Hadronic Exotics: molecular and compact scenarios

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Collaboration:
(Tuebingen Group & Beijing Group)

At Petersburg Nuclear Physics Institute, Gatchina
Oct. 31, 2024

Outline

1, Introduction: Hadronic Exotic states:
(XYZ-particles: 4-quark, 5-quark states)
★interpretations:
Molecular & Compact scenarios

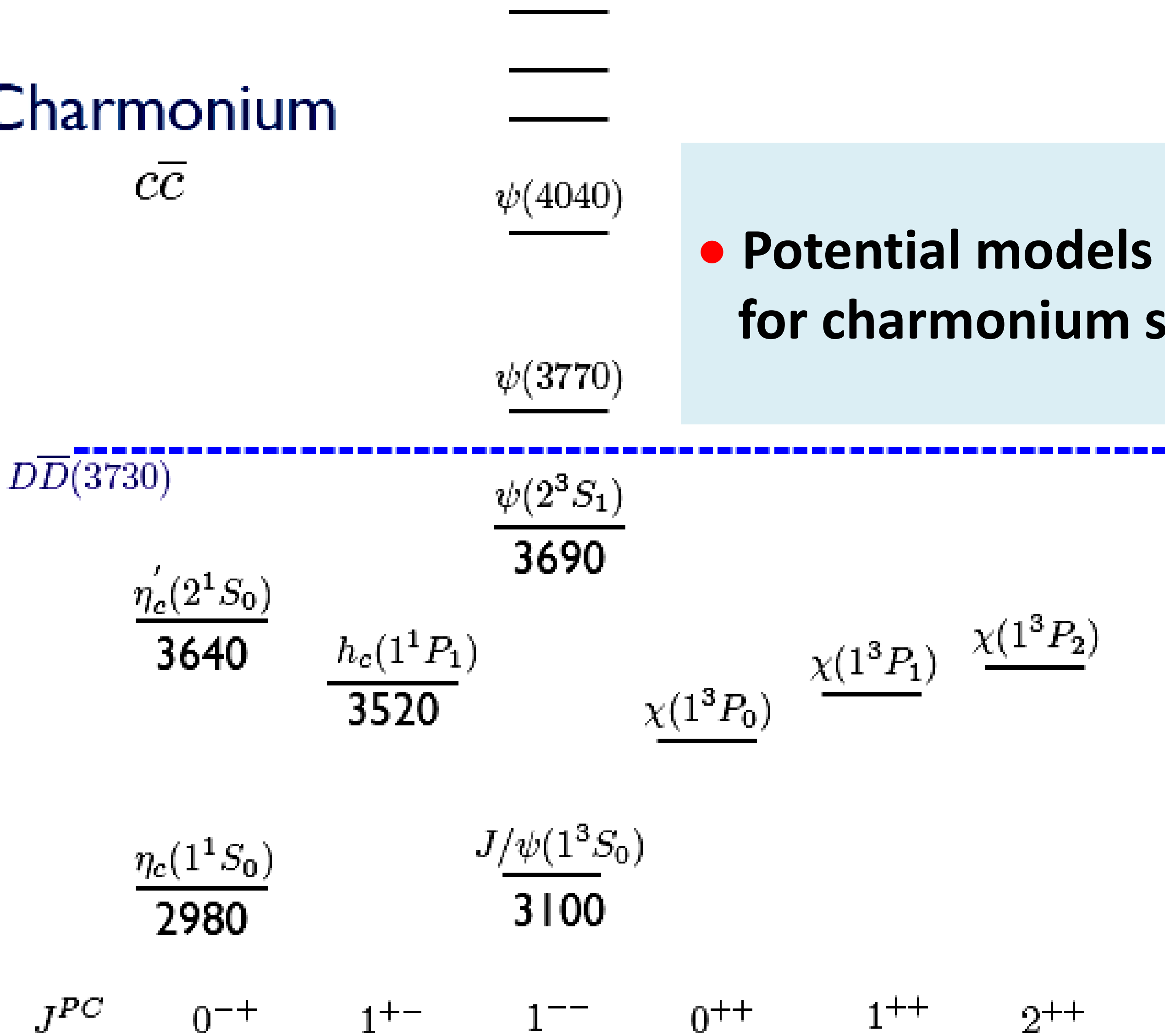
2, ● Example$_1$: X(3872) molecular scenario

3, Exotic (6-quark system)
● Example$_2$: d*(2380) compact scenario

4, Summary and discussion

1，Introduction

- Charmonium



- **Potential models worked well for charmonium spectroscopy**

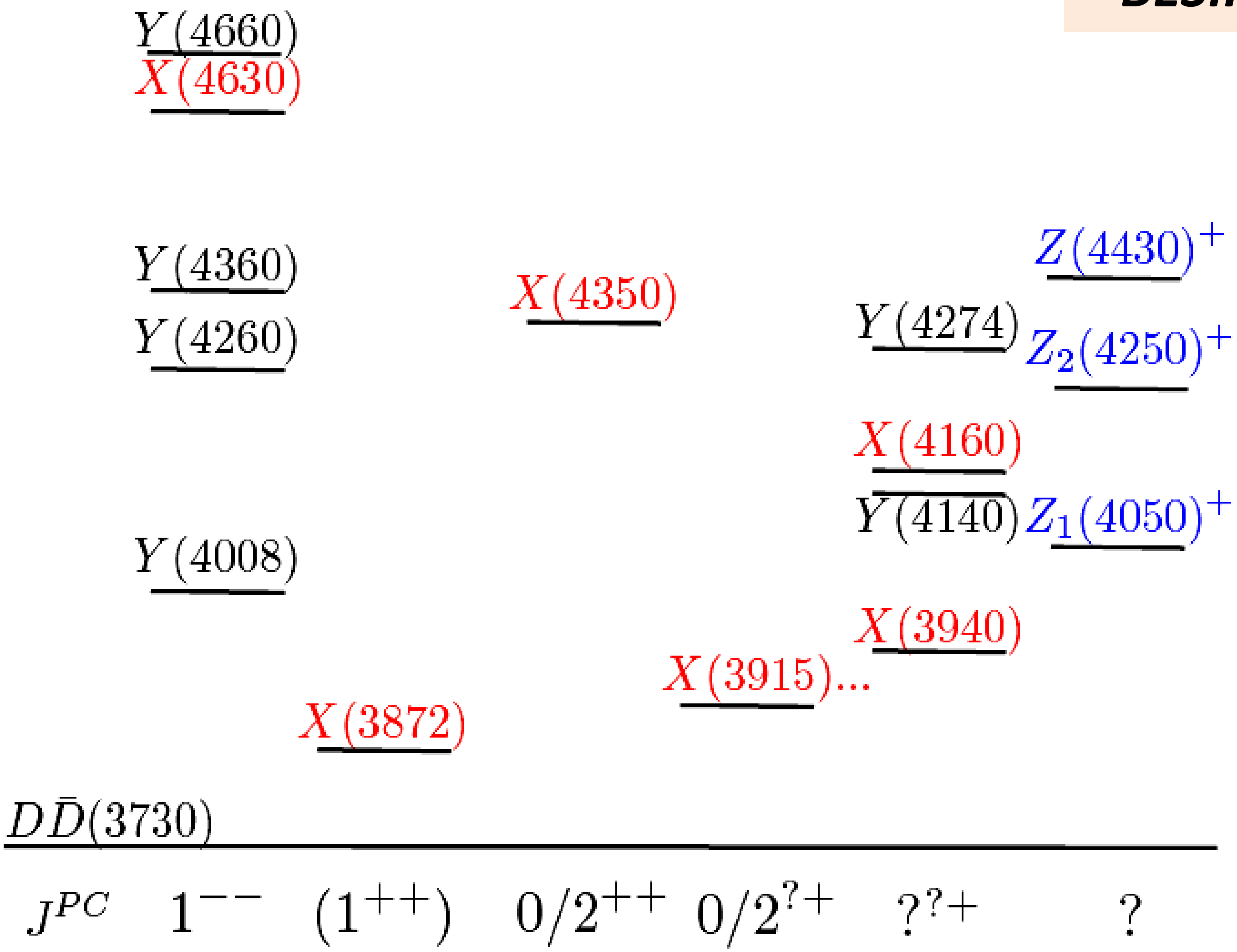
- **Cornell-potential**
- **Non-relativistic Or Semi-relativistic**
- **Spin-dependence velocity-dependent**

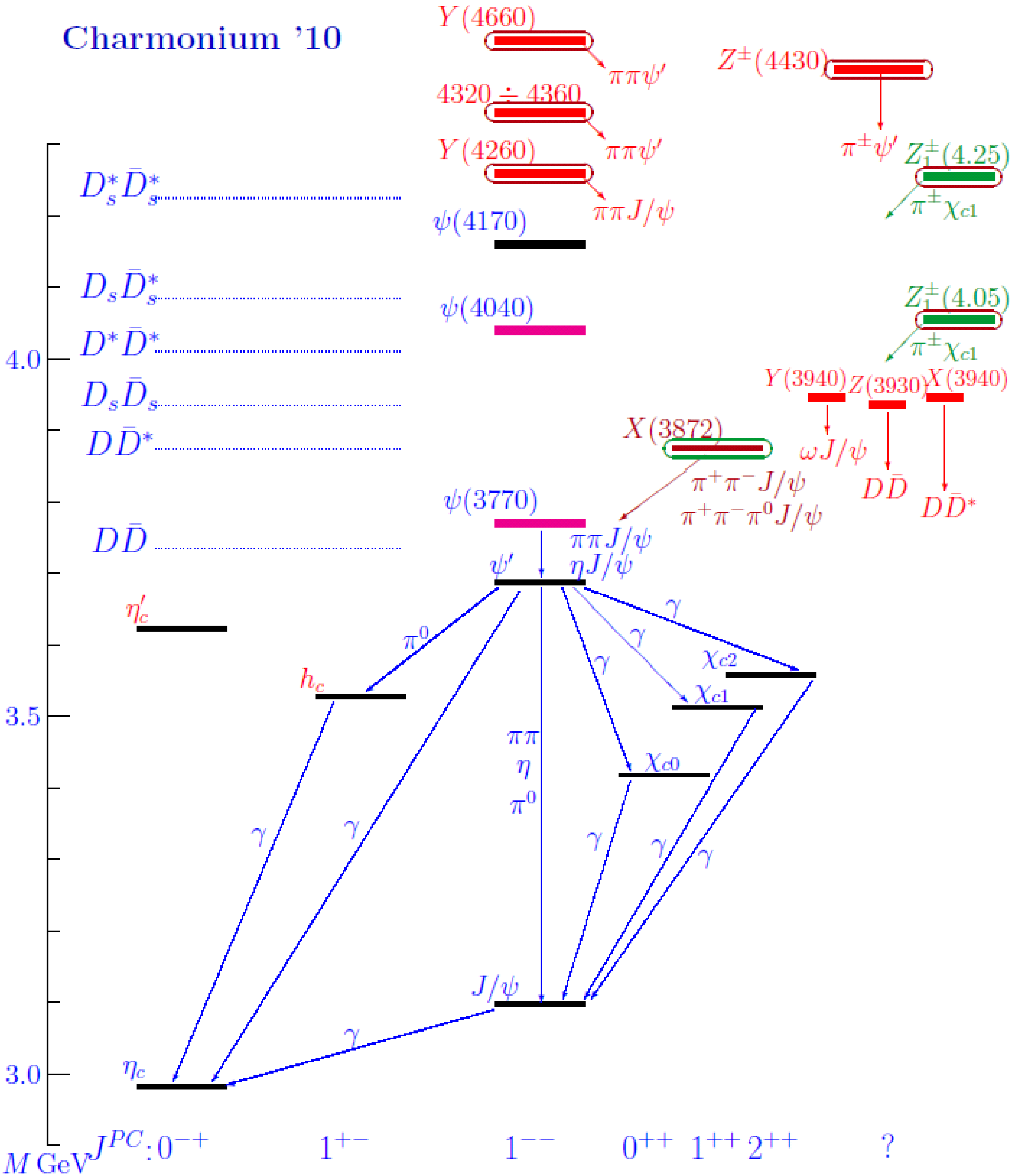

J粒子发现50周年研讨会
50 Years Discovery of the J Particle
会议日程
Agenda


Date and Time October 20th, 2024, 09:00-18:20
Indico https://indico.ihep.ac.cn/event/23322/
Agenda
Morning Session, Chair: Yifang Wang (IHEP
09:00-09:10 Opening remarks
Speaker: Jianguo Hou (Chinese Academy of
09:10-10:00 Discovery of the J particle
Speaker: Samuel C.C. Ting (Massachusetts I
Technology)
10:00-10:30 Charm and Standard Model

X, Y, Z states from Brambilla et al., 1010.5827

- ***BaBar, Belle, BESIII, LHCb, ….***





♥ **Charged charmonium spectrum**

-- A completely new scenario of strong QCD!

