On the Study of Dibaryon d*(2380)

---calculations in quark model

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Outline

1, Observation of exotics, dibaryon d*(2380)

2, Possible interpretations

3, **Ours: Compact 6-quark dominanted structure in chiral constituent quark model

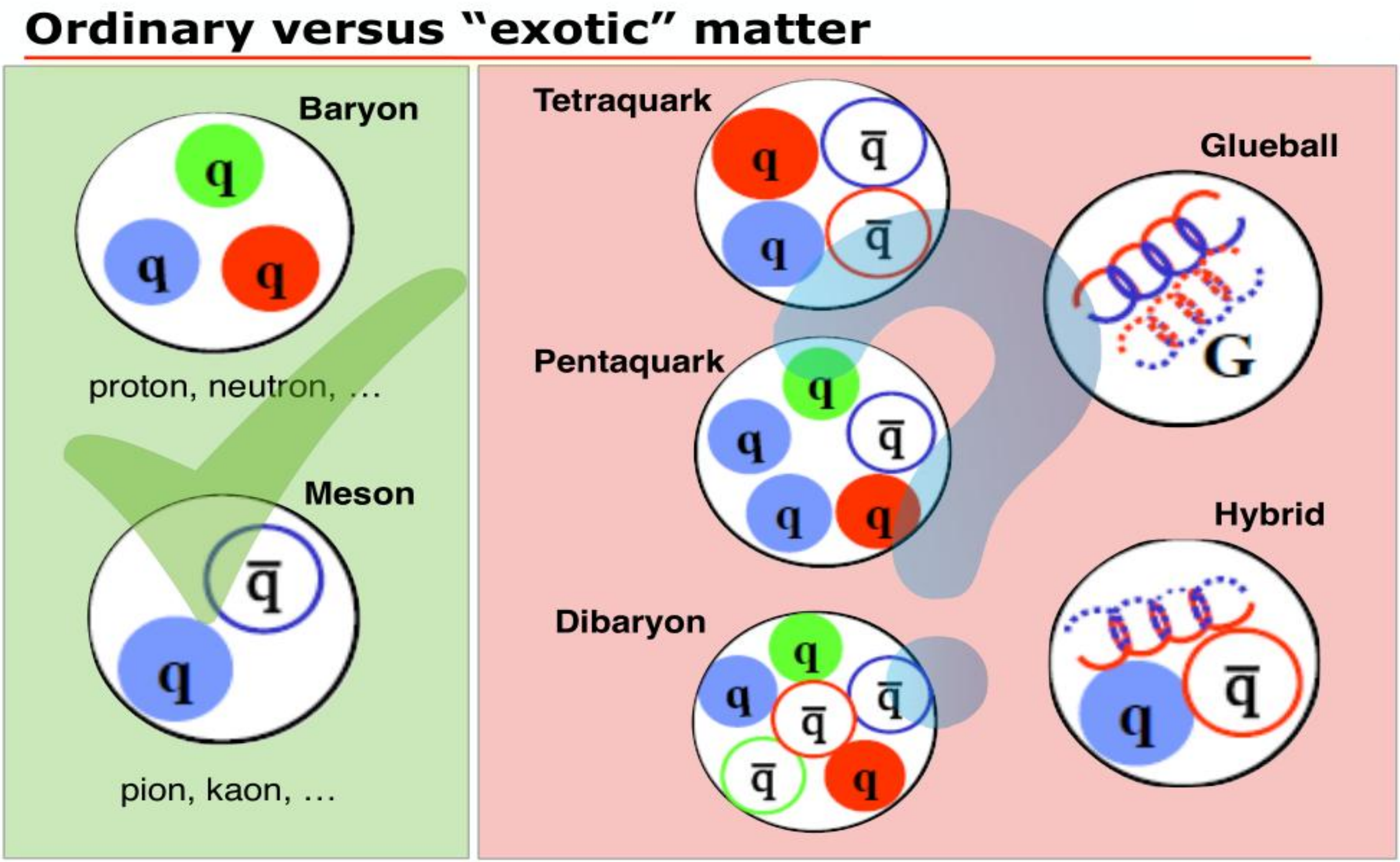
(A) Mass and wave function

(B) Strong decays

(C) Form factors

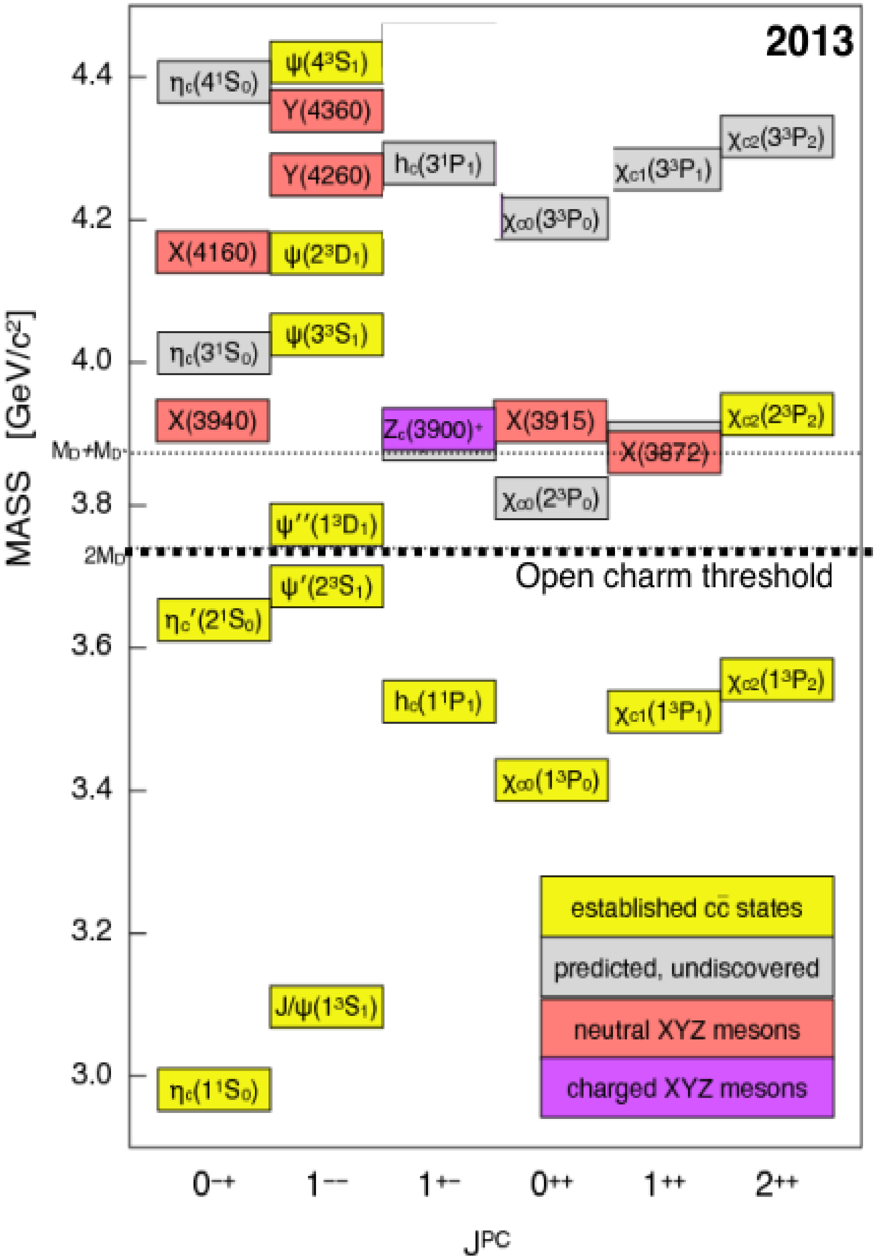
4, Summary and outlook

