A study of d*(2380) resonance

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IV International conference of particle physics and astrophysics

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3、 Compact 6-quark dominanted structure in chiral constituent quark model

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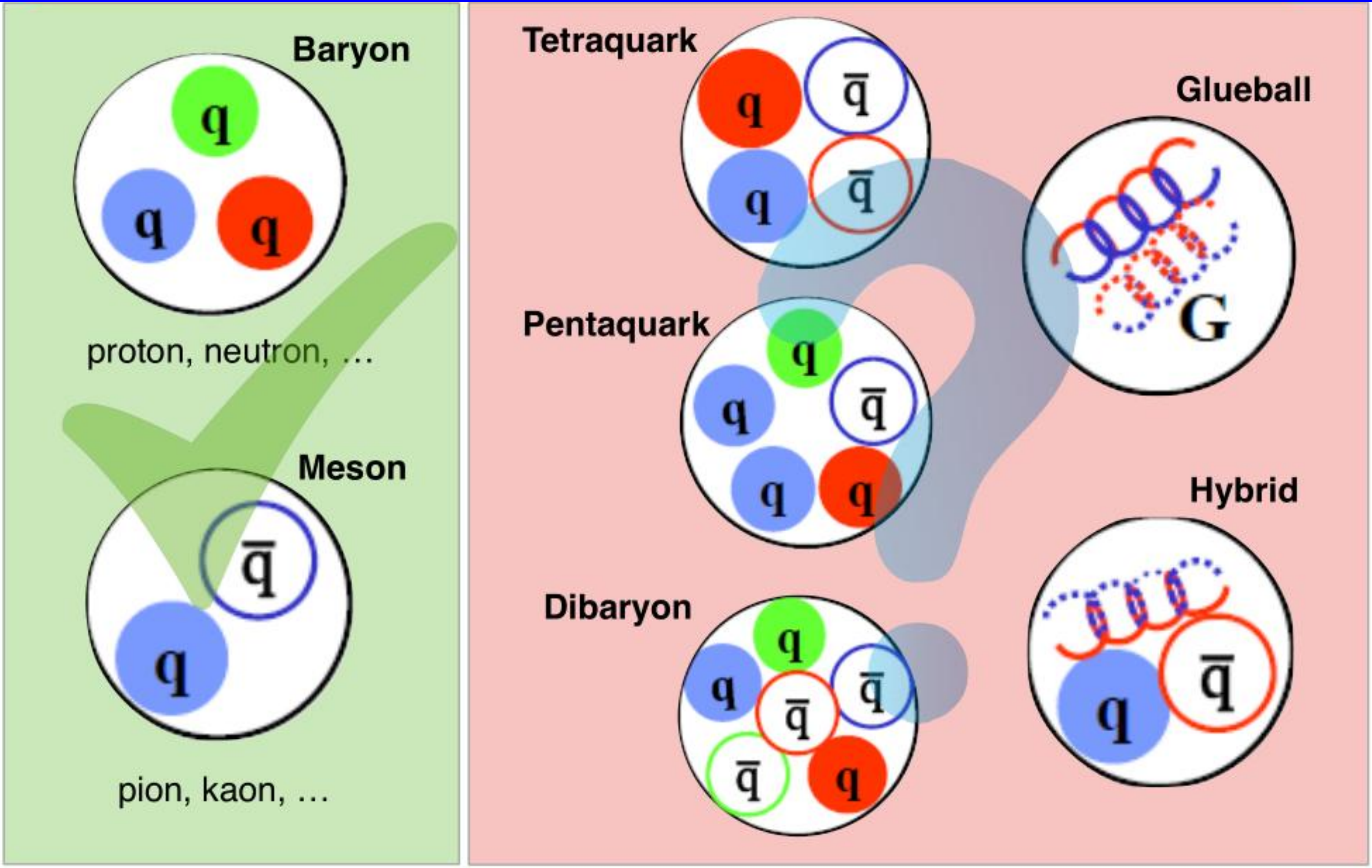
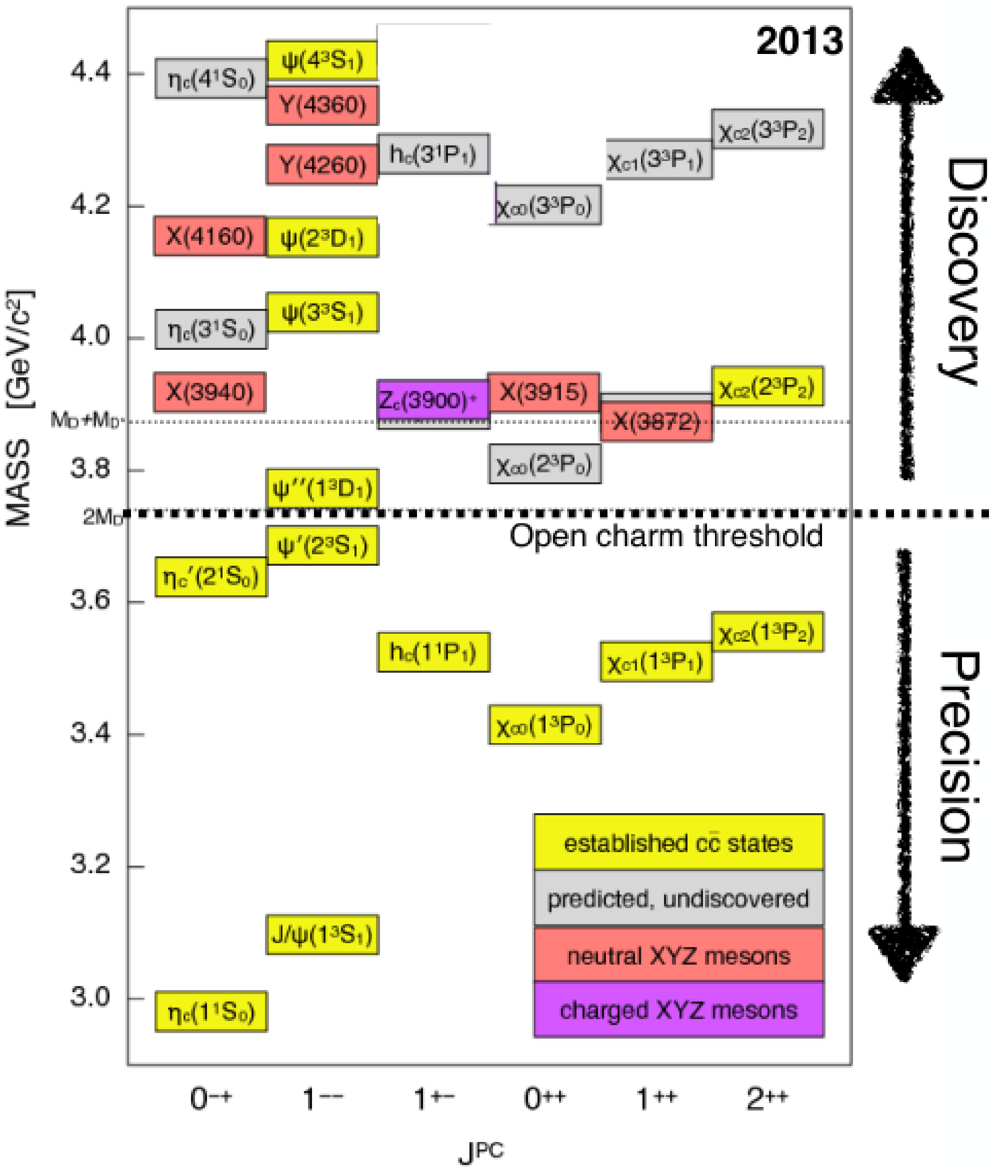
Ordinary or exotic