♥ **States close to open thresholds**

-- The role played by open D meson channels?

Close to DD* threshold

The XYZ states

BESIII, Belle and CLEO-c → $Z_c(3900)$

$M_{Zc(3900)} = (3899 \pm 3.6 \pm 4)$ MeV

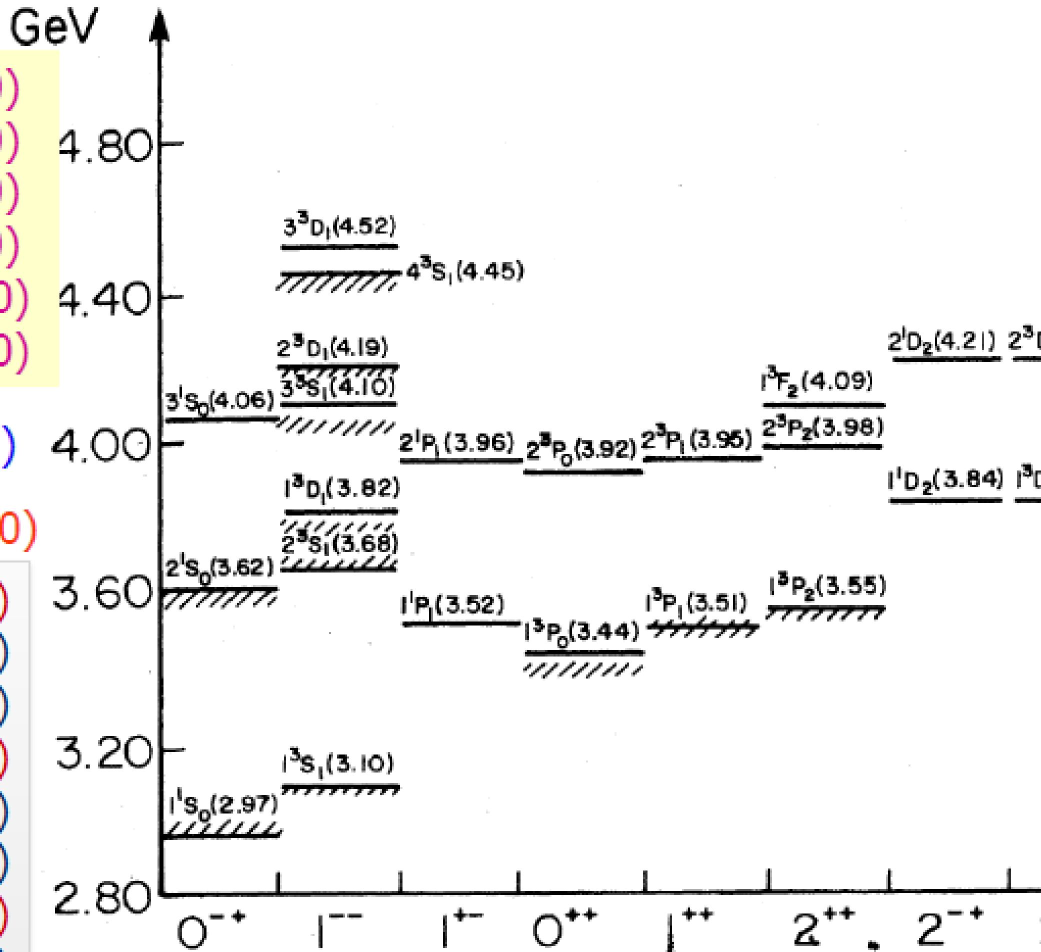
$\Gamma_{Zc(3900)} = (46 \pm 10 \pm 20)$ MeV

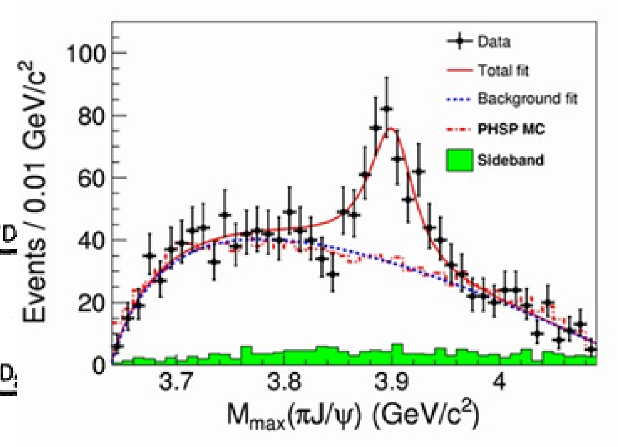
Z(4430)
Z(4250)
Z(4050)
Z(4200)
Zc(3900)
Zc(4020)

X(3872)

XYZ(3940)

X(3915)
X(4160)
Y(4008)
Y(4140)
Y(4260)
Y(4360)
X(4350)
Y(4660)



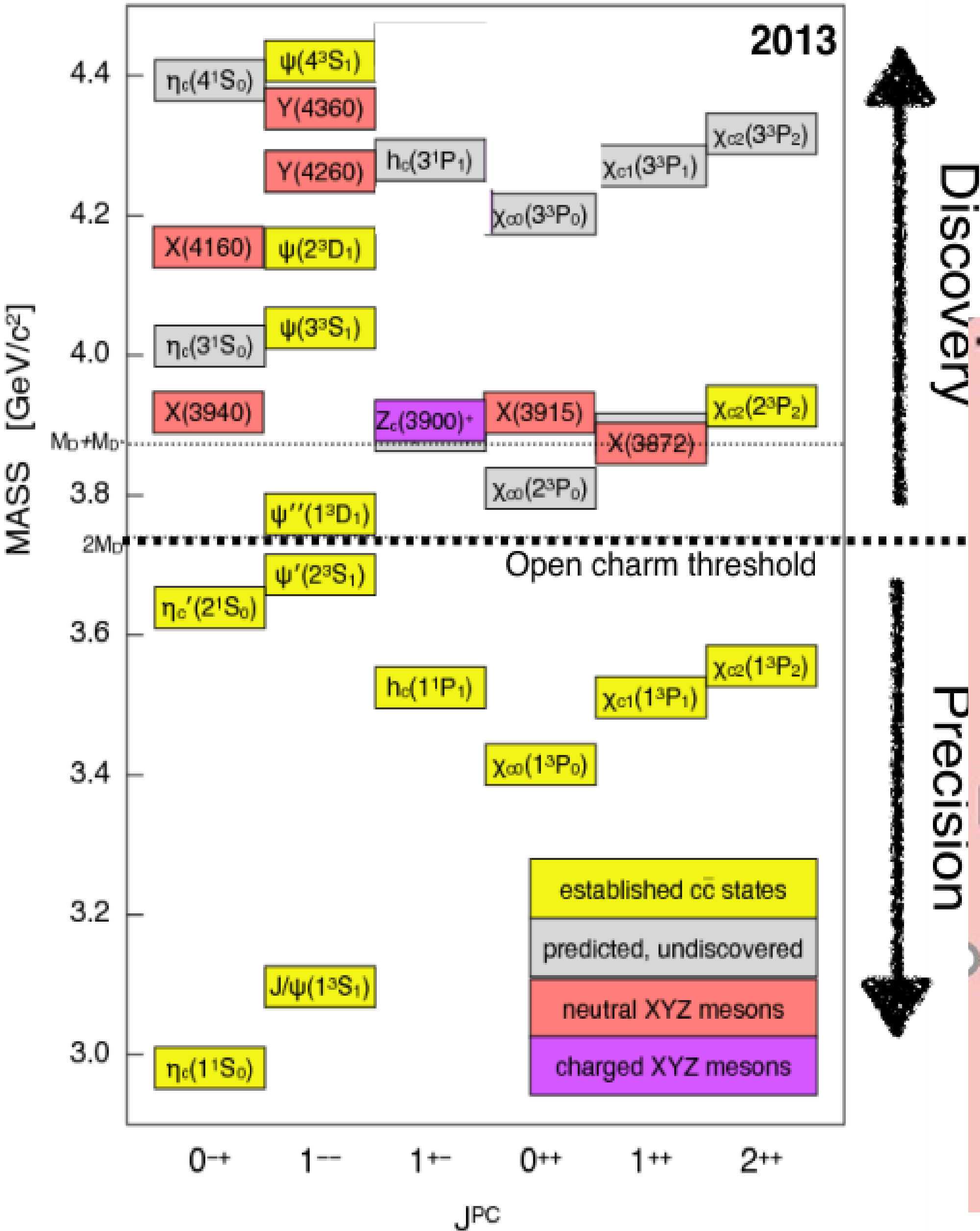


Charmonium?
Hybrid?
Tetraquark?
Molecule?
...

Not all XYZ states are charmonia!

Courtesy of C. Z.Yuan

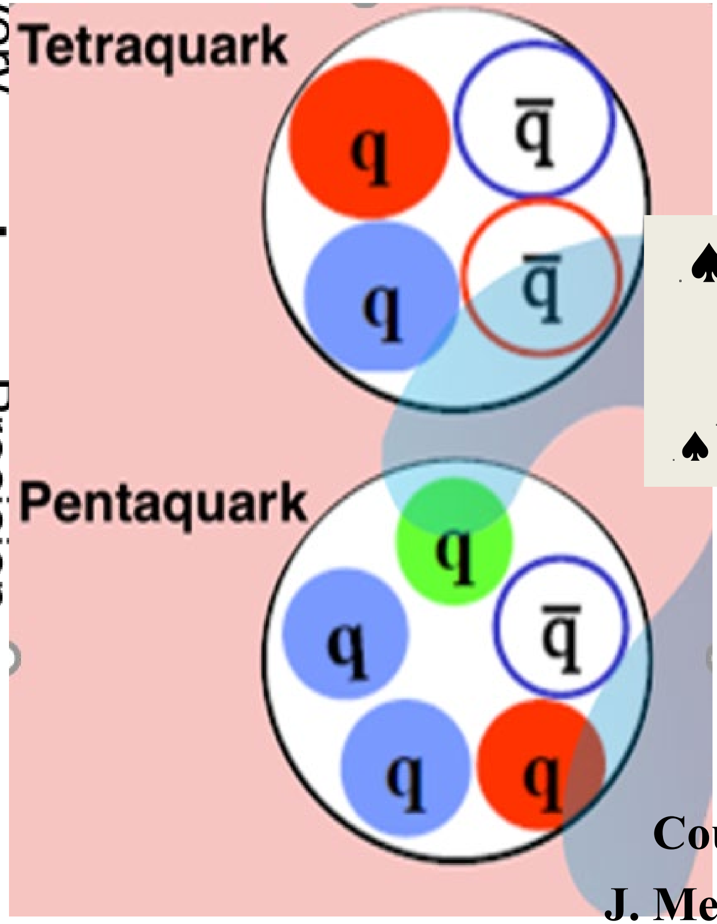
Recent studies on hadronic exotic structures_(4-body)



