPA 928, 73(2014)



S-matrix pole equation for $\mathcal{D}_{03}(2370)$ $\Delta\Delta$ dibaryon



$N\Delta$ dibaryon's Lippmann–Schwinger equation

a). Δ' N is NNπ 3-body system:

Nπ Interaction: P33 channel separable potential (Δ')

By solving Faddeev eq. to obtain Δ' N interaction,

D_{12} -Pole ：（2165~2174）- *i*（64~60） MeV

b). Take Δ'Δ as Δ' N π 3-body system:

Δ' N Interaction from solution a) , Nπ separable potential

Solving Faddeev eq. to get the Δ' N π resonance

$M_{\Delta' N\pi} = 2383$ MeV	$\Gamma \cong$ 82~94 MeV
$M_{\Delta' N\pi} = 2343$ MeV	$\Gamma \cong$ 48~62 MeV

$m_\Delta = (1211 + i\ X\ 49.5)$ MeV

Where X = 1 或 2/3

ps. ΔNπ (or $D_{12}\pi$) case

A.Gal, PLB769 (2017) 436-440

If in the ΔNπ (or $D_{12}\pi$) only case

Branching ratio for $d^*(2380) \to NN\pi$ is 18%

If in the mixing case

$$\alpha\Gamma_< + (1-\alpha)\Gamma_> = \Gamma^{d^*}_{NN\pi\pi}$$

taking $\Gamma_> = 100$ MeV $\quad \Gamma^{d^*}_{NN\pi\pi} = 60$ MeV

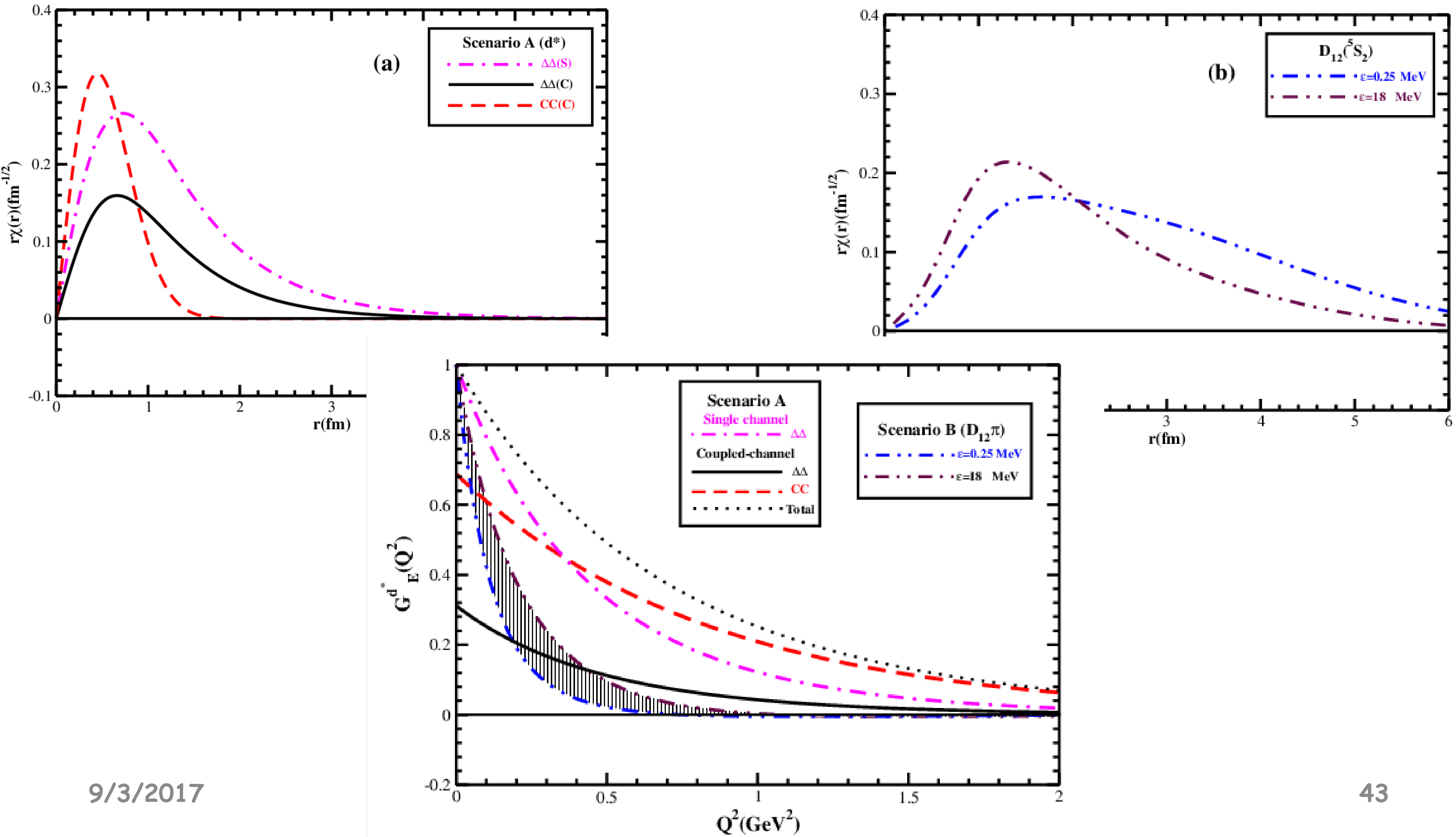
if $\Gamma_< = 44$ MeV, $\quad \alpha = \frac{5}{7}$