Charmonium-like particles - Exotic XYZ states



Example from Barnes, Godfrey, Swanson:

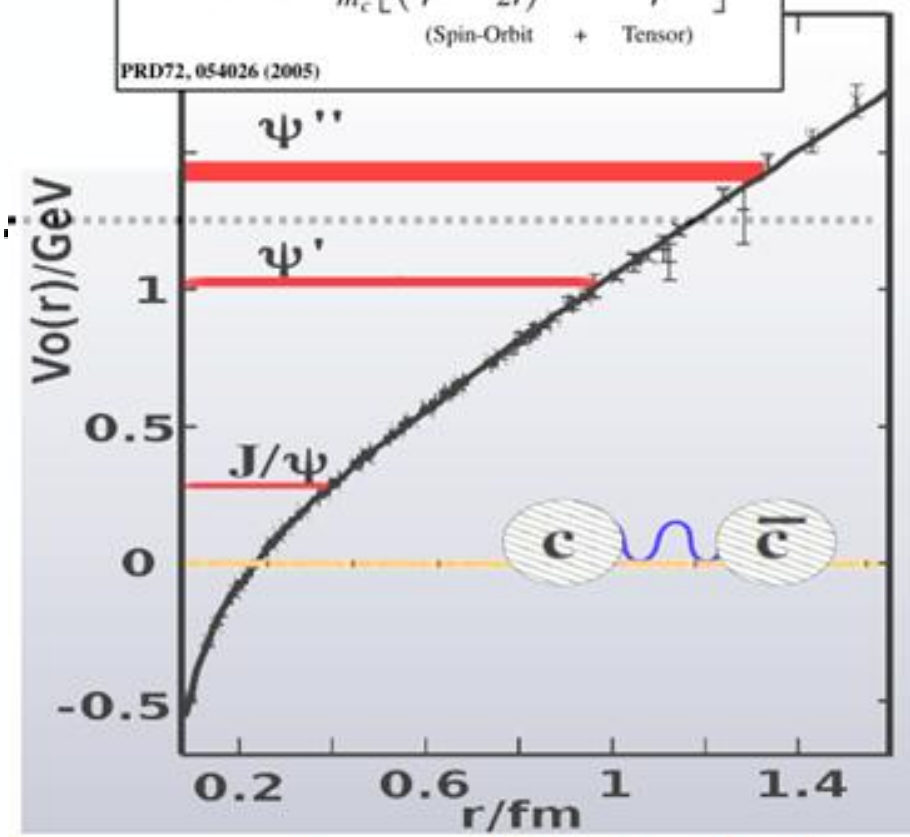
$$V_0^{(c\bar{c})}(r) = -\frac{4}{3}\frac{\alpha_s}{r} + br + \frac{32\pi\alpha_s}{9m_c^2}\tilde{\delta}_\sigma(r)\vec{S}_c \cdot \vec{S}_{\bar{c}}$$

(Coulomb + Confinement + Contact)

$$V_{\text{spin-dep}} = \frac{1}{m_c^2}\left[\left(\frac{2\alpha_s}{r^3} - \frac{b}{2r}\right)\vec{L}\cdot\vec{S} + \frac{4\alpha_s}{r^3}T\right]$$

(Spin-Orbit + Tensor)

PRD72, 054026 (2005)



(New resonances, Five-Quark)