XYZ states Charmonium-like

★Near threshold
★Narrow width
★Heavy flavor

"XYZ" Puzzle



♠ normal mesons & ♠ baryons

Courtesy of J. Messchendor

Recent studies on hadronic exotic structures$_{b\text{-}quark}$

$$Z_b(10610): \; M = 10608.4 \pm 2.0 \; MeV; \; \Gamma = 15.6 \pm 2.5 \; MeV$$

$$Z'_b(10650): \; M = 10653.2 \pm 2.0 MeV; \; \Gamma = 14.4 \pm 3.2 \; MeV$$

$$I^G(J^P) = 1^+(1^+)$$

$$(\mathrm{B}\overline{\mathrm{B}}^* + \overline{\mathrm{B}}\mathrm{B}^*), \; (\mathrm{B}^*\overline{\mathrm{B}}^*)$$

$$\pi^\pm \Upsilon(nS), \; \pi^\pm h_b(nP)$$

Many new structures

charmonium-like or bottomium-like…

They are hadronic exotics

★Near threshold

★Narrow width

★Heavy flavor

Recent studies on exotic structures_(5-body)

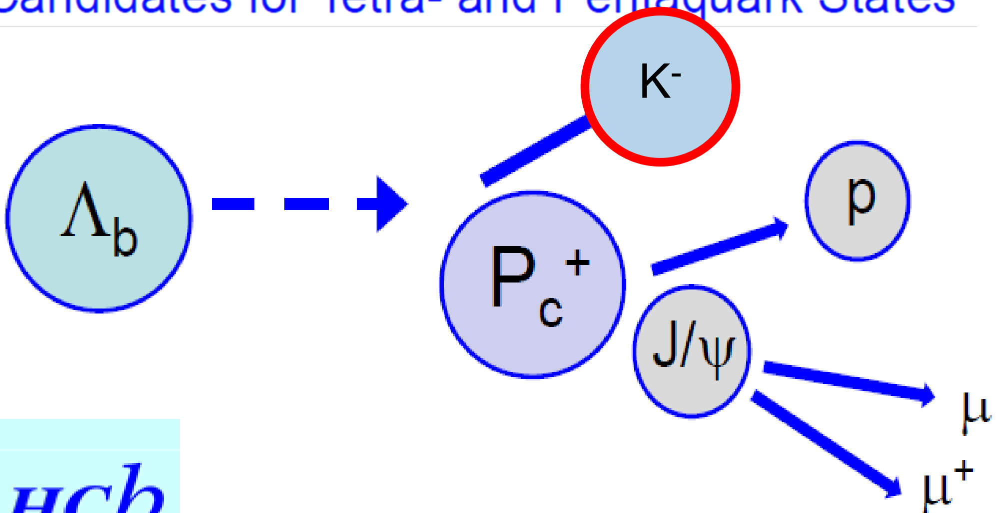
Pentaquark states $P_c(4380)^+$, & $P_c(4450)^+$

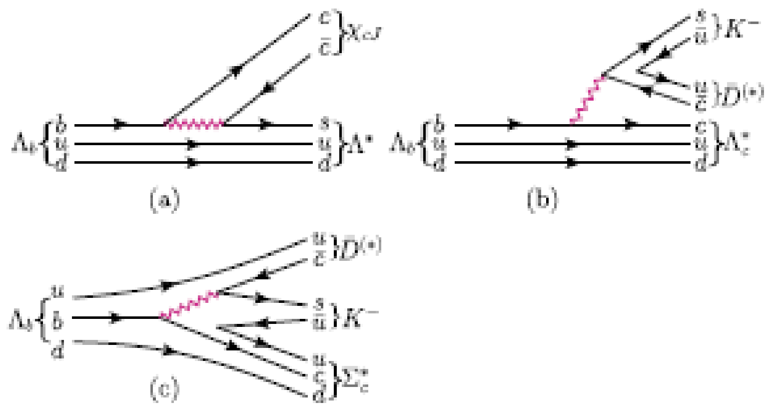
Observation of J/ψp resonances consistent with pentaquark states

PRL 115, 07201, arXiv:1507.03414

$b \to c + \overline{c}s$

Exotic Hadron Spectroscopy at LHCb:
Candidates for Tetra- and Pentaquark States



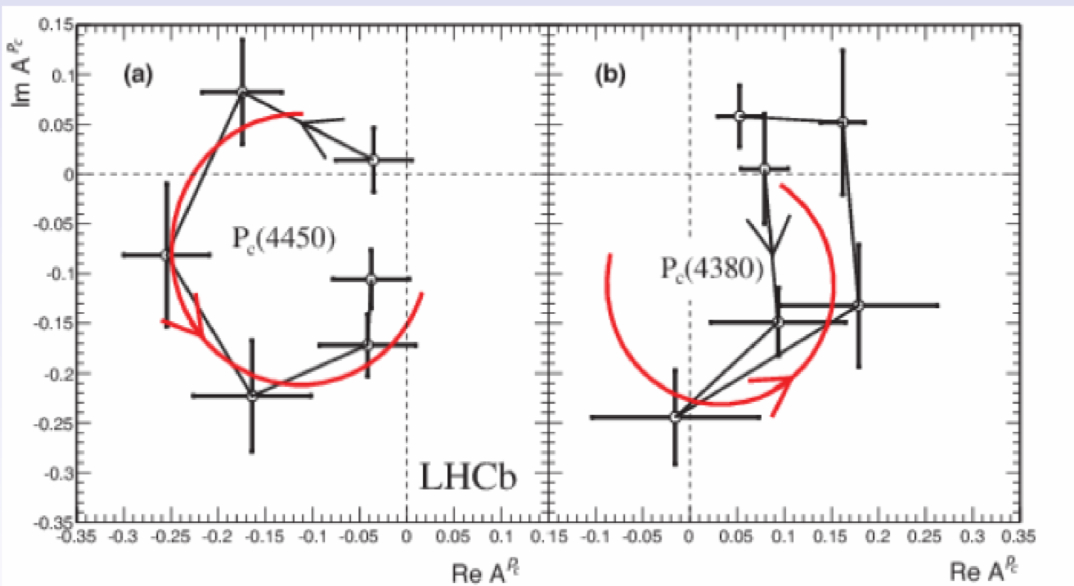


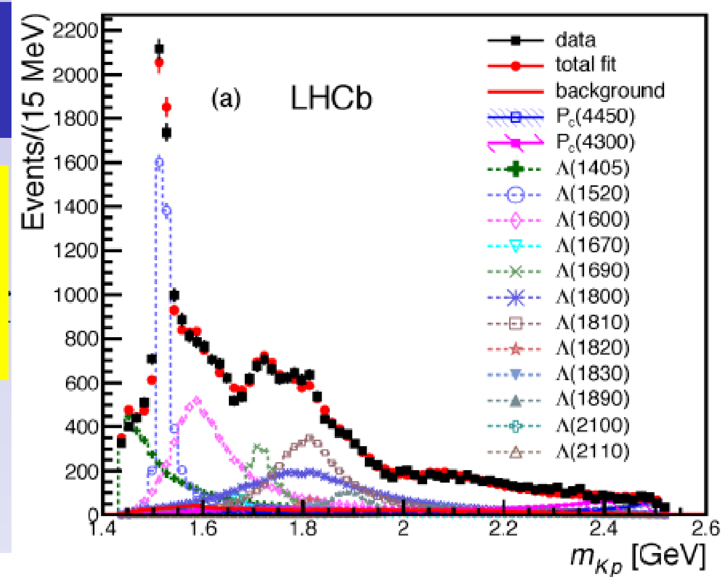
Pentaquark states

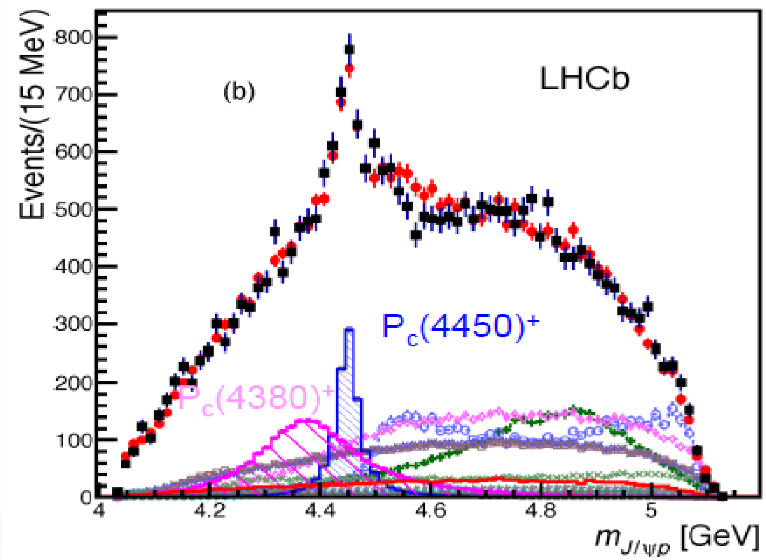
$P_c^+(4380):(M;\Gamma)=(4380\pm8\pm29;205\pm18\pm86)MeV$

$P_c^+(4450):(M;\Gamma)=(4449.8\pm1.7\pm2.5;39\pm5\pm19)MeV$

Spin-parity: $(3/2^-,5/2^+)$, $(3/2^+,5/2^-)$, or $(5/2^+,3/2^-)$.







$P_c(4450)^+$	12σ
$P_c(4380)^+$	9σ
$P_c(4450)$ & $P_c(4380)$	15σ

hys. Rev. Lett. 115, 072001 (2015)

$$\mathcal{B}(\Lambda_b^0\to J/\psi K^- p) = 3.04\pm0.04\pm0.06\pm0.33^{+0.43}_{-0.27}\times10^{-4},$$

$$\mathcal{B}(\Lambda_b^0\to P_c^+(4380)K^-)\mathcal{B}(P_c^+(4380)\to J/\psi p) = 2.56\pm0.22\pm1.28^{+0.46}_{-0.36}\times10^{-5},$$

arXiv:1507.03414v1 [hep-ex] 13 Jul 2015

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays

The LHCb collaboration

Abstract

Observations of exotic structures in the $J/\psi p$ channel, that we refer to as pentaquark-charmonium states, in $\Lambda_b^0 \to J/\psi K^- p$ decays are presented. The data sample corresponds to an integrated luminosity of 3 fb^{-1} acquired with the LHCb detector from 7 and 8 TeV pp collisions. An amplitude analysis is performed on the three-body final-state that reproduces the two-body mass and angular distributions. To obtain a satisfactory fit of the structures seen in the $J/\psi p$ mass spectrum, it is necessary to include two Breit-Wigner amplitudes that each describe a resonant state. The significance of each of these resonances is more than 9 standard deviations. One has a mass of $4380 \pm 8 \pm 29$ MeV and a width of $205 \pm 18 \pm 86$ MeV, while the second is narrower, with a mass of $4449.8 \pm 1.7 \pm 2.5$ MeV and a width of $39 \pm 5 \pm 19$ MeV. The preferred J^P assignments are of opposite parity, with one state having spin 3/2 and the other 5/2.