Branching ratio for $d^*(2380) \to NN\pi$ is 9%

(A)Compact quark model (B) N three-body system

d*(2380) Charge distribution

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

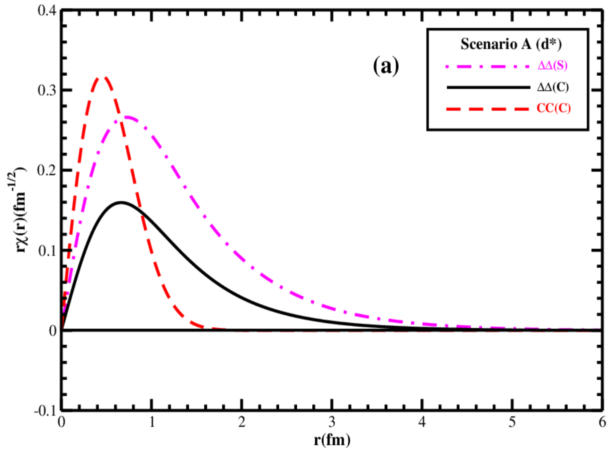


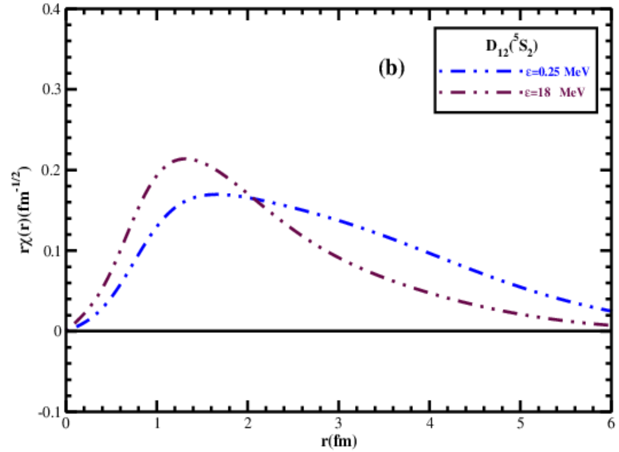
- **Binding energy**

$$\mathrm{BE}_{\mathrm{d}^*}^{\mathrm{th}} = 84\mathrm{MeV} \qquad \mathrm{BE}_{\mathrm{d}^*}^{\mathrm{exp't}} = 84\mathrm{MeV}$$

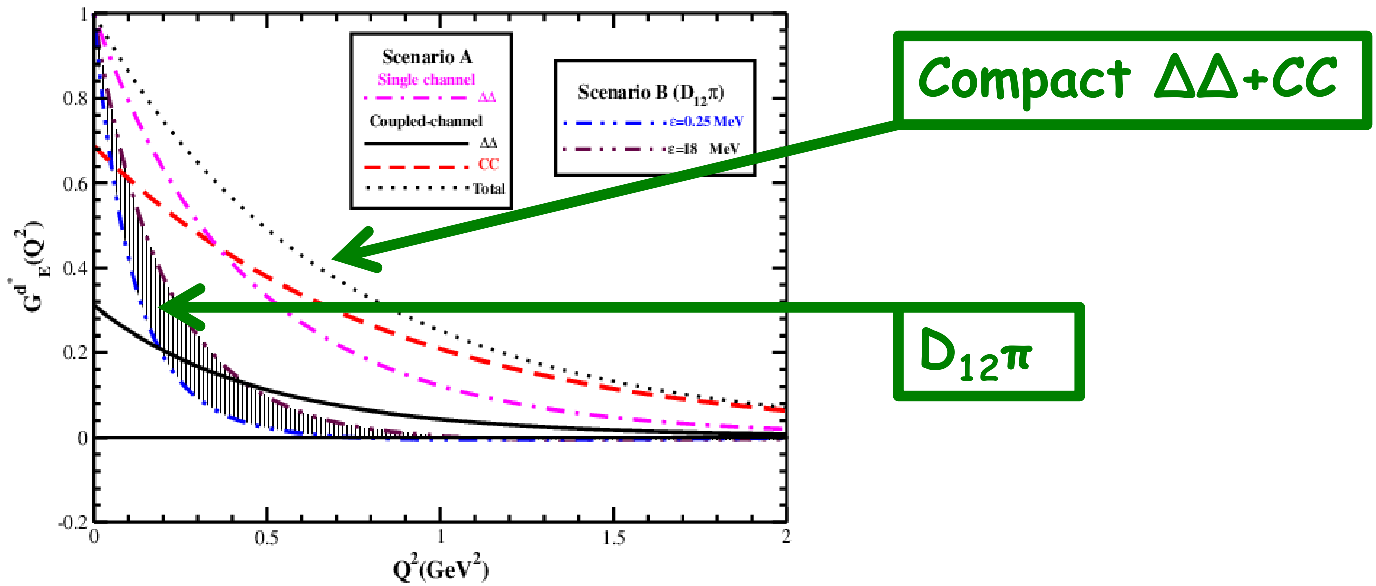
		SU(3)		Ext. SU(3) (f/g=0)		Ext. SU(3) (f/g=2/3)	
		ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)	ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)	ΔΔ (L=0,2)	ΔΔ-CC (L=0,2)
d^* Binding Energy(MeV)		28.9	47.9	62.3	83.9	47.9	70.3
Fraction of Wave Function (%)	ΔΔ (L=0)	97.18	33.11	98.01	31.22	97.71	32.51
	ΔΔ (L=2)	2.82	0.62	1.99	0.45	2.29	0.51
	CC (L=0)	0	66.25	0	68.33	0	66.98
	CC (L=2)	0	0.02	0	0.00	0	0.00