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

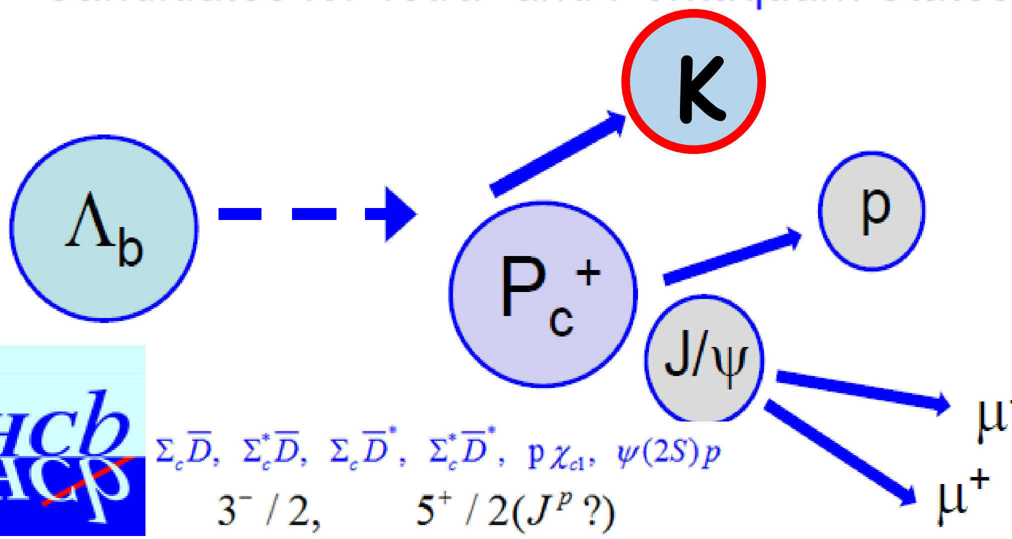
Observation of J/ψp resonances consistent with pentaquark states

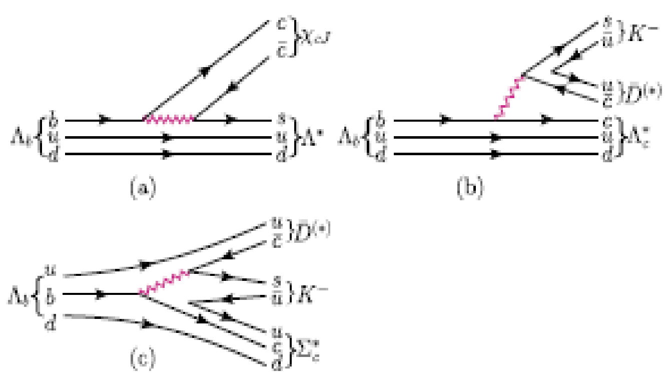
PRL 115. 07201. arXiv:1507.03414

Exotic Hadron Spectroscopy at LHCb:

Candidates for Tetra- and Pentaquark States

$$b \rightarrow c + \bar{c}s$$



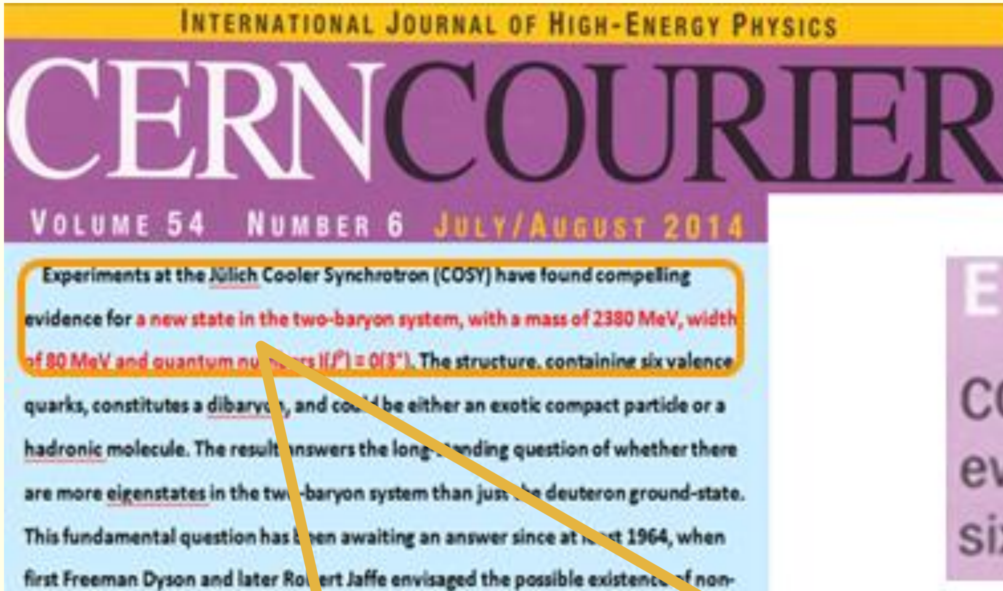


$\Sigma_c\bar{D},\ \Sigma_c^*\bar{D},\ \Sigma_c\bar{D}^*,\ \Sigma_c^*\bar{D}^*,\ p\,\chi_{c1},\ \psi(2S)p$