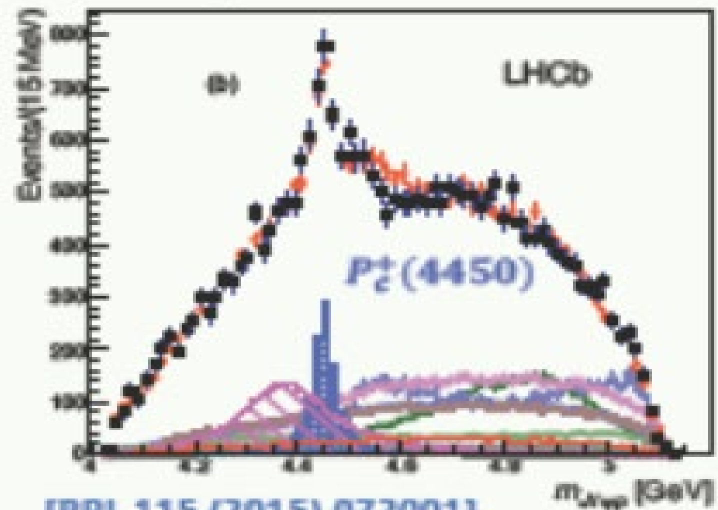
Five-quark

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

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

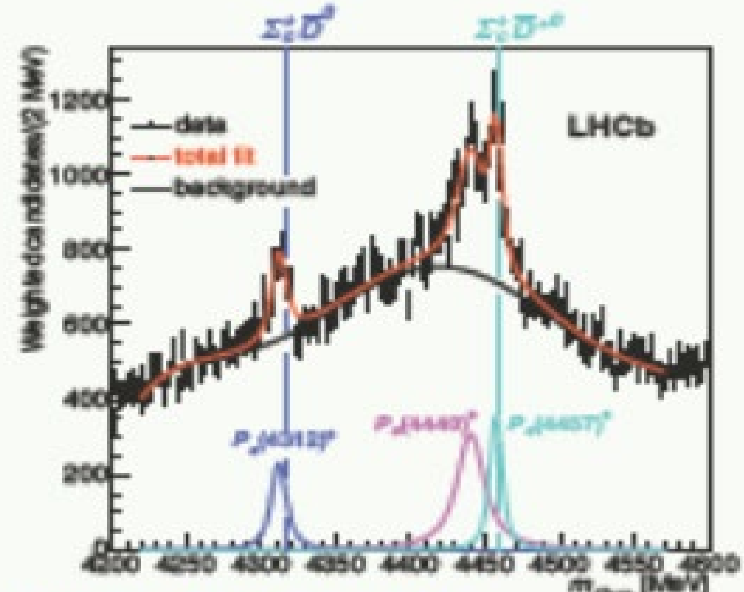
$P_c(4380),\qquad P_c'(4449)$

$\Lambda_b^0 \to [J/\psi\, p]K^-$



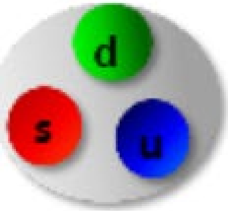
[PRL 115 (2015) 072001]

$P^+_{c\bar{c}}$ observation



[PRL 122 (2019) 222001]

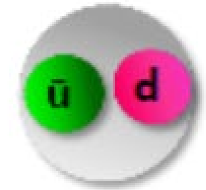
♥ Real particles are color singlet



Baryons are red-blue-green triplets

Λ=usd

Mesons are color-anticolor pairs

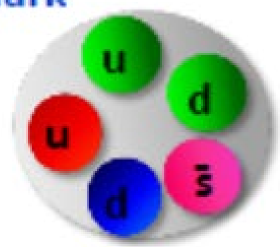


π=ūd

Other possible combinations of quarks and gluons :

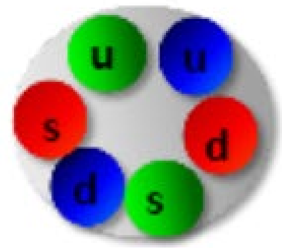
Pentaquark

S= +1 Baryon



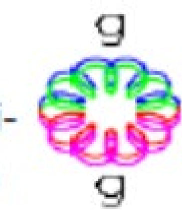
Hexaquark

Tightly bound 6 quark state



Glueball

Color-singlet multi-gluon bound state

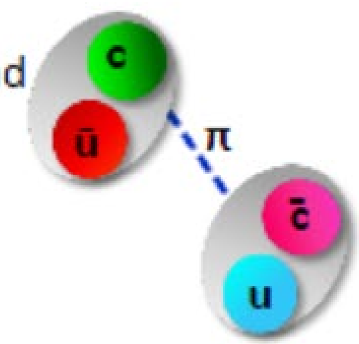


Tetraquark

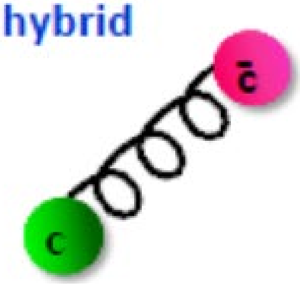
Tightly bound diquark & anti-diquark

Molecule

loosely bound meson-antimeson "molecule"



$q\bar{q}$ -gluon hybrid mesons



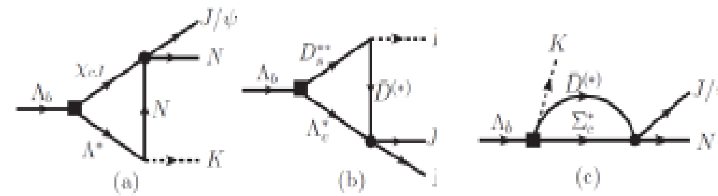
Courtesy of V. Bhardwaj

Interpretations of two Pc

*Kinematic effects in non-perturbative re-scattering processes (CUSPS or triangle singularity)

e.g. arXiv:1507.04950, 1507.05359, 1507.06552, et.al..

from arXiv:1507.05359

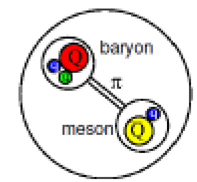


*bound states(or resonances) by open-charm baryon and meson

4.g. arXiv: 1507.03717, 1507.03704,1507.05200, 1507.4249 et. al.

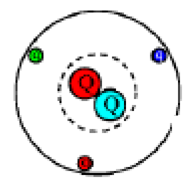
Meson-exchange interaction

$\Sigma_c\bar{D}$, $\Sigma_c^*\bar{D}$, $\Sigma_c\bar{D}^*$, $\Sigma_c^*\bar{D}^*$



*baryon+charmonia

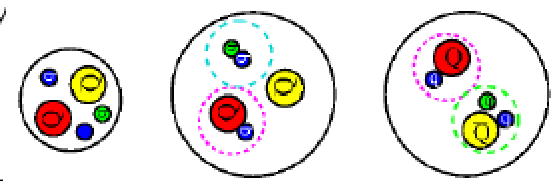
e.g. arXiv:1507.07478,1508.00888, 1512.00426



$\chi_{c1}p$, $\psi(2S)p$

*Tightly bound pentaquark states

e.g.arXiv; 1201.0807,1507.04980,1507.07652,1508.00356,1507.05867, 1507.08252, 1508.01468,1508.04189

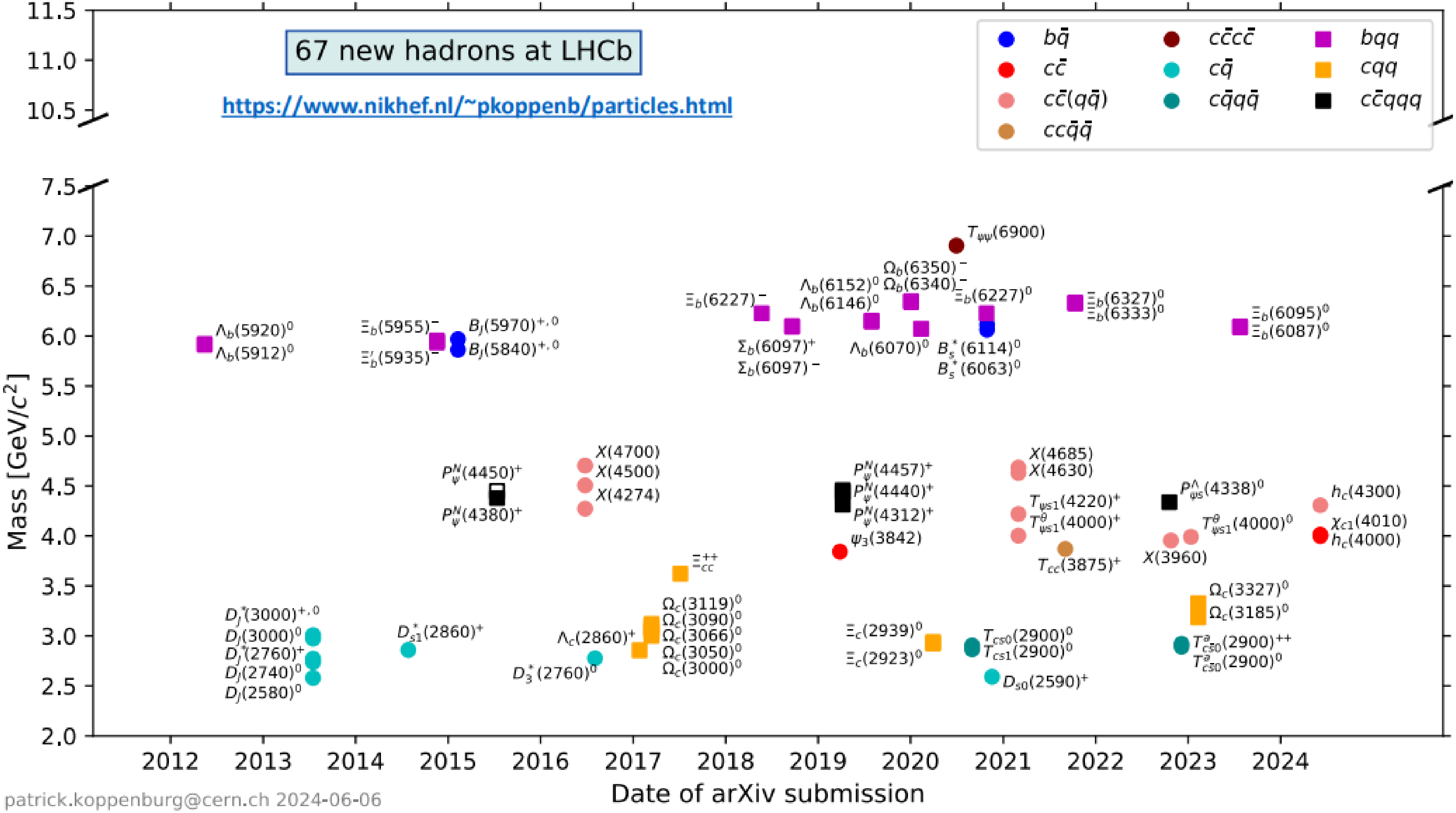


*coupled-channle unitary approach: A series of meson-baryon dynamically generators