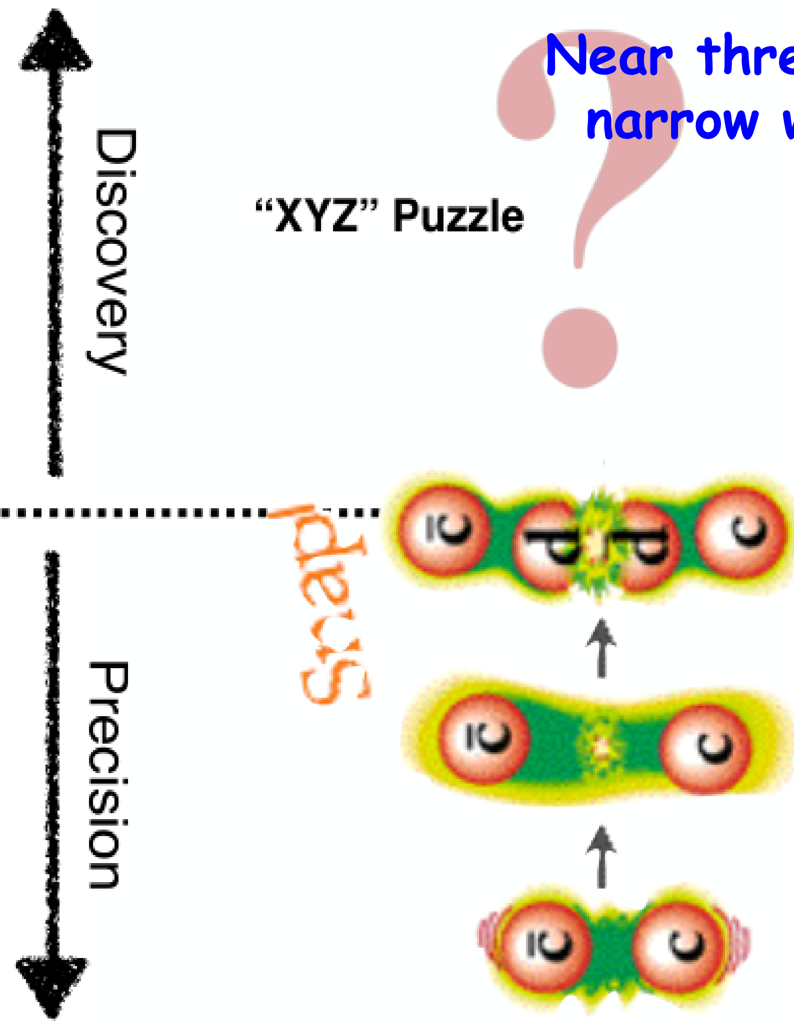
1, Observations of exotics



Courtesy of J. Messchendorp

Charmonium-like particles - XYZ states





Near threshold, narrow width

"XYZ" Puzzle

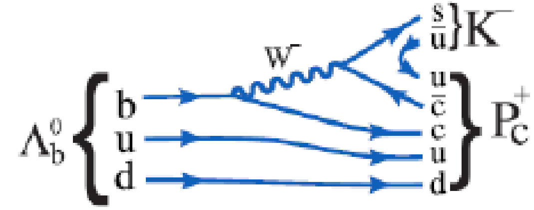
Courtesy of J. Messchendorp

Five-Quark

Pentaquark states Pc(4380)+, & Pc(4450)+: (2015)

LHCb, Phys.Rev.Lett. 115 (2015) 072001 :

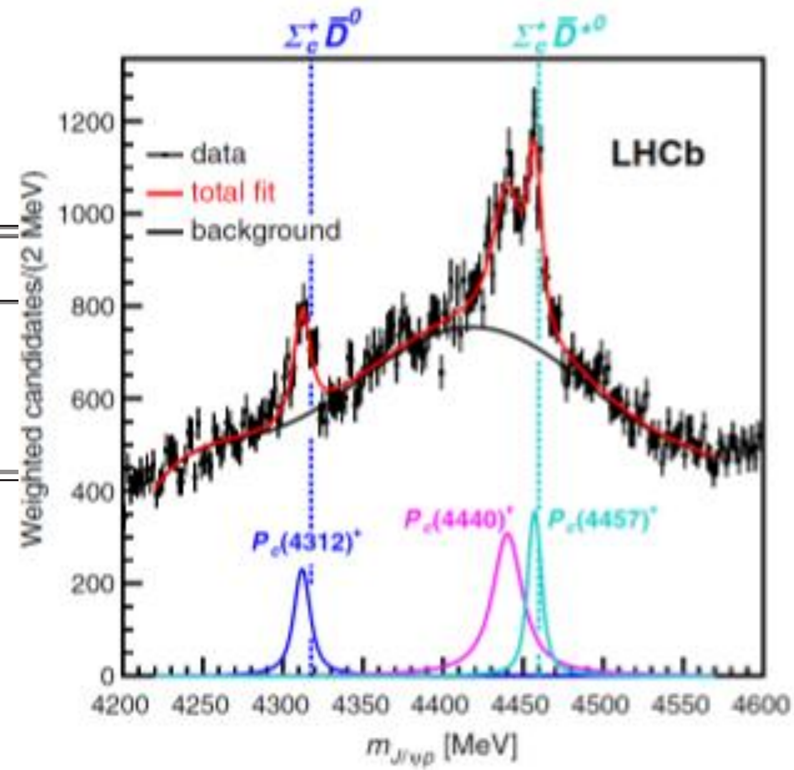
Observation of two N* from $\Lambda_b^0 \to J/\psi K^- p$