$3^-/2,\qquad 5^+/2(J^P\,?)$

$P_c(4380),\qquad P_c'(4449)$

1,Observation of d*(2380)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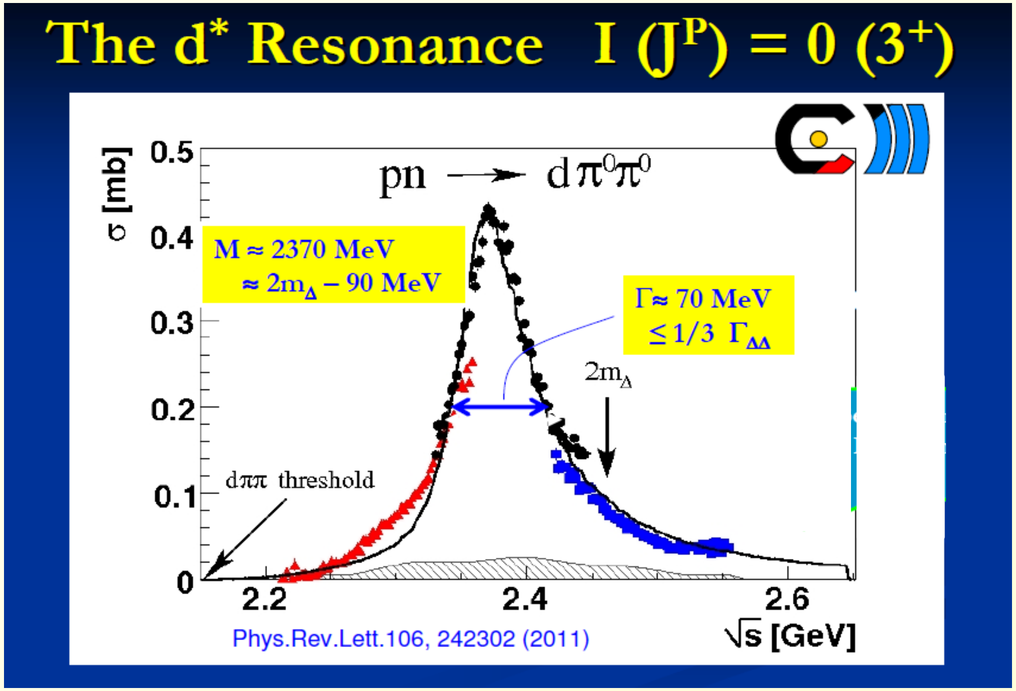
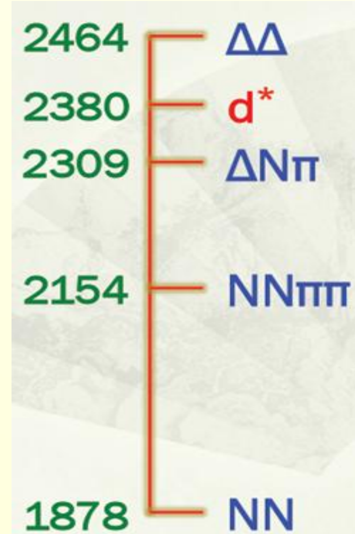
VOLUME 54 NUMBER 6 JULY/AUGUST 2014

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 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





84MeV

71MeV

Baryon number=2

Unusual narrow width

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

$\approx 2M_\Delta - 84$ MeV

$> M_{\Delta N\pi}$

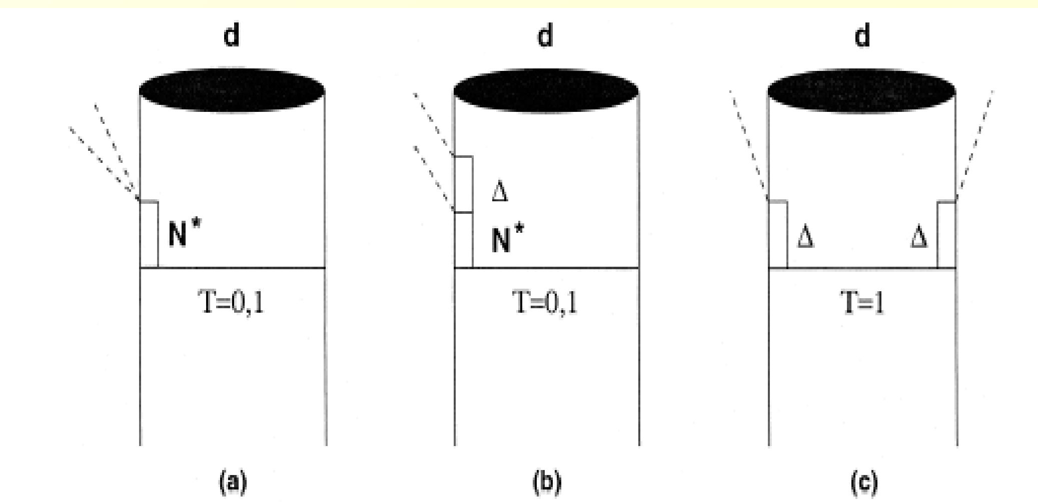
$> M_{NN\pi\pi}$

$> M_{NN}$

$2\Gamma_\Delta \approx 230$ MeV

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

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



Neither NN (Roper),

nor ΔΔ

Intermediate state

d*(2380)

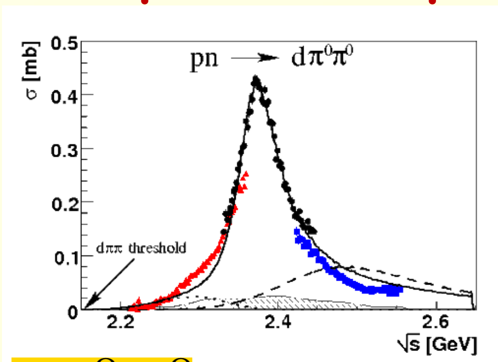
Signals in np procese @ COSY

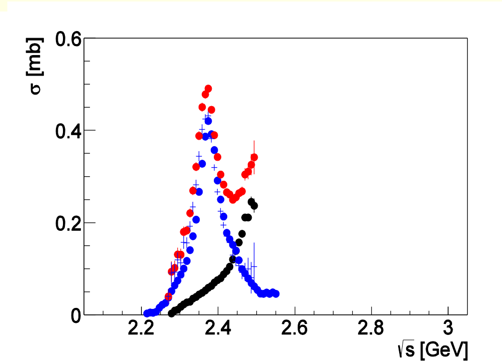
2π production processes

PRL 106 (2011) 242302

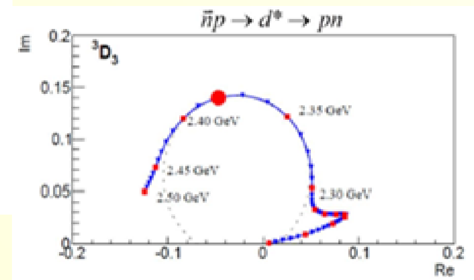
PLB 721 (2013) 229

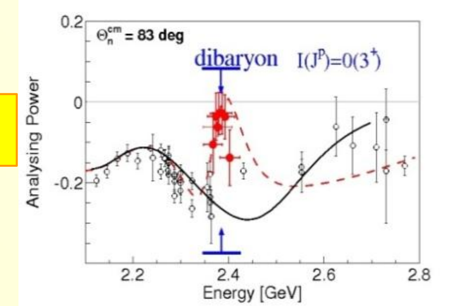
WASA data





np scattering process





Fusion

$d\pi^0\pi^0$

$d\pi^+\pi^-$

pn → d*(2380)