e.g. arXiv:PRL105,232001; PRC84,015202, PRD92,094003, etl.al…

* Observations: BESIII, BelleII, BABAR, LHCb…

Hadrons observed at LHCb



Interpretations approaches/descriptions

QCD sum rule

Non-relativistic QCD

Heavy quark effective theory

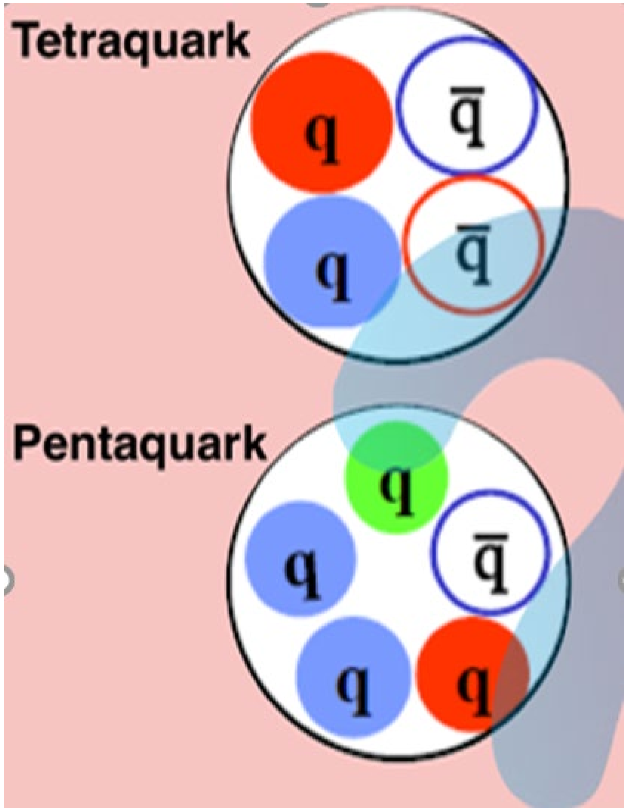
Heavy hadron chiral perturbation theory

Potential models, EFT

Lattice calculations

★Near threshold,
★Narrow width,
★Heavy flavor

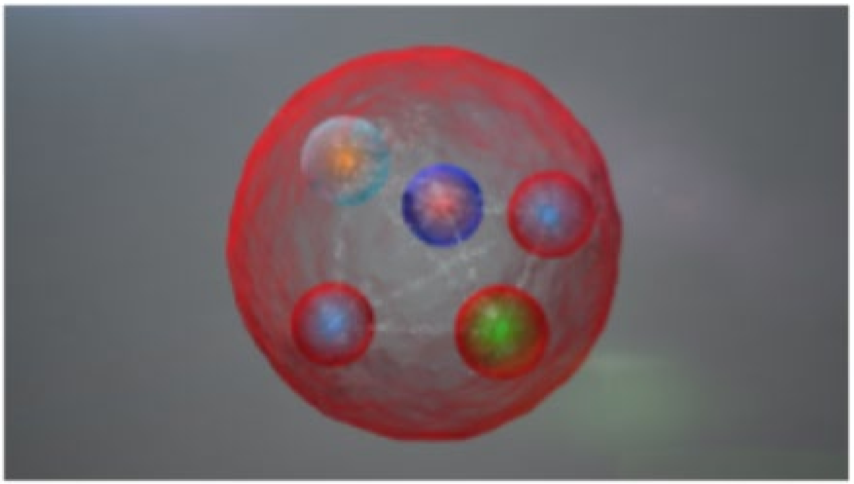
- Molecule, baryonium
- tetraquark
- Hybrids
- Coupling channel…



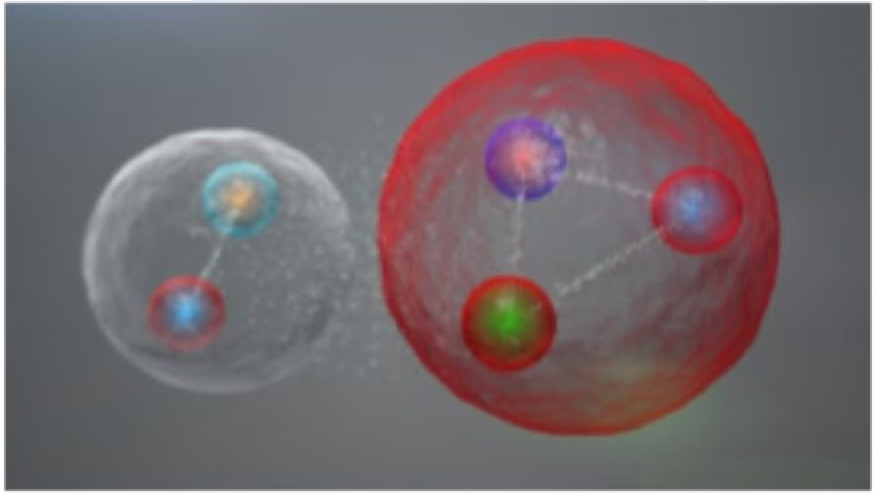
Interpretations approaches/descriptions

★Two main scenarios
(Molecular & Compact scenarios)

Compact System



Molecular System



Compact System

- Diquark bounded by colored force
- Typical Size ～1 fm
- Mass near to threshold accidental
  $SU(3)_f$ multiplets from combination of diquarks
- No (strong) hierarchy of couplings

Molecular System

- Formed by mesonic exchange
- Size >1 fm
- Mass near to threshold natural
- $SU(3)_f$ multiplets from combinations of component hadrons
- Fall-apart decay dominant

Other possible interpretations: hadro-quarkonium, hybrid…
Experimental observations essential to check all models

Hadronic molecules

- **Weekly bound state of two or three hadrons**
- **Typical examples: Nuclei and hyper-nuclei**
- **Baryon-baryon bound state: $M_H < M_1 + M_2$**

- **The Molecule idea has a long history**

- **Voloshin, Okun (1976)**
- **De Rujula, George, and Glashow (1977)**

Long-range one-pion exchange (Tornqvist, *ZPC*1993)

Meson-exchange models (Lohse, et al., 1990)

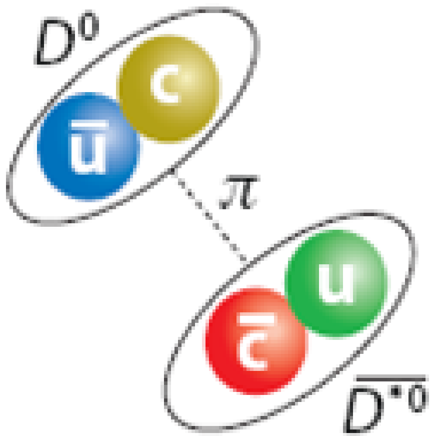
Unitarized coupled channel models with chiral Lagrangians

(Olier, et al., 1997; Jido et al., 2005,

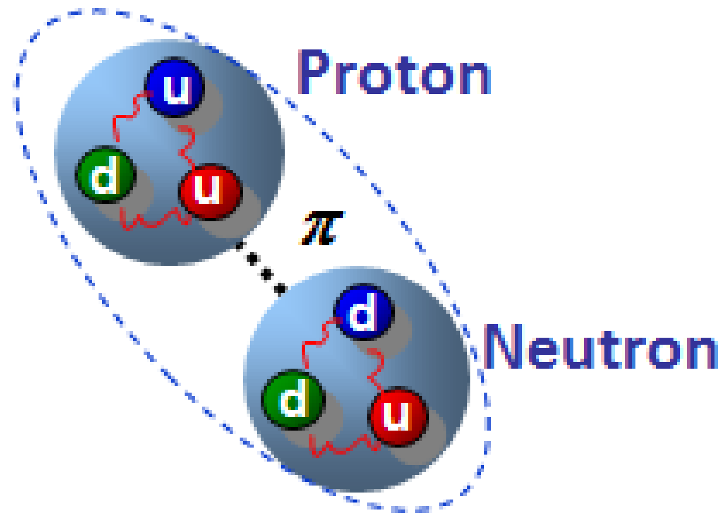
Gammermann et al., 08) +……Chinese+

Hadronic molecule – an analogue to Deuteron

Heavy-light quark-antiquark pairs form heavy mesons, and the meson-antimeson pair moves at distances longer than the typical size of the meson. The mesons are interacting through exchange of light quarks and gluons, similar to nuclear force.



D^0–$\overline{D^{*0}}$ "molecule"



Deuteron: p-n molecule

New exotics : X(3872)

Basics about $X(3872)$

- first seen in $X(3872) \to J/\psi\pi^+\pi^-$ by BELLE (2003), also seen by CDF, D0 (2004) and BABAR (2005).
- $\Gamma_X \approx 3$ MeV
- quantum numbers:

  C=+ from $X(3872) \to \gamma J/\psi$, I=0 no signal in $X \to \pi\pi^0 J/\psi$

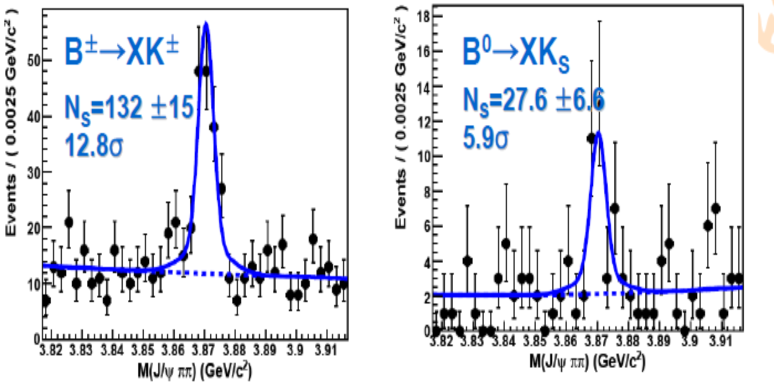
  $J^{PC} = 1^{++}$ or $J^{PC} = 2^{-+}$ from $X(3872) \to J/\psi\pi^+\pi^-$ helicity amplitude analysis

- $X(3872.2 \pm 0.8)$ close to $D^0 D^{*0}$ threshold with $m_{thr} = 3871.81 \pm 0.36$ MeV;
- S-wave $D^0 D^{*0}$ hadron molecule favors $J^{PC} = 1^{++}$
- charmonium interpretation disfavored, $1^{++}(2^3P_1)$ too low in mass compared to $m(2^3P_2) \approx m(Z(3930))$

$X(3872) \to \pi^+\pi^- J/\psi$

arXiv:0809.1224 605 fb^{-1}

recent results



M(X(3872))=(3871.46±0.37±0.07) MeV by combining two modes together

$$B(B^0 \to X(3872)(K^+\pi^-)_{NR}) \times B(X(3872) \to J/\psi\pi^+\pi^-) = (8.1 \pm 2.0^{+1.1}_{-1.4}) \times 10^{-6}$$

Decay modes of X(3872)

Basics about $X(3872)$, Decay Modes

- $\Gamma(X \to J/\psi\pi^+\pi^-\pi^0)/\Gamma(X \to J/\psi\pi^+\pi^-) = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst})$
  BELLE (hep-ex/0505037)
  isospin violating decay modes
  decays dominated by subthreshold decays of $\omega J/\psi$ and $\rho J/\psi$

- $\Gamma(X \to J/\psi\gamma)/\Gamma(X \to J/\psi\pi^+\pi^-) = 0.14 \pm 0.05$ (Belle); 0.33 ± 0.12 (BABAR)
  BELLE (hep-ex/0505037), BABAR PRL 102 (2009)
  large radiative decay mode !!

- $\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma) = 3.5 \pm 1.4$
  BABAR, PRL 102, (2009)
  possible evidence for charmonium component ?