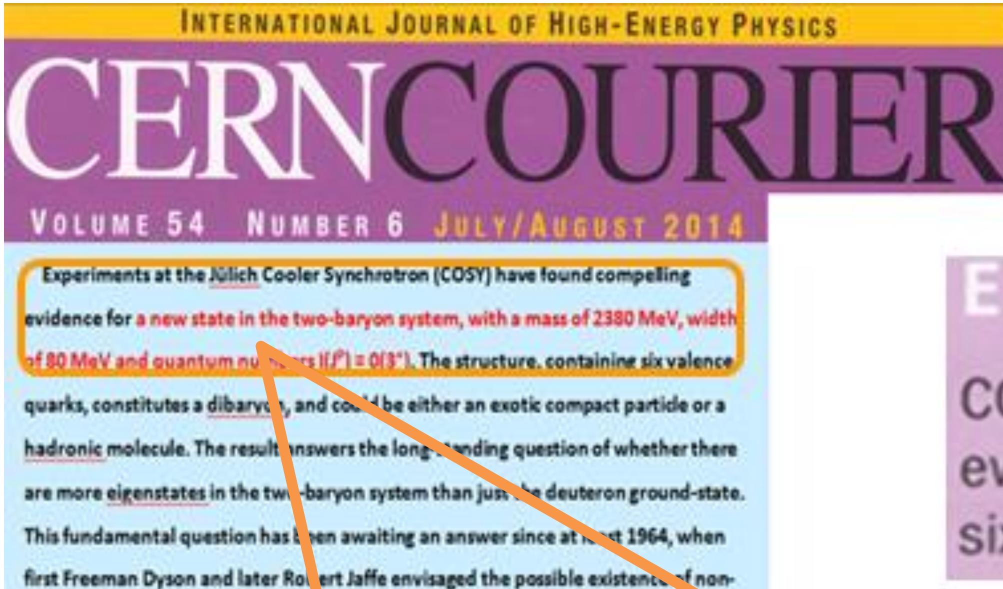
New observations: three resonances

LHCb, Phys.Rev.Lett. 122 (2019) 222001

State	M [MeV]	Γ [MeV]	(95% C.L.)
$P_c(4312)^+$	$4311.9 \pm 0.7^{+6.8}_{-0.6}$	$9.8 \pm 2.7^{+3.7}_{-4.5}$	(<27)
$P_c(4440)^+$	$4440.3 \pm 1.3^{+4.1}_{-4.7}$	$20.6 \pm 4.9^{+8.7}_{-10.1}$	(<49)
$P_c(4457)^+$	$4457.3 \pm 0.6^{+4.1}_{-1.7}$	$6.4 \pm 2.0^{+5.7}_{-1.9}$	(<20)



Observation: d*(2380)


INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

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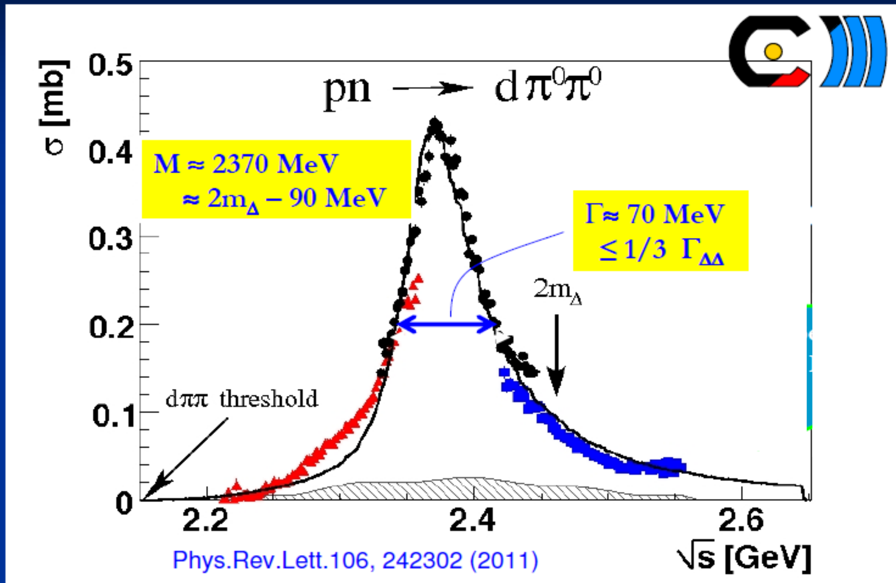
VOLUME 54 NUMBER 6 JULY/AUGUST 2014

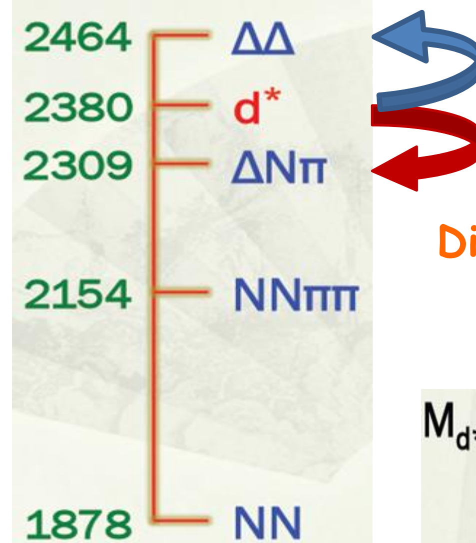
Experiments at the Jülich Cooler Synchrotron (COSY) have found compelling evidence for a new state in the two-baryon system, with a mass of 2380 MeV, width of 80 MeV and quantum nu[…]rs $I(J^P) = 0(3^+)$. The structure, containing six valence quarks, constitutes a dibaryo[…], and co[…] be either an exotic compact particle or a hadronic molecule. The result […]nswers the long-[…]nding question of whether there are more eigenstates in the tw[…]-baryon system than jus[…] the deuteron ground-state. This fundamental question has b[…]en awaiting an answer since at le[…]st 1964, when first Freeman Dyson and later Ro[…]ert 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