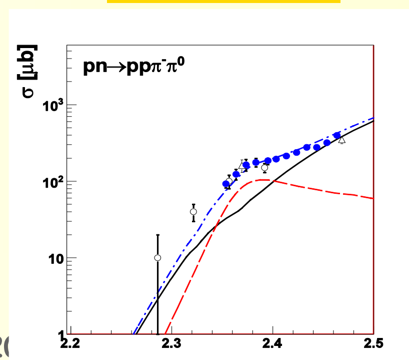
pn

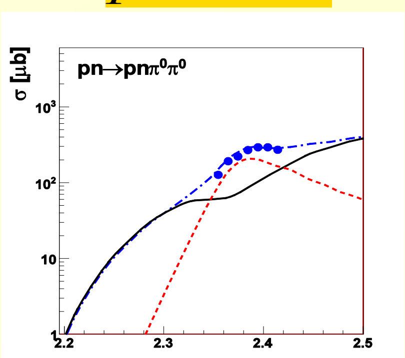
Non-fusion

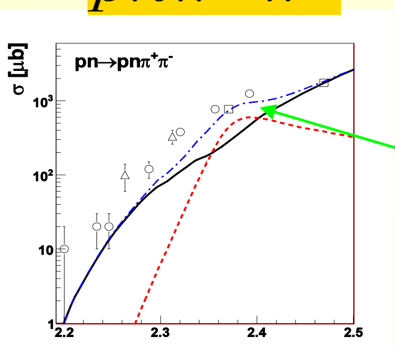
$pp\pi^-\pi^0$

$pn\pi^0\pi^0$

$pn\pi^+\pi^-$







PRL 112 (2014) 202301

HADES

PRC 88 (2013) 055208

PLB 743 (2015) 325

Proc. STORI 2015

Measured also in fusion reactions to helium isotopes:

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

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

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

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

Signals in other reactions @ COSY

fusion 2π processes

Characters of d*(2380) $I(J^P) = 0(3^+)$

- 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

d*(2380)

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

▲ Before COSY's observation

- Consists with COSY's measurement

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

Thomas(83) ----- bag model

Yuan(99) ------- ΔΔ+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 channels QM

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

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

A. Compact 6q dominated exotic state

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

- ***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

(A)Mass and wave function

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

SU(3) chiral QM + RGM approach

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

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

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

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

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

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

▲ Hadronization----Channel wave function:

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

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

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

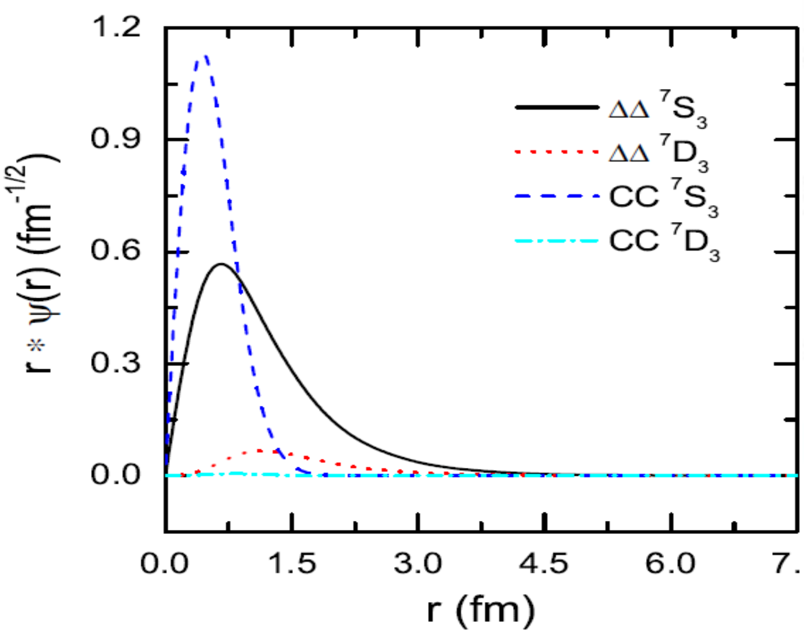
The two components are orthogonal due to the quark exchange effect

▲ Results:

Wave function

CPC 39 (2015) 071001

d* WFs



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

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

- **Binding energy**

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

		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%)