2. Example-Molecular scenario for X(3872)

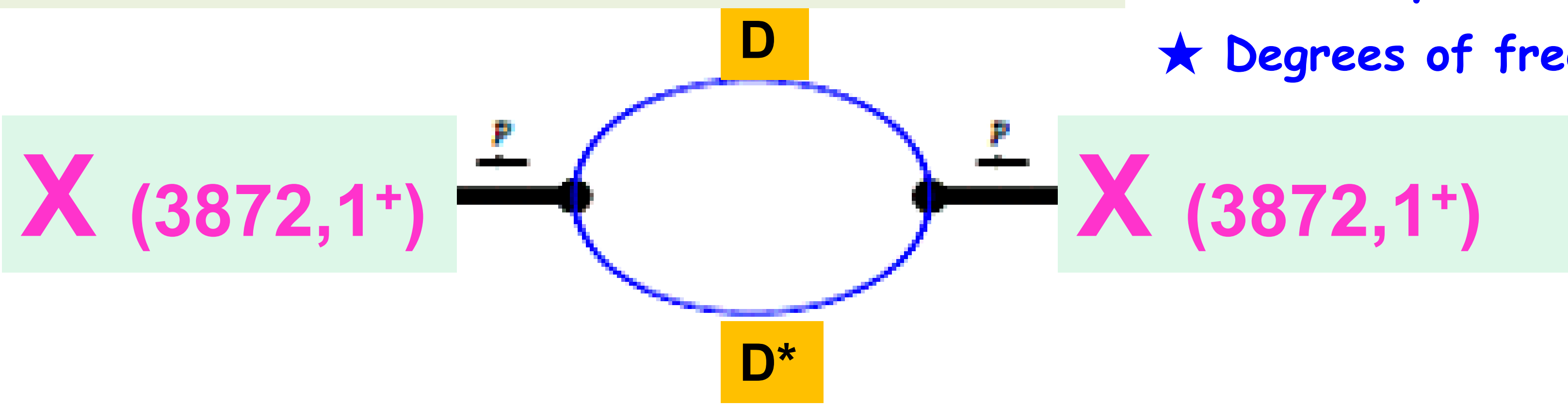
Phenomenological Lagrangian approach

(with Tuebingen group, Prog.part.nucl.phys., 94 (2017), 282)

★Near threshold
★Narrow width
★Heavy flavor

★ Degrees of freedom

The mass operator represented by $\widetilde{\Pi}(p^2)$



$$\mathcal{L}_{XDD^*} = X_\mu J^\mu$$

$$= \frac{g_X}{\sqrt{2}} X_\mu(x) \int d^4 y \left(\Phi_X(y^2)\right) \left[D(x+y/2)\bar{D}^{*\mu}(x-y/2) + \bar{D}(x+y/2) D^{*\mu}(x-y/2) \right]$$

Correlation function

Two fields

a, Compositeness condition:

Bound state description of hadronic molecules in QFT based on compositeness condition: Weinberg, PR1963; Salam, Nuov.Cim. 1962
Heyashi et al.,Fortsch. Phys. 1967

The coupling g_X is determined by the condition

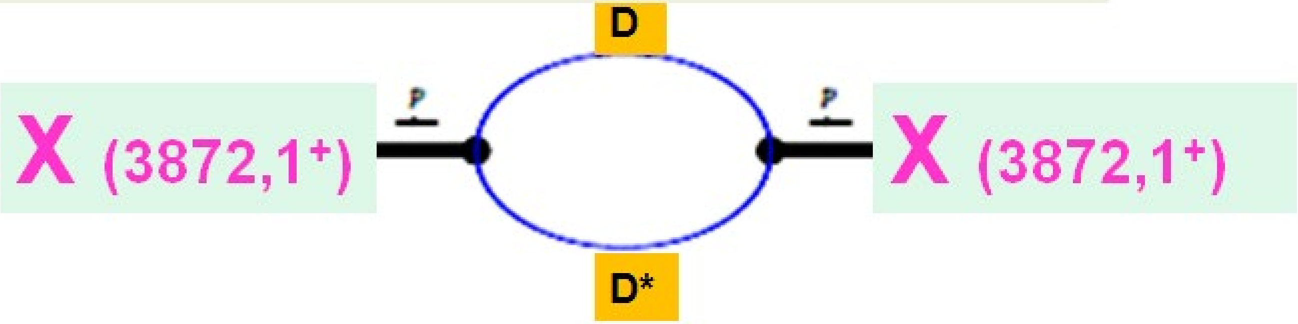
$$Z_M = 1 - \Sigma'_M(m_M^2) = 0$$

with the derivative of the mass operator

Exp. input

$$\Sigma'_M(m_M^2) = g_M^2 \Pi'_M(m_M^2) = g_M^2 \frac{d\Pi_M(p^2)}{dp^2}\Big|_{p^2=m_M^2}$$

The mass operator represented by $\widetilde{\Pi}(p^2)$



b, Vertex function

Characterize the finite size of the hadron
& the distributions in the hadron

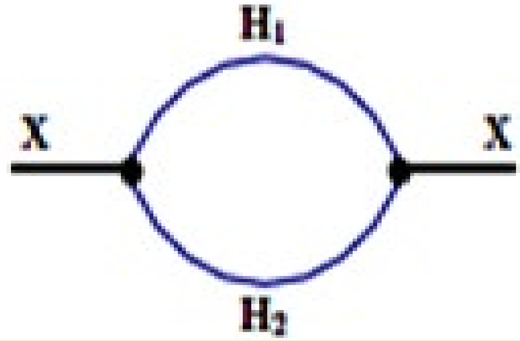
Gaussian-type is chosen for the function

$$\Phi_M(y^2) = \int \frac{d^4k}{(2\pi)^4} e^{-ik\cdot y} \tilde{\Phi}(-k^2), \qquad \tilde{\Phi}(-k_E^2) = exp\left(-k_E^2/\Lambda_M^2\right)$$

Local limit $\Phi(y^2) \rightarrow \delta^4(y^2)$

Parameter: Gaussian with free size parameter Λ_M

Four-dimensional covariant calculation



$$\mathcal{L}_{XDD^*} = X_\mu J^\mu$$
$$= \frac{g_X}{\sqrt{2}} X_\mu(x) \int d^4 y \left(\Phi_X(y^2)\right)\left[D(x+y/2)\bar{D}^{*\mu}(x-y/2) + \bar{D}(x+y/2)D^{*\mu}(x-y/2)\right]$$

PRD79,094013

2009

Strong decay$_1$

(two-body)

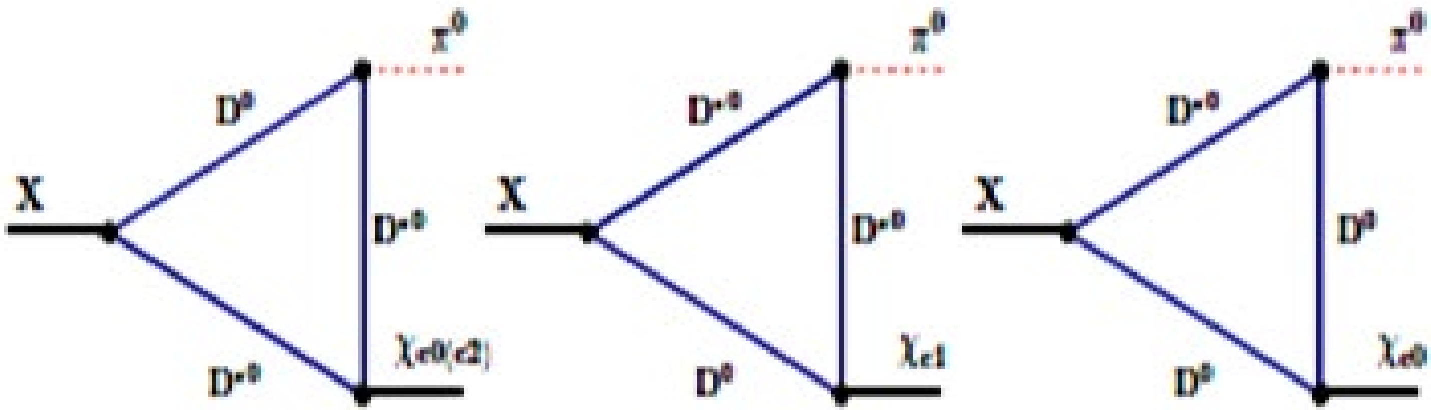


FIG. 2: Diagrams contributing to the hadronic transitions $X(3872) \to \chi_{cJ} + \pi^0$.

Strong decay$_2$
(three-body)

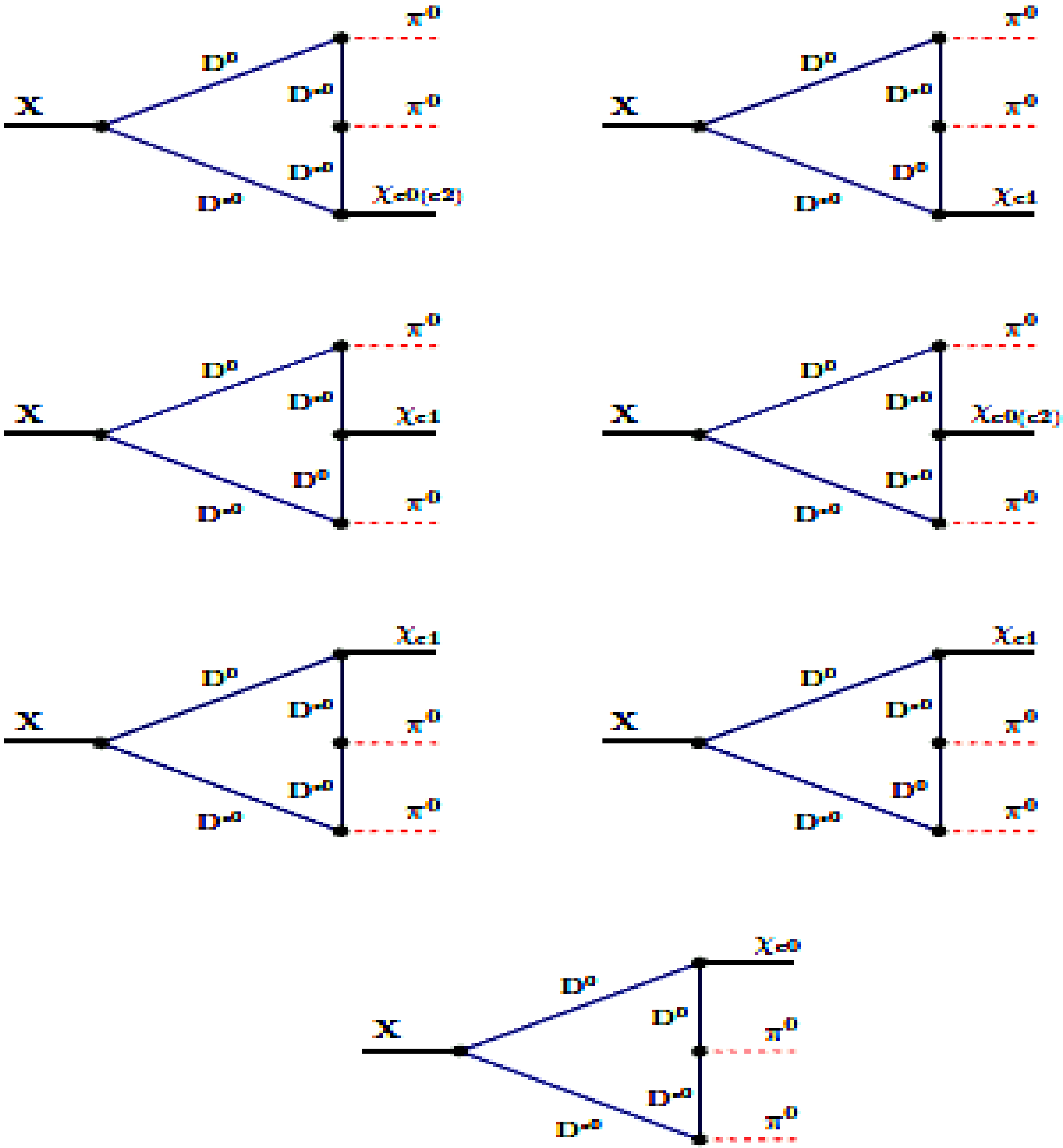


FIG. 3: Diagrams contributing to the hadronic transitions $X(3872) \to \chi_{cJ} + 2\pi^0$.