Wave Function





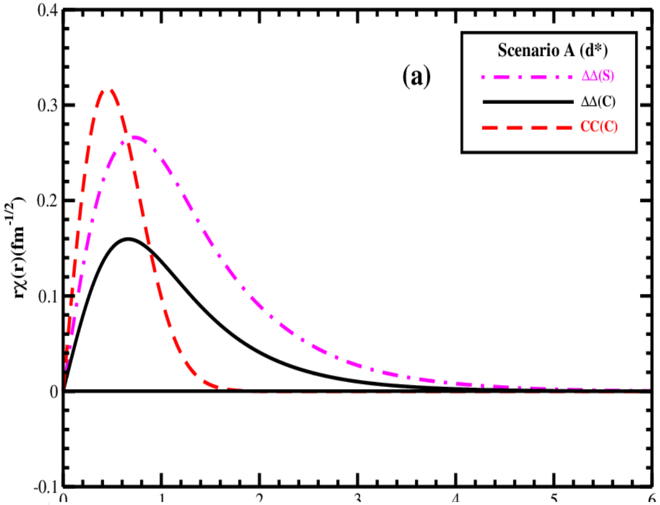
Charge Distribution



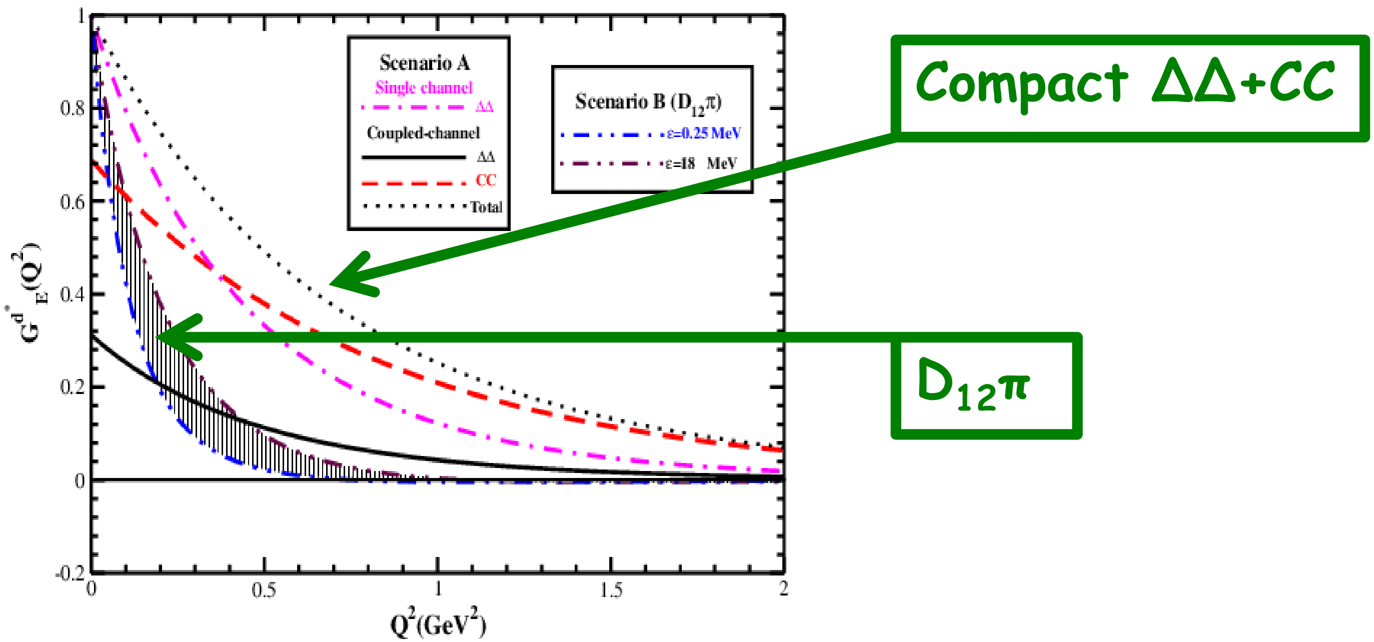
rms

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

Wave Function



Charge Distribution



rms

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