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

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

1). Intrinsic character of d* ----- $\langle P^{sfc}_{36} \rangle$

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

▲ 2π decay widths

PRC91, (2015) 064002

PRC94, (2016) 014003

Three-body decay

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

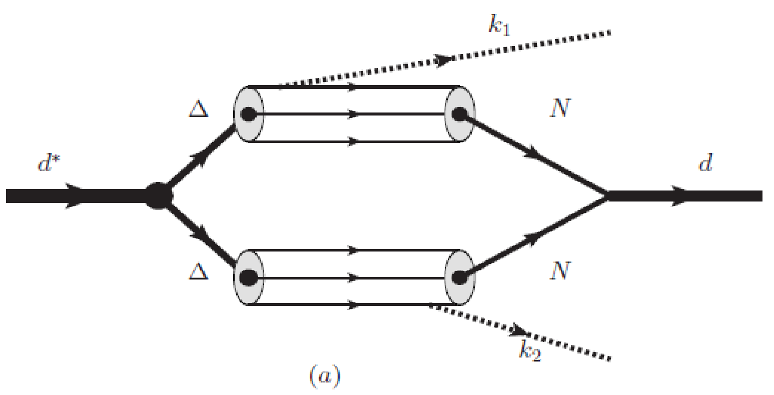
$d^* \to pp\pi^-\pi^0$

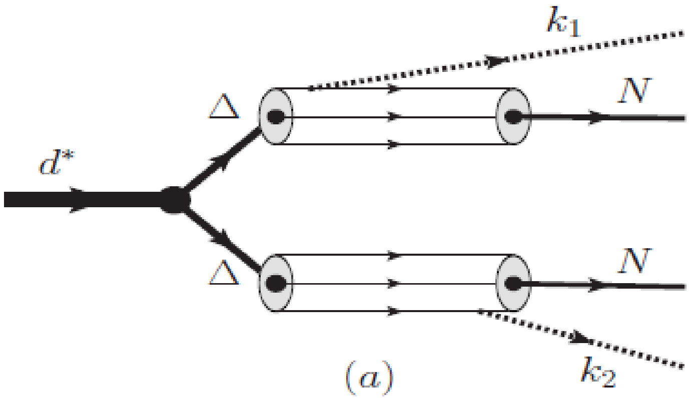
Typical diagrams

Four-body decay

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

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





Parameter:

$q q \pi$ **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

* 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

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

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

Idearl

* All partial and total widths agree with data

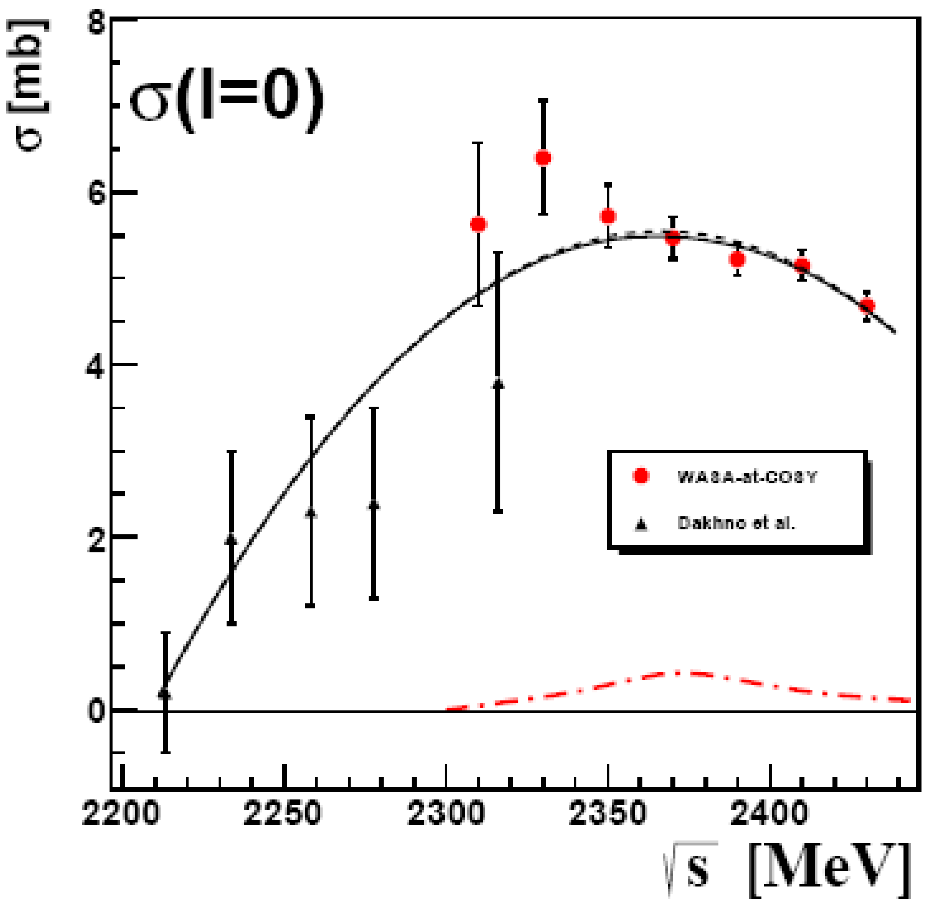
$$\Gamma^{exp't} = 70 \sim 75\, MeV$$

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

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 for different interpretations,

since the result of the ΔπN (or $D_{12}\pi$) is about 18%.

• Theoretical status

▸ compact 6q dominated case:

PLB769 (2017) 223-226

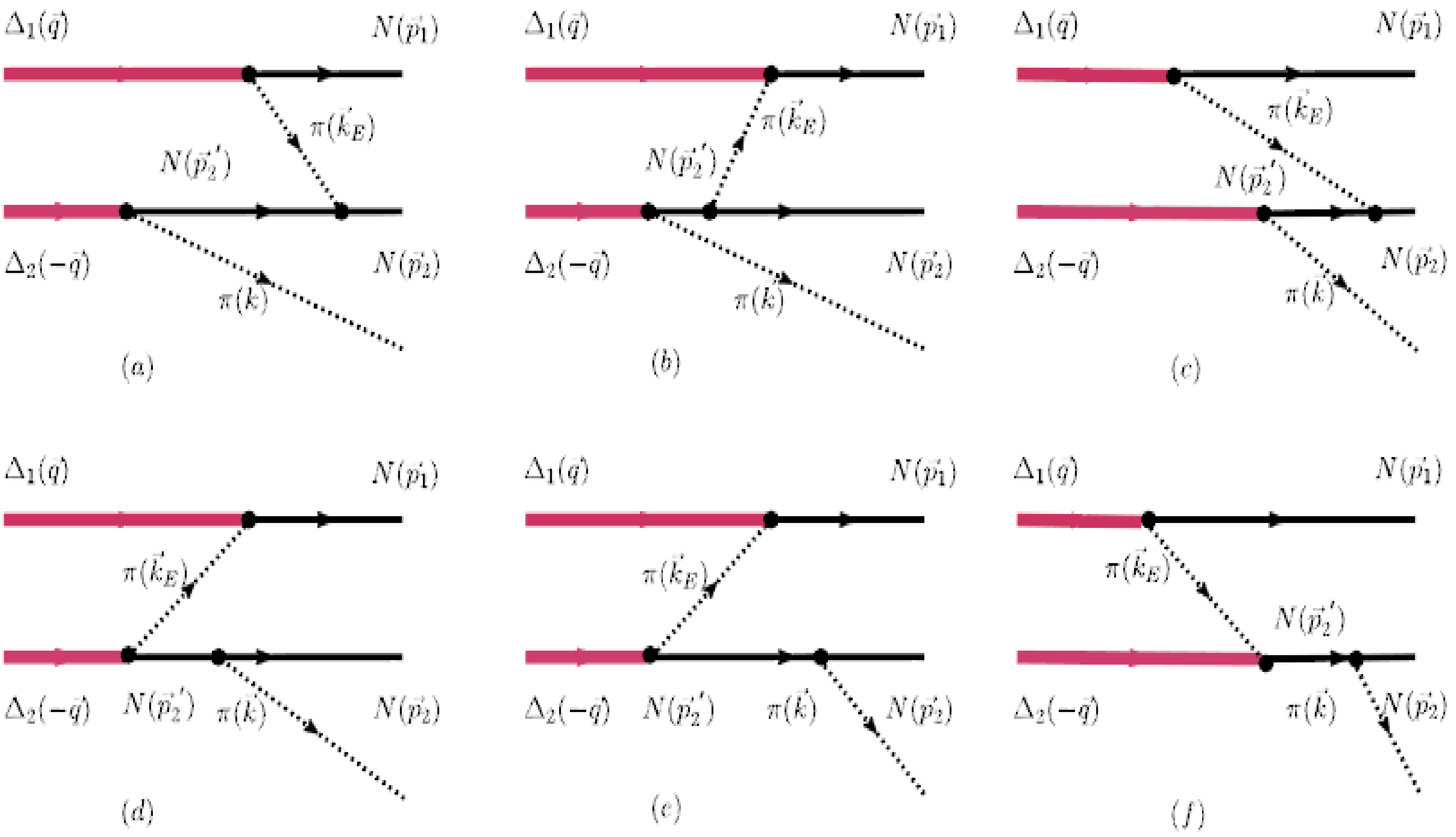
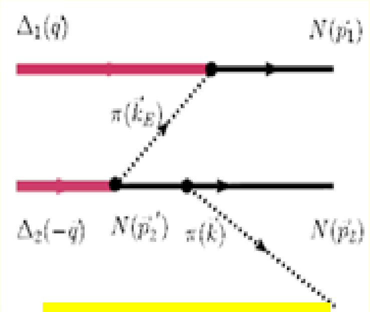


Fig. 1. Six possible ways to emit pion only from the $\Delta\Delta$ component of d^* in the $d^* \to NN\pi$ decay process. The outgoing pion with momenta $\vec{k}$ is emitted from Δ_2. The other six sub-diagrams with pion emitted from Δ_1 are similar, and then are not shown here for reducing the size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

Typical diagrams: pion emitted from cluster II



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

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

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

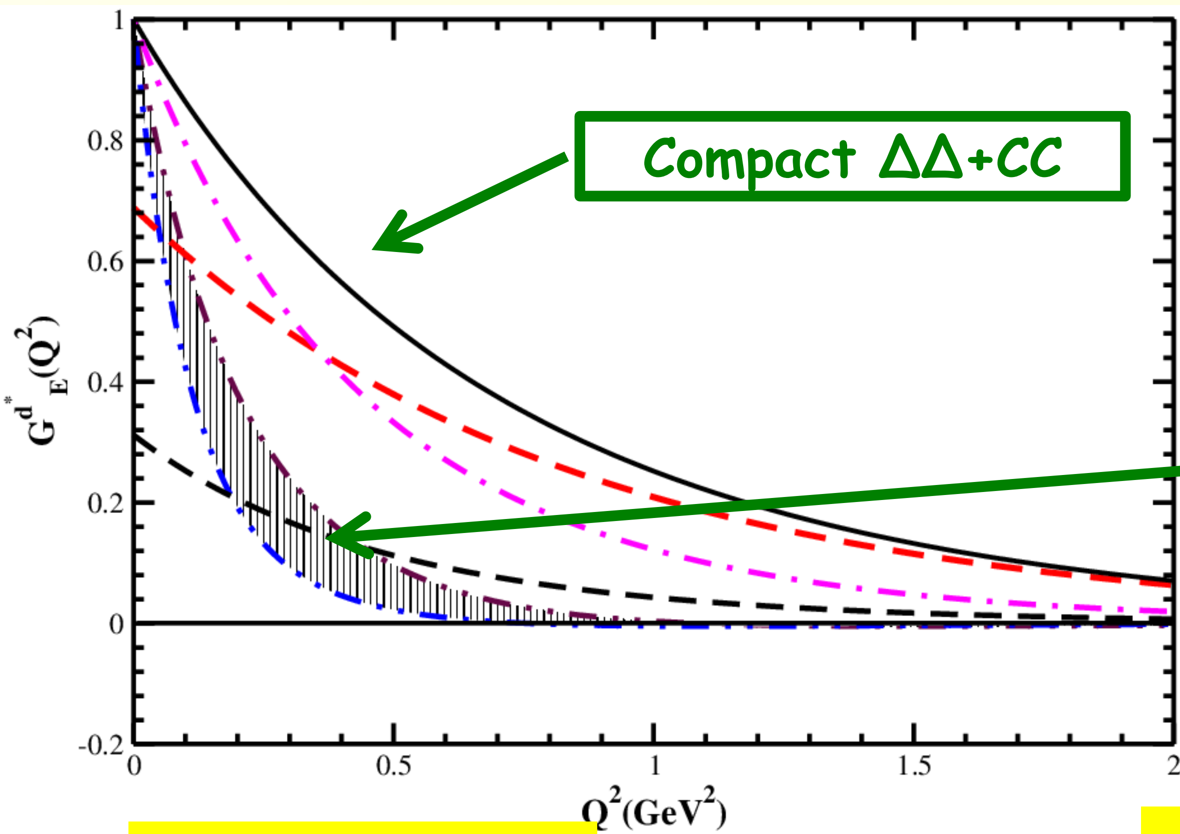
The suppressions enable to ignore the contribution from the CC component in d*