2009

Strong decay(two-body, three-body)

$$|X(3872)\rangle = \frac{Z^{1/2}_{D^0D^{*0}}}{\sqrt{2}}(|D^0\bar{D}^{*0}\rangle + |D^{*0}\bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}}(|D^+D^{*-}\rangle + |D^-D^{*+}\rangle) + Z^{1/2}_{J_\psi\omega}|J_\psi\omega\rangle + Z^{1/2}_{J_\psi\rho}|J_\psi\rho\rangle,$$

$$\frac{\Gamma(X\to J/\psi\pi^+\pi^-\pi^0)}{\Gamma(X\to J/\psi\pi^+\pi^-)} = 1.0 \pm 0.4(\text{stat}) \pm 0.3(\text{syst}) \qquad (1)$$

and

$$\frac{\Gamma(X\to J/\psi\gamma)}{\Gamma(X\to J/\psi\pi^+\pi^-)} = 0.14 \pm 0.05(\text{Belle}); \quad 0.33 \pm 0.12(BABAR). \qquad (2)$$

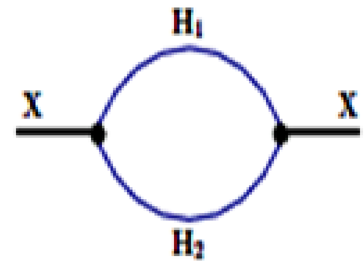
TABLE III. Properties of $X \to J_\psi + h$ decays. The numbers in brackets and for the ratios R_1, R_2 from explicit values for $Z_{J_\psi\rho}$, $Z_{J_\psi\omega}$ and $\sigma = (Z_{J_\psi\rho}/Z_{J_\psi\omega})^{1/2}$ of Eq. (34).

Quantity	Local case	Nonlocal case
$\Gamma(X\to J/\psi\pi^+\pi^-)$, keV	$7.5\times10^3 Z_{J_\psi\rho}(45.0)$	$9.0\times10^3 Z_{J_\psi\rho}(54.0)$
$\Gamma(X\to J/\psi\pi^+\pi^-\pi^0)$, keV	$1.92\times10^3 Z_{J_\psi\omega}(78.9)$	$1.38\times10^3 Z_{J_\psi\omega}(56.6)$
$\Gamma(X\to J/\psi\pi^0\gamma)$, keV	$0.32\times10^3 Z_{J_\psi\omega}(13.2)$	$0.23\times10^3 Z_{J_\psi\omega}(9.4)$
$\Gamma(X\to J/\psi\gamma)$, keV	$49.18 Z_{J_\psi\omega}(1+1.94\sigma)^2(6.1)$	$35.19 Z_{J_\psi\omega}(1+2.51\sigma)^2(5.5)$
R_1	1.75	1.05
R_2	0.14	0.10

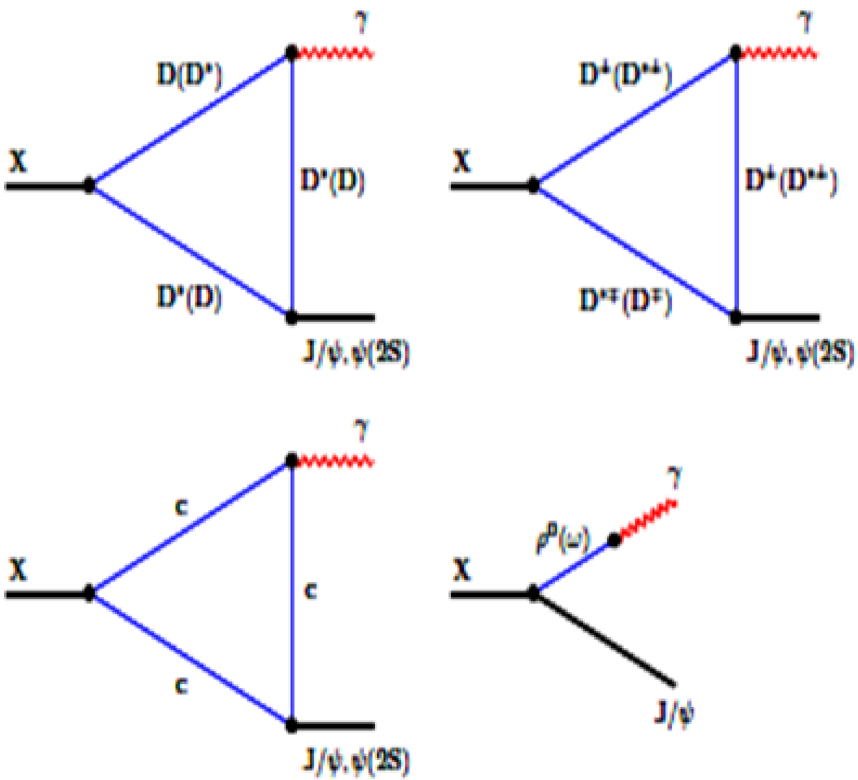
Local limit $\Phi(y^2)\to\delta^4(y^2)$

♠ Radiative decays

$$X(3872) \to J/\psi, \psi(2S) + \gamma$$



1: $H_1 H_2$ hadron-loop diagrams contributing to the mass operator of the $X(3872)$ meson.



Decay width (keV)

Approach	$\Gamma(X(3872) \to \gamma J/\psi)$
[$c\bar{c}$], Ref. [9]	11
[$c\bar{c}$], Ref. [33]	71
[$c\bar{c}$], Ref. [33]	139
[molecule], Ref. [33]	8
Our results	124.8 - 231.3 ($\epsilon = 0.7$ MeV) 129.8 - 239.1 ($\epsilon = 1$ MeV) 138.0 - 251.4 ($\epsilon = 1.5$ MeV)

PRD77, 094013, 2008

New measurement of LHCb-1

- $\Gamma(X \to \psi(2S)\gamma)/\Gamma(X \to J/\psi\gamma) = 3.5 \pm 1.4$
  BABAR, PRL 102, (2009)
  possible evidence for charmonium component ?

Exotic charmonium-like spectroscopy at LHCb: a study of the X(3872) and of the $Z(4430)^-$ states

Radiative Decay $X(3872) \to J/\psi\,\gamma,\ \psi'\gamma$

- $X(3872) \to J/\psi\,\gamma$, E_γ=775 MeV
  VMD contributes (ρ, ω)
- $X(3872) \to \psi'\gamma$, E_γ=186 MeV
  can only proceed through light quark annihilation
  → expected small
  → BaBar measurement surprising
- New measurement by Belle Preliminary, QWG10, 711/fb

LHCb 1409.6472

$^1S_0$ $^3S_1$

To study this further, LHCb has recently measured [7] the ratio of branching fractions

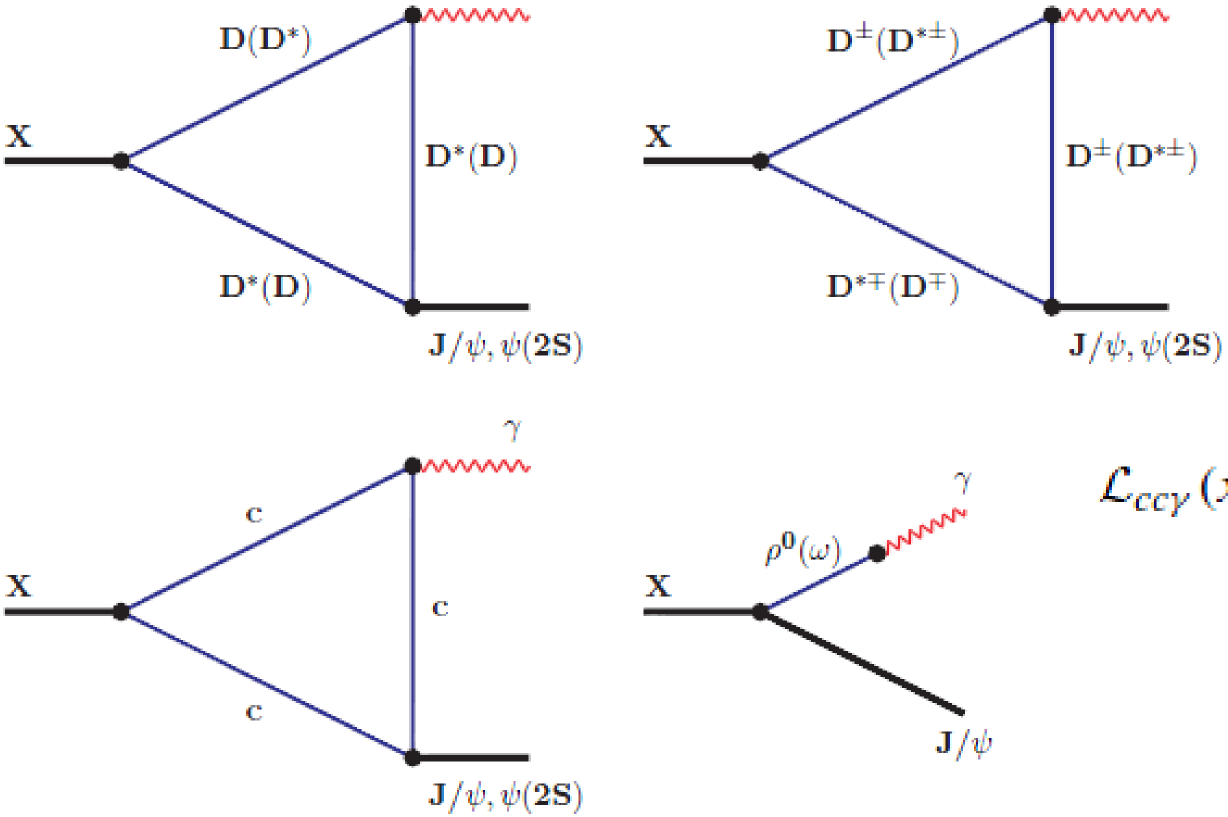
$$R_{\psi\gamma} = \frac{B(X(3872) \to \psi(2S)\gamma)}{B(X(3872) \to J/\psi\gamma)},$$

as a constraint on the charmonium content of the $X(3872)$. The branching fraction $B(X(3872) \to \psi(2S)\gamma)$ is in fact expected to be very small for a pure molecule ($O(10^{-3})$) [8–10], but it could be enhanced for an admixture of a $D^{*0}\overline{D}^0$ molecule and charmonium. The BaBar collaboration has measured a relative large branching fraction for the $X(3872)$ into $\psi(2S)\gamma$, with $R_{\psi\gamma} = 3.4 \pm 1.4$ [11], a result generally inconsistent with a pure molecular interpretation; in contrast, no significant signal was found by Belle [12].

$$R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

Including of $c\bar{c}$

$$|X(3872)\rangle = \cos\theta \left[\frac{Z^{1/2}_{D^0 D^{*0}}}{\sqrt{2}} (|D^0 \bar{D}^{*0}\rangle + |D^{*0} \bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}} (|D^+ D^{*-}\rangle + |D^- D^{*+}\rangle) + Z^{1/2}_{J_\psi \omega} |J_\psi \omega\rangle + Z^{1/2}_{J_\psi \rho} |J_\psi \rho\rangle \right] + \sin\theta \; |c\bar{c}\rangle .$$



$$\mathcal{L}_{cc\gamma}(x) = \frac{2e}{3} A_\mu(x) \bar{c}(x) \gamma^\mu c(x),$$

Diagrams contributing to the radiative transitions $X(3872) \to J/\psi + \gamma$ and $X(3872) \to \psi(2S) + \gamma$.