The d* Resonance $I(J^P) = 0(3^+)$





84MeV

71MeV

Different from Deuteron

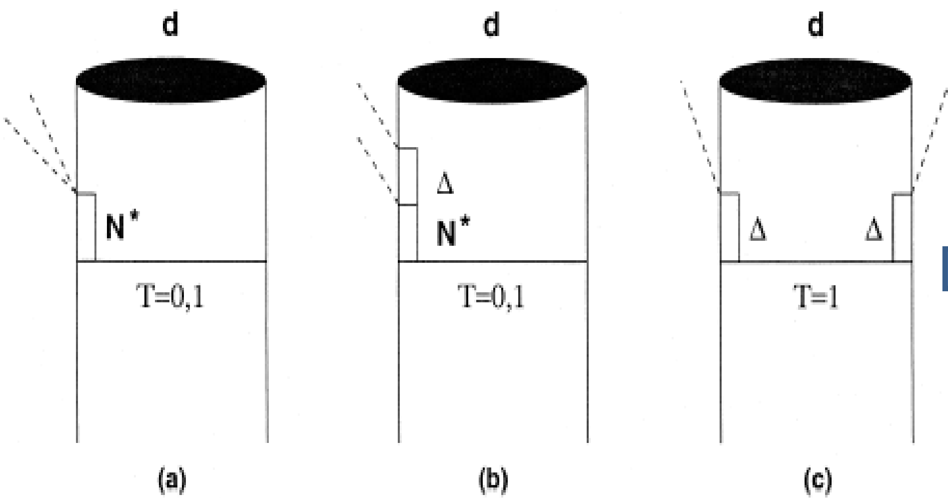
$M_{d^*} \approx 2380$ MeV
$\approx 2M_\Delta - 84$ MeV
$> M_{\Delta N\pi}$
$> M_{NN\pi\pi}$
$> M_{NN}$

$2\Gamma_\Delta \approx 230$ MeV

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

Unusual narrow width

Baryon number=2



Neither NN (Roper), nor ΔΔ Intermediate state

d*(2380)

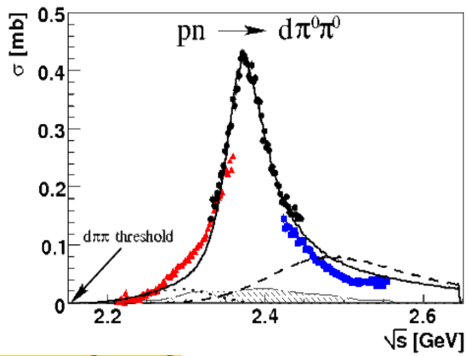
Signals in np procese @ COSY

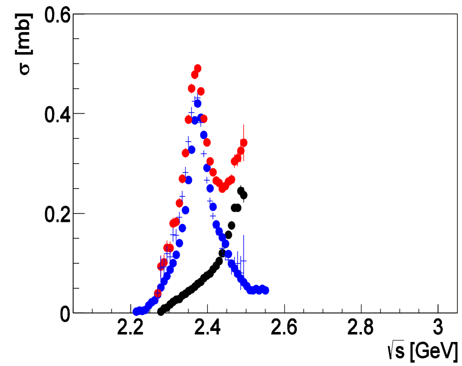
2π production processes

PRL 106 (2011) 242302

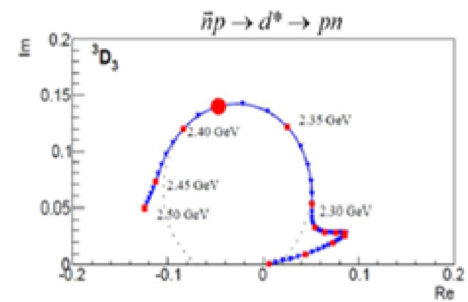
PLB 721 (2013) 229

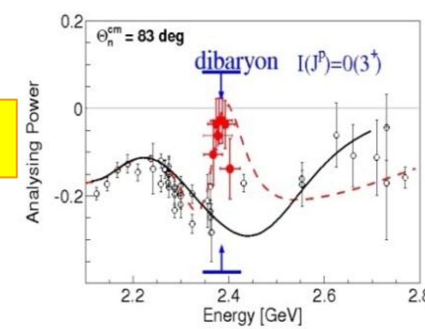
● ● ● WASA data





np scattering process





PRL 112 (2014) 202301

Fusion

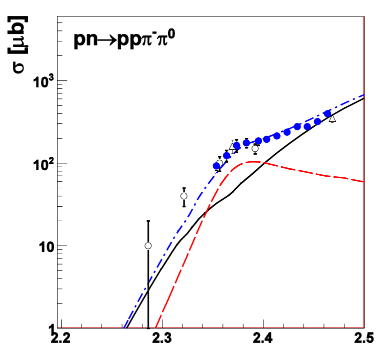
$d\pi^0\pi^0$ $d\pi^+\pi^-$

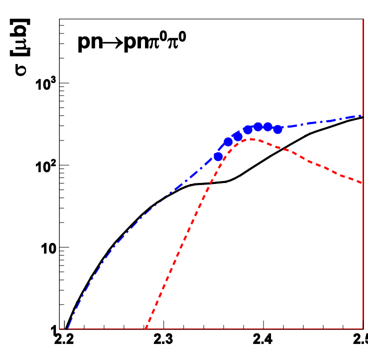
$pn \rightarrow d^*(2380)$

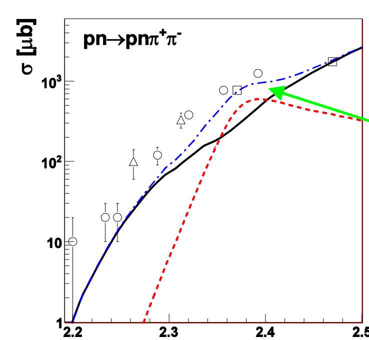
pn

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:

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

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

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

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

Characters of d*(2380)

- d* mass locates between $\Delta\Delta$ and $\Delta N\pi$ thresholds

  Effect from threshold is expected small

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

$M_{\Delta N\pi} = 2310\text{MeV}$

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

$M_{\Delta\Delta} = 2464\text{MeV}$

71MeV

84MeV

- d* narrow width → Possible 6q structure

  might be different

  from normal hadrons

Review article: by Heinz Clement, Progress in Particle and Nuclear Physics, 93 (2017), 195-142

2, Possible interpretations

▲ Before COSY's observations

d*(2380)

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

- Consists with COSY's measurement

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

Thomas (83) ----- bag model

Yuan (99) -------- ΔΔ+CC quark cluster model

Jaffe(77)

Swart(78)

Oka(80)

Maltman(85)

Goldman(89)

Wang (95)……

▲ After COSY's observations

- **Quark model**

J.Ping (09/14)-10 coupled channels QM

F.Huang,Y.B.Dong et al. (14-18)--ΔΔ+CC QM

Bashkanov, Brodsky, Clement (13) -- ΔΔ+CC

A. Compact 6q dominated dibayon state

- **Hadronic model**

Gal (14) ---ΔNπ

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

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

3, Compact 6q dominated d*(2380) in chiral constituent quark model

Quark model framework

PRC 60 (1999) 045203
CPC 39 (2015) 071001

SU(3) chiral QM + RGM approach

▲ **Interactions:** $\mathbf{V_{ij} = V_{ij}^{conf} + V_{ij}^{OGE} + V_{ij}^{ch} + V_{ij}^{chv}}$