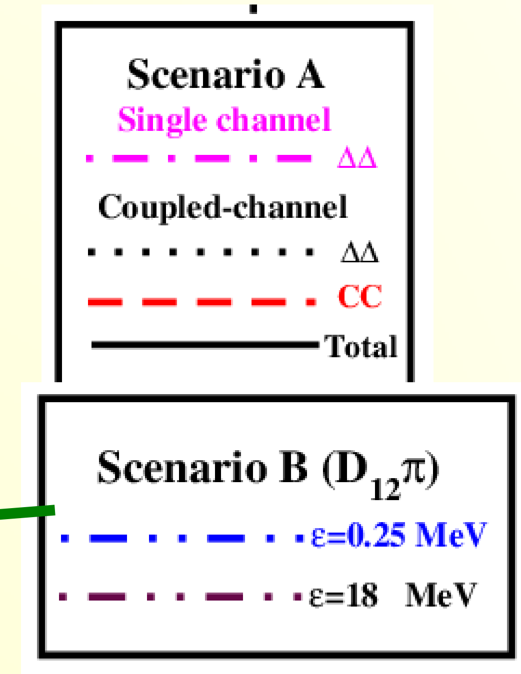
Our prediction, 1% is compatible with the Exp't upper-limits

C, Form factors (charge distributions)

2S+1=7 form factors

PRD96 094001 (2017)





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

4、Summary and Remarks

d*: Hexaquark dominated state :

(CC component ~ 66-68% in ΔΔ+CC)

Compact 6q dominated

PLB769 (2017) 223

ΔNπ (or $D_{12}\pi$) system

A.Gal, PLB769 (2017) 436

Good ← **Mass** → Good

Double-pion strong decays

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

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

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

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

BR can be 9%

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 !

Decay widths

Three-body decay

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

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

Four-body decay

$$\Gamma_{d^*\to pn\pi^0\pi^0} = \frac{1}{2!2!}\int d^3k_1d^3k_2d^3p_1(2\pi)\delta(\Delta E) \times |\,\overline{\mathcal{M}(k_1,k_2;p_1)}\,|^2$$

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

$\Longleftrightarrow$ FSI

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

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

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

C, Form factors (charge distributions)

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

Nucleon(1/2):

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

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

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):

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

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

$$G_C(Q^2) \;=\; G_1(Q^2) + \frac{2}{3}\eta_D G_2(Q^2)\ , \qquad G_M(Q^2) = G_2(Q^2)\ ,$$
$$G_Q(Q^2) \;=\; G_1(Q^2) - G_2(Q^2) + (1+\eta_D)G_3(Q^2)\ ,$$

Breit frame

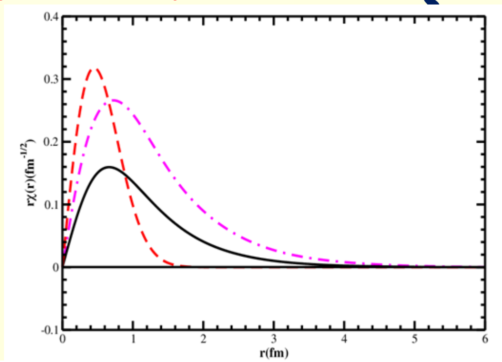
$$G_C(Q^2) \longrightarrow \tfrac{1}{3}\sum_\lambda < p', \lambda \mid J^0 \mid p, \lambda >.$$

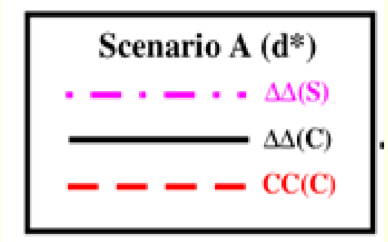
C, Form factors (charge distributions)

For a spin=3 system: PRD96 094001 (2017)

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

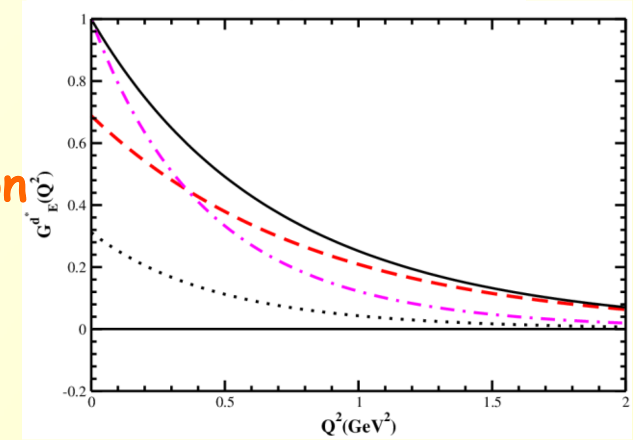
Wave Function

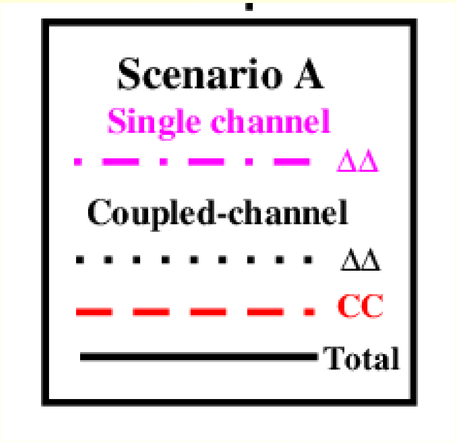




Compact ΔΔ+CC

Charge Distribution





rms

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