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

Interactive Lagrangian

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

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

▲ Trial wave function of d*: $\mathbf{I(J^P) = 0(3^+)}$

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

6-quark RGM

$$\Delta: \quad (0s)^3\,[3]_{\rm orb}, S=3/2, I=3/2, C=(00),$$
$$C: \quad (0s)^3\,[3]_{\rm orb}, S=3/2, I=1/2, C=(11),$$

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

▲ Hadronization----Channel wave function:

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

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

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

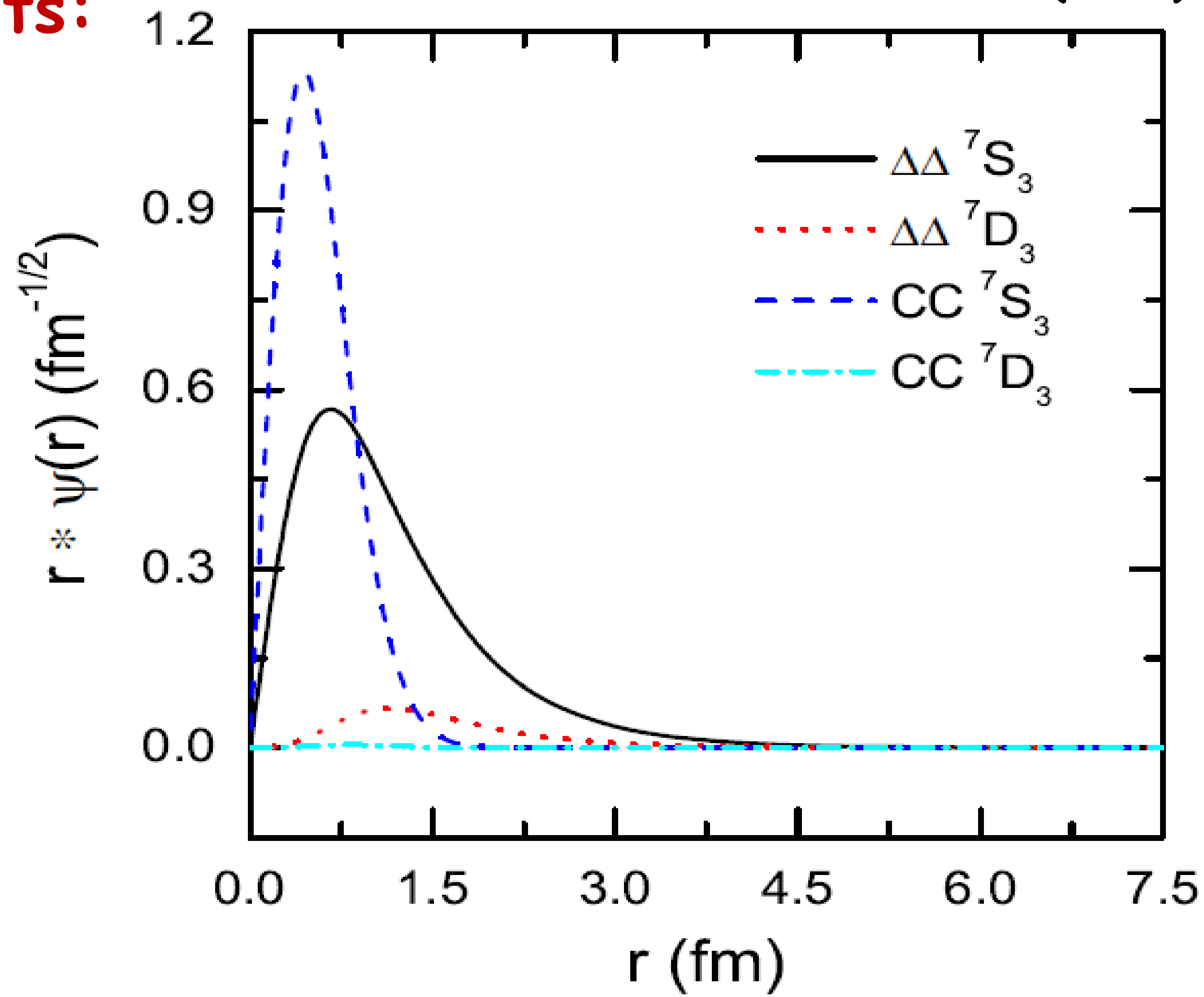
The two components are orthogonal due to the quark exchange effect

(A), Mass and wave function of d* $I(J^P) = 0(3^+)$

CPC 39 (2015) 071001

▲ **Results:**

d* (WFs)



- **Binding energy**

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

		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 ⟶ large CC component

⟶ d* deep bound and narrow width

d* might be a 6q dominant state!

(B), Strong decays

PRC91, (2015) 064002

PRC94, (2016) 014003

▲ 2π decay widths

Three-body decay

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

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

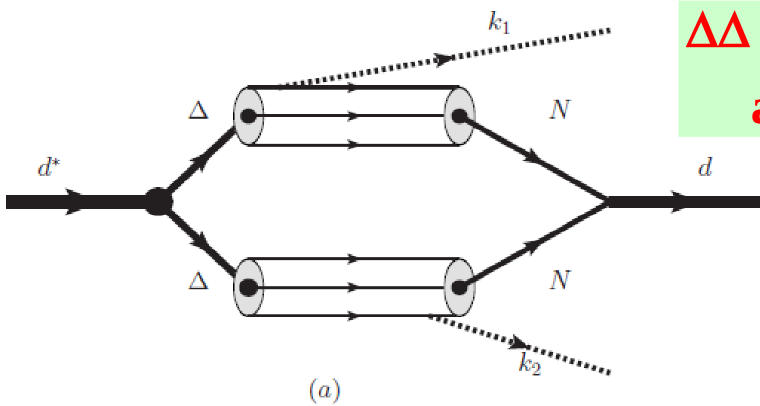
Four-body decay

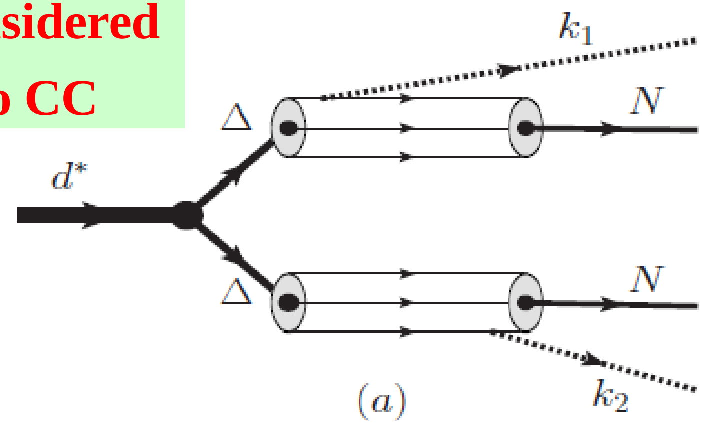
$d^* \to np\pi^0\pi^0 \ (np\pi^+\pi^-)$

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

Typical diagrams

ΔΔ is considered and no CC





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

	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

Discussions:

* FSI is about 26~30%

* Isospin breaking factor

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

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

Idearl

* 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

* All partial and total widths agree with data

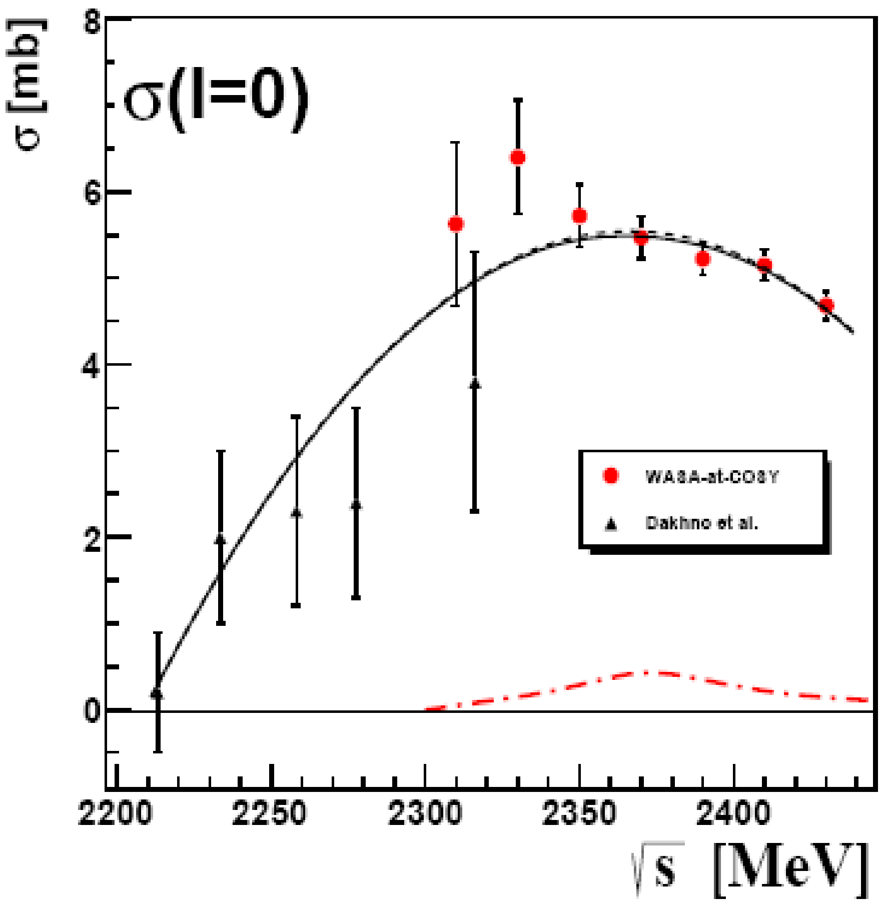
$$\Gamma^{exp't} = 70 \sim 75\, MeV$$

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

The narrow width is due to large CC component

▲ Single-π decay

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



- **Experimental status**

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

PLB774 (2017), 599-607

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

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

This channel might serve as a test!

- compact 6q dominated case:

PLB769 (2017) 223-226

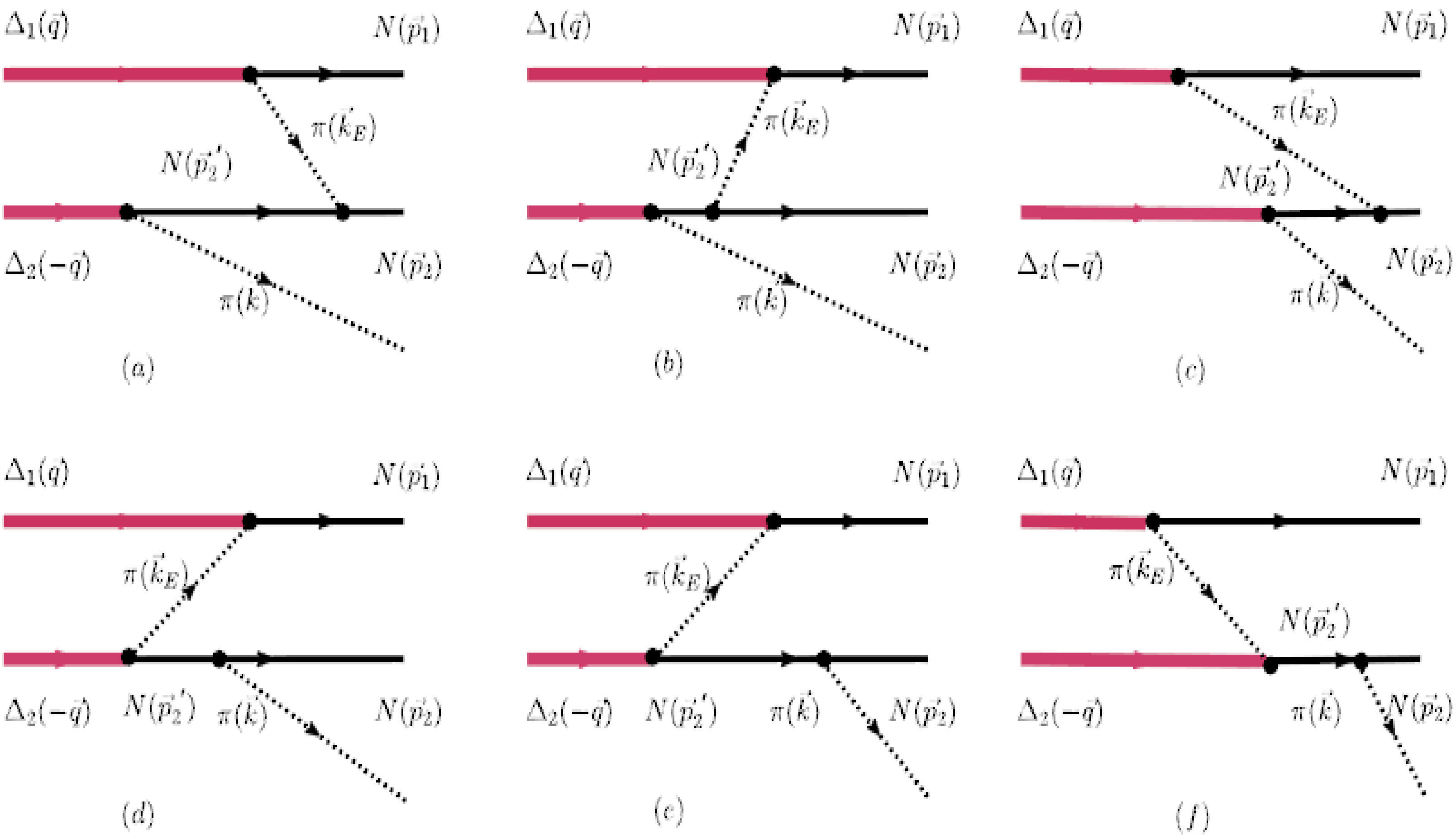
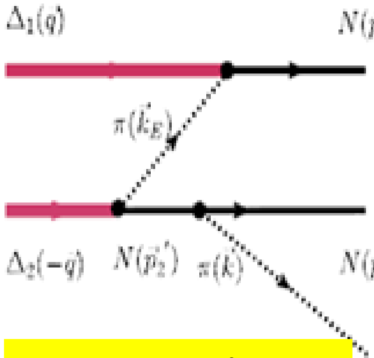


Fig. 1. Six possible ways to emit pion only from the $\Delta\Delta$ component of d^* in the $d^* \to NN\pi$ decay process. The outgoing pion with momenta $\vec{k}$ is emitted from Δ_2. The other six sub-diagrams with pion emitted from Δ_1 are similar, and then are not shown here for reducing the size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

Typical diagrams: one pion emitted from cluster II



Sample

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

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

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

Intermediate states: (N,N*,Δ,Δ*)

Low-lying resonances need to be 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, 1% is compatible with the Exp't upper-limits

(C). Form factors

Form factors: 2S+1 **relative to size** arXiv:1704.01253

Nucleon (1/2):

$$< N(p') \mid J_N^\mu \mid N(p) >= \bar{U}_N(p')\Big[F_1(Q^2)\gamma^\mu + i\frac{\sigma^{\mu\nu}q_\nu}{2M_N}F_2(Q^2)\Big]U(p),$$

$$G_E(Q^2) = F_1(Q^2) - \eta F_2(Q^2), \qquad G_M(Q^2) = F_1(Q^2) + F_2(Q^2),$$

Breit frame

$$< N(\vec{q}/2) \mid J_N^0 \mid N(-\vec{q}/2) > \; = \; (1+\eta)^{-1/2}\chi_{s'}^+\chi_s G_E(Q^2)$$

$$< N(\vec{q}/2) \mid \vec{J}_N \mid N(-\vec{q}/2) > \; = \; (1+\eta)^{-1/2}\chi_{s'}^+\frac{\vec{\sigma}\times\vec{q}}{2M_N}\chi_s G_M(Q^2).$$

Deuteron (1):

$$J^\mu_{jk}(p',p) = \epsilon_j'^{*\alpha}(p')S^\mu_{\alpha\beta}\epsilon_k^\beta(p)$$

$$S^\mu_{\alpha\beta} = -\Big[G_1(Q^2)g_{\alpha\beta} - G_3(Q^2)\frac{Q_\alpha Q_\beta}{2m_D^2}\Big]P^\mu - G_2(Q^2)(Q_\alpha g^\mu_\beta - Q_\beta g^\mu_\alpha)\ ,$$

$$G_C(Q^2) \; = \; G_1(Q^2) + \frac{2}{3}\eta_D G_2(Q^2)\ , \qquad G_M(Q^2) = G_2(Q^2)\ ,$$

$$G_Q(Q^2) \; = \; G_1(Q^2) - G_2(Q^2) + (1+\eta_D)G_3(Q^2)\ ,$$

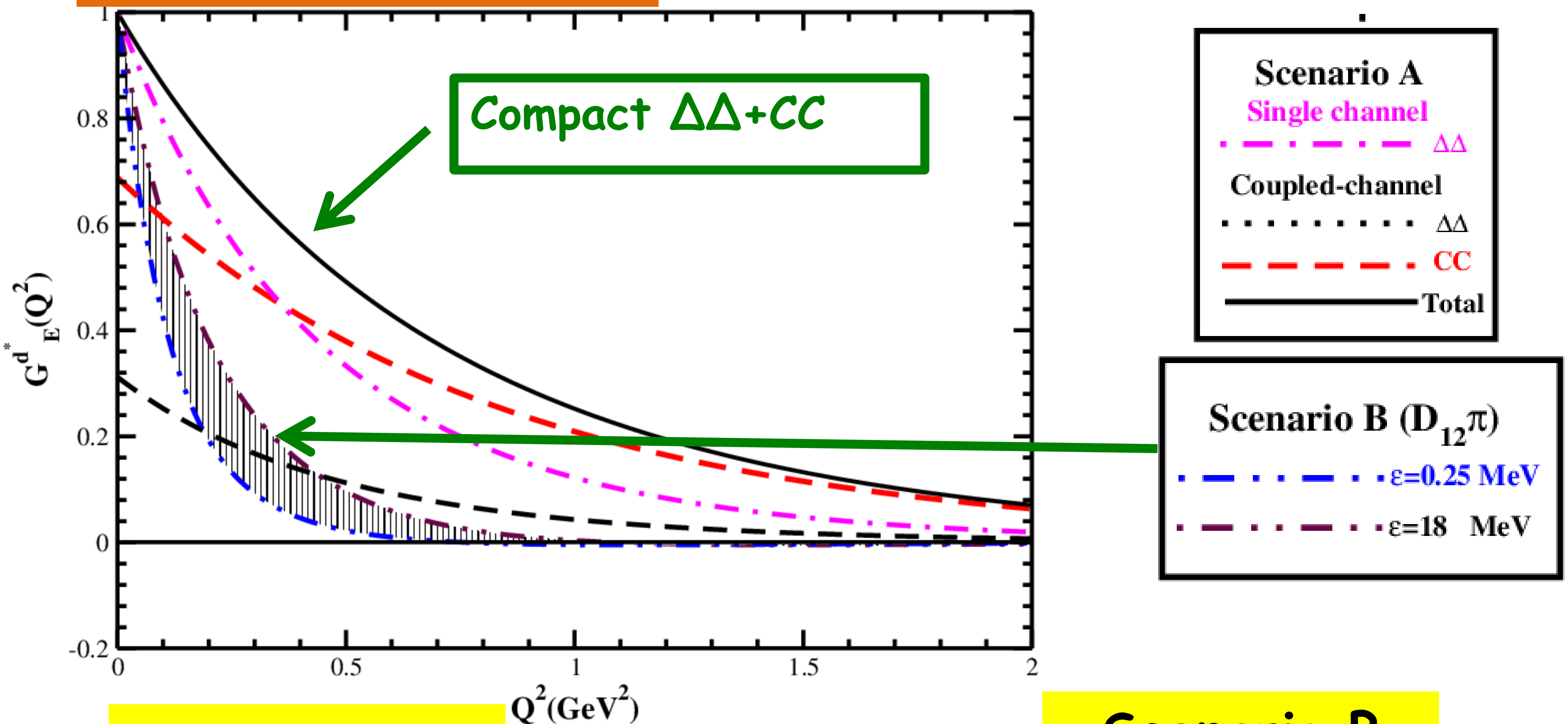
Breit frame

$$G_C(Q^2) \longrightarrow \tfrac{1}{3}\textstyle\sum_\lambda < p', \lambda \mid J^0 \mid p, \breve{\lambda} >.$$

Form factors of d*(2380), spin=3 system
2S+1=7 form factors

PRD96 094001 (2017)

Charge Distributions (related to the size of system)



Scenario A

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

rms

Scenario B

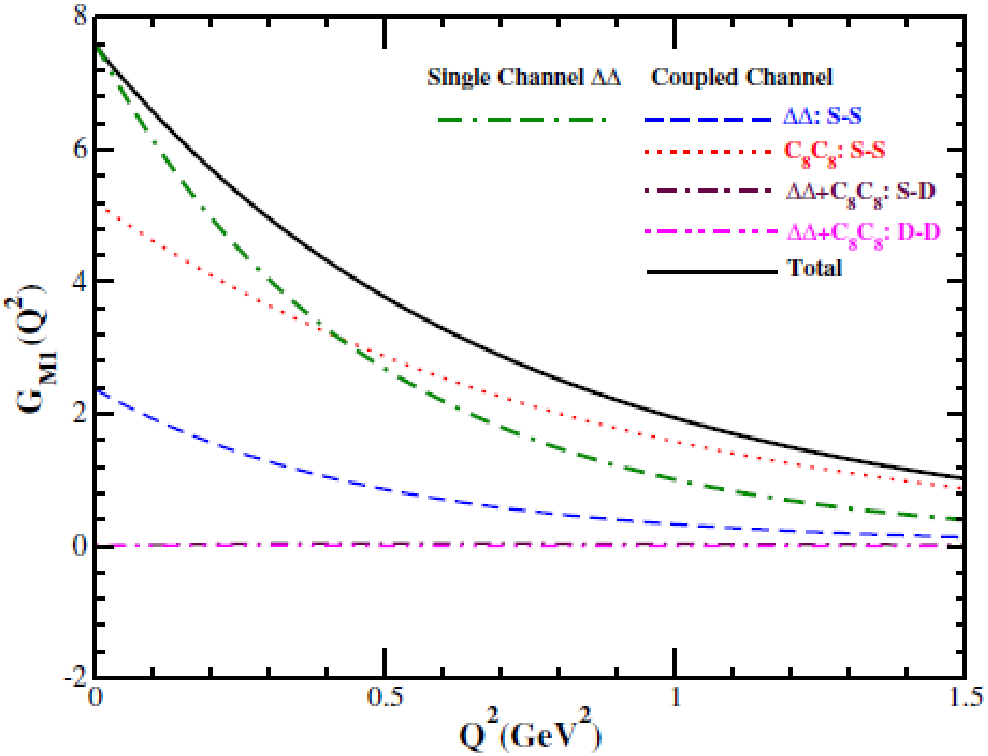
D_{12}		
Cases	B1	B2
rms (fm)	2.64	1.87

Magnetic Moment

Naïve quark model Nucleon $\frac{\mu_p}{\mu_n} = -\frac{3}{2} \rightarrow -\frac{2.79}{1.91}_{EXPT.}$

d*(2380) ΔΔ+CC $\mu_{d*} = \frac{M_{d*}}{m_q} \approx 7.6$

d*(2380) $D_{12}\pi$ $\mu_{d*} = \frac{2M_{d*}}{3m_q} \approx 5.1$



The magnetic dipole form factor $M1$ of d^*.

$$G_{M1}^{NCQM}(0) = [\mathcal{P}^S_{\Delta\Delta} + \mathcal{P}^S_{C_8C_8}]\frac{3M_{d^*}}{M_N} \sim \frac{3M_{d^*}}{M_N} = 7.62,$$

$$R^{\Delta\Delta}_{C_8C_8} = \frac{G^{\Delta\Delta}_{M1}}{G^{C_8C_8}_{M1}} = \frac{2.37}{5.20} = 0.4558,$$

$$-\frac{d}{dQ^2}G^{\Delta\Delta}_{M1}(Q^2)\Big|_{Q^2\to 0} = 5.014\,\text{GeV}^{-2} = 0.195\,\text{fm}^2,$$

$$-\frac{d}{dQ^2}G^{C_8C_8}_{M1}(Q^2)\Big|_{Q^2\to 0} = 6.139\,\text{GeV}^{-2} = 0.239\,\text{fm}^2,$$

4、Summary and outlook

d*: Hexaquark dominated state :
(CC: component ~ 66-68% in ΔΔ+CC)

Compact 6q dominated — Dong et al., PLB769 (2017) 223

ΔNπ (or $D_{12}\pi$) system — A.Gal, PLB769 (2017) 436

Good ← **Mass / Double-pion strong decays** → Good

d*(2380) single-π decay Exp't BR ≤ 9% $d^*(2380) \to NN\pi$

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

the resultant BR for ΔNπ (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 $\Gamma_< = 44\ \text{MeV} \qquad \alpha = \frac{5}{7}$

BR can be 9%

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}]

- $e^+ + e^- \rightarrow \bar{d}^* + p + n$ Processes (Belle?)

If the d* is further confirmed by experiments, Our interpretation looks reasonable. Thus, it might be a state with 6q structure dominant and moreover, the more information about the short range interaction is expected.

Thanks !

BACKUP SLICES

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

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

Decay widths

Three-body decay

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

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

Four-body decay

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

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

⟺ FSI

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

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

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