YBD, Faessler, Gutsche & Lyubovitskij, JPG38, 015001

Results (including) $c\bar{c}$

YBD, Faessler, Gutsche & Lyubovitskij, J. Phys. G38, 015001

Quantity	$c\bar{c}$	DD^*	$J/\psi V$	$DD^* + J/\psi V$	Total
Γ_{J_ψ}, keV	45	3.6	1.5	8	1.94
Γ_{ψ}, keV	64	0.01	0	0.01	6.8
R	1.1	3.3×10^{-3}	0	1.5×10^{-3}	$3.5\ (\theta = -20.2^0)$

$$|X(3872)\rangle = \cos\theta \left[\frac{Z^{1/2}_{D^0 D^{*0}}}{\sqrt{2}} (|D^0 \bar{D}^{*0}\rangle + |D^{*0} \bar{D}^0\rangle) + \frac{Z^{1/2}_{D^\pm D^{*\mp}}}{\sqrt{2}} (|D^+ D^{*-}\rangle \right.$$

$$\left. + |D^- D^{*+}\rangle) + Z^{1/2}_{J_\psi \omega} |J_\psi \omega\rangle + Z^{1/2}_{J_\psi \rho} |J_\psi \rho\rangle \right] + \sin\theta\ |c\bar{c}\rangle.$$

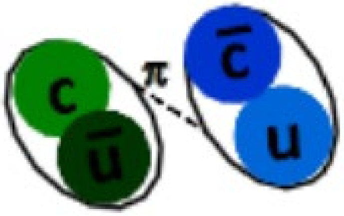
Interference effect, by the admixture θ, plays a crucial role to understand the measured ratio

BABAR

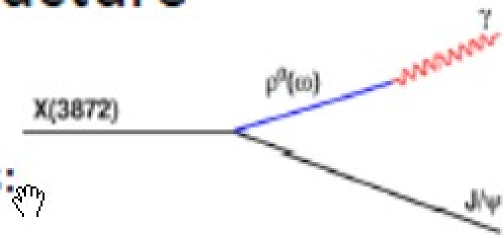
$$R = \frac{\mathcal{B}(X(3872) \to \psi(2S)\gamma)}{\mathcal{B}(X(3872) \to J/\psi\gamma)} = 3.5 \pm 1.4.$$

$$R_{\psi\gamma} = 2.46 \pm 0.64 \pm 0.29,$$

LHCb

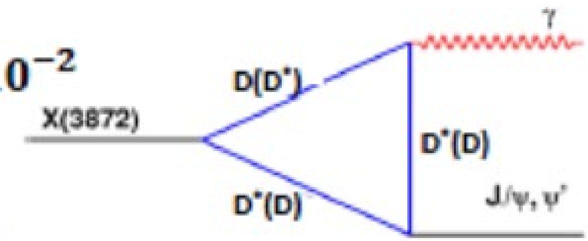


Radiative decay and X(3872) structure



Radiative decays can proceed via two mechanisms:

- ✓ Vector meson dominance
- ✓ Light quark annihilation



If pure molecular :- Phys.Rept. 429,243(2006)

$\mathcal{BR}(X(3872) \to \psi'\gamma) < \mathcal{BR}(X(3872) \to J/\psi\gamma)$ $\sim 10^{-2}$

If tetraquark PRD 109,074009(2024)

$\mathcal{BR}(X(3872) \to \psi'\gamma) \gtrsim \mathcal{BR}(X(3872) \to J/\psi\gamma)$ $\sim 0.8 - 1.1$

If X(3872) is 1^{++} $c\bar{c}$:- PRD 73,014014(2006)

$\mathcal{BR}(X(3872) \to \psi'\gamma) > \mathcal{BR}(X(3872) \to J/\psi\gamma)$ $\sim 5 - 15$

If X(3872) is admixture of $D^0 \bar{D}^{*0}$ bound state with a $c\bar{c}$ meson :

$\mathcal{BR}(X(3872) \to \psi'\gamma) / \mathcal{BR}(X(3872) \to J/\psi\gamma)$ will suggest the admixture ratio. $\sim 0.5 - 5$

Precise measurement of this ratio is important to understand X(3872) nature.

17

Courtesy of V. Bhardwaj

LHCb meets Theory: Probing the nature of the $X(3872)$ state using radiative decays

星期四 2024年6月27日 00:40 → 19:30 Europe/Zurich

17/1-007 (CERN)

Lorenzo Capriotti (Universita e INFN, Ferrara (IT)), Mengzhen Wang (Università degli Studi e INFN Milano (IT)), Vanya Belyaev (Sapienza Universita e INFN, Roma I (IT))

Probing the nature of the χ_{c1} state using radiative decays

LHCb Collaboration *arXiv:2406.17006*

The radiative decay of $\chi_{c1} \rightarrow \psi(2S)+\gamma$ are used to probe the nature of the $\chi_{c1}(3872)$ state using proton-proton collision data collected with the LHCb detector, corresponding to an integrated luminosity of 9 fb^{-1}. Using the $B^+ \rightarrow \chi_{c1}(3872)\, K^+$ decay, the $\chi_{c1} \rightarrow \psi(2S)+\gamma$ is observed for the first time and the ratio of its partial width to that of the $\chi_{c1} \rightarrow J/\Psi+\gamma$ decay is measured to be

$$\frac{\Gamma(\chi_{c1}(3872) \rightarrow \psi(2S)\gamma)}{\Gamma(\chi_{c1}(3872) \rightarrow J/\psi\gamma)} = 1.67 \pm 0.21 \pm 0.12 \pm 0.04$$

★Near threshold
★Narrow width
★Heavy flavor

where the first uncertainty is statistical, the second systematic and the third is due to the uncertainties on the branching fractions of the $\psi(2S)$ and J/Ψ mesons. The measured ratio makes the interpretation of the $\chi_{c1}(3872)$ state as a pure $[D^0 \bar{D}^{*0} + \bar{D}^0 D^{*0}]$ molecule questionable and strongly indicates a sizeable compact charmonium or tetraquark component with the $\chi_{c1}(3872)$ state

LHCb meets Theory: Probing the nature of the $X(3872)$ state using radiative decays

星期四 2024年6月27日 00:40 → 19:30 Europe/Zurich

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$$\frac{\Gamma(\chi_{c1}(3872)\to\Psi(2S)\gamma)}{\Gamma(\chi_{c1}(3872)\to J/\psi\,\gamma)} = 1.67\pm0.21\pm0.12\pm0.04$$

Discussions (XYZ particles):

Molecular scenarios: threshold effect

narrow width

large size

heavy flavor

Admixture: loosely bounded + compact part

3. Compact scenario of d*(2380) dibaryon

Phenomenological quark model approach

(with Beijing group, Prog.part.nucl.phys.,131 (2023),104045)

Dibaryon: deuteron--1932

- Binding energy ~2.2MeV, or 1.1MeV/A

  Which has to be compared to the averaged binding energy of 8 MeV/A in Nuclei

- Its charge radius of 2.1fm (loosely bounded)

  The centers of the proton and neutron are far apart from each other than the pion exchange range r~hc/mπ ~1.4fm

- Proton-neutron (dominated),

  six-quark content (2-3% or 0.15-0.3%)+ ΔΔ(0.4%)

Beginning: (★Dyson and Xuong, 1964)

1964, when quarks were still perceived as merely mathematical entities SU(6) multiplet in 56×56 product: contains the SU(3) \bar{10} and 27;

Deuteron D_{01} and NN virtual state D_{10}➔$D_{12}(N\Delta)$ and $D_{03}(\Delta\Delta)$

$M \sim A + B[I(I+1) + S(S+1) - 2]$ with the NN threshold mass 1878, a value B ~ 47MeV was reached by assigning D_{12} to $pp \leftrightarrow \pi^+ d$ resonance at $\sqrt{s} = 2160\,MeV$ (near the $N\Delta$ threshold)

➔$M(D_{03})$=2350MeV. This dibaryon has been the subject of several quark-based model calculations since 1980---by A. Gal

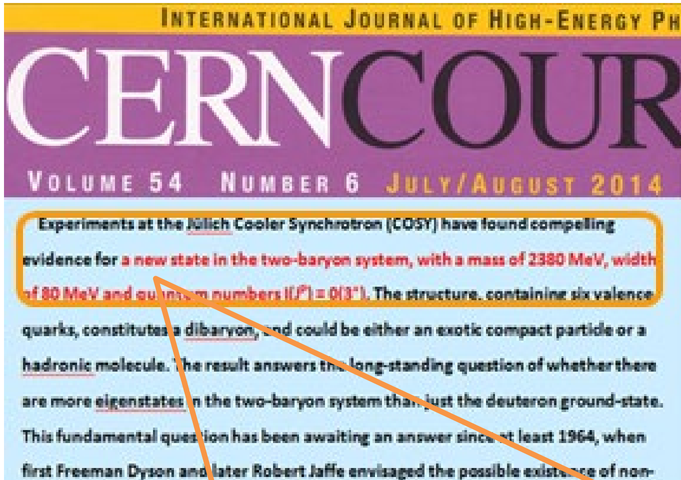
non-strange

Nonstrange s-wave dibaryon SU(6) predictions

$\mathcal{D}_{IS}$

Mass$_{MeV}$	dibaryon	I	S	SU(3)	legend	mass
1876	$\mathcal{D}_{01}$	0	1	$\overline{10}$	deuteron	A
1876	$\mathcal{D}_{10}$	1	0	27	nn	A
2160	$\mathcal{D}_{12}$	1	2	27	$N\Delta$	$A+6B$
2160	$\mathcal{D}_{21}$	2	1	35	$N\Delta$	$A+6B$
2350	$\mathcal{D}_{03}$	0	3	$\overline{10}$	$\Delta\Delta$	$A+10B$
2350	$\mathcal{D}_{30}$	3	0	28	$\Delta\Delta$	$A+10B$

observation: d*(2380)_light flavor dibaryon



INTERNATIONAL JOURNAL OF HIGH-ENERGY PHYSICS

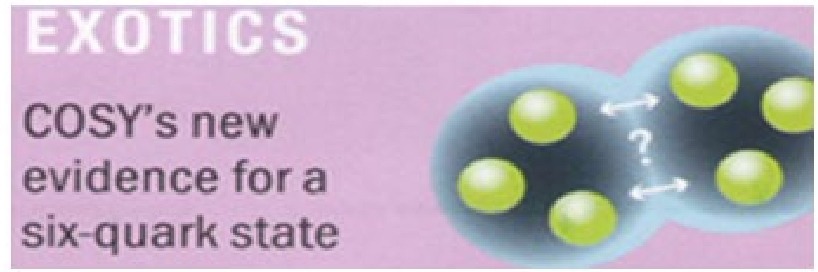
CERNCOURIER

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-

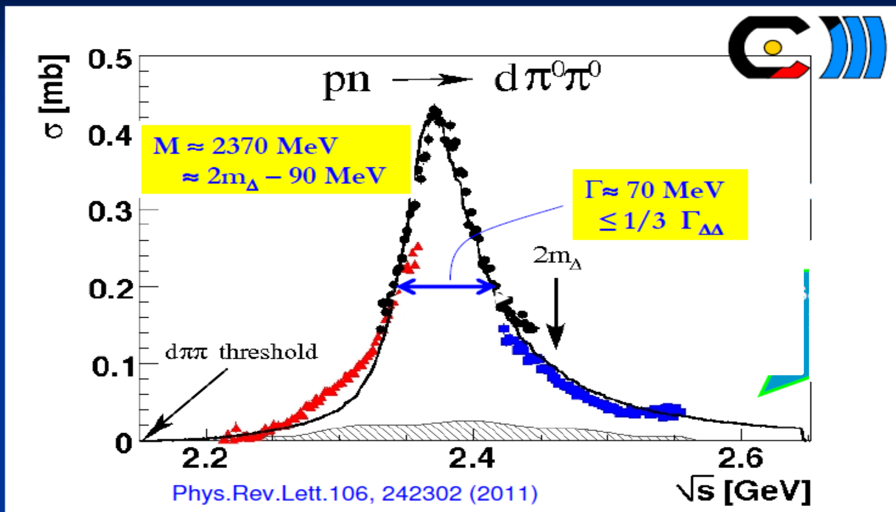
cerncourier.com/cws/article/cern/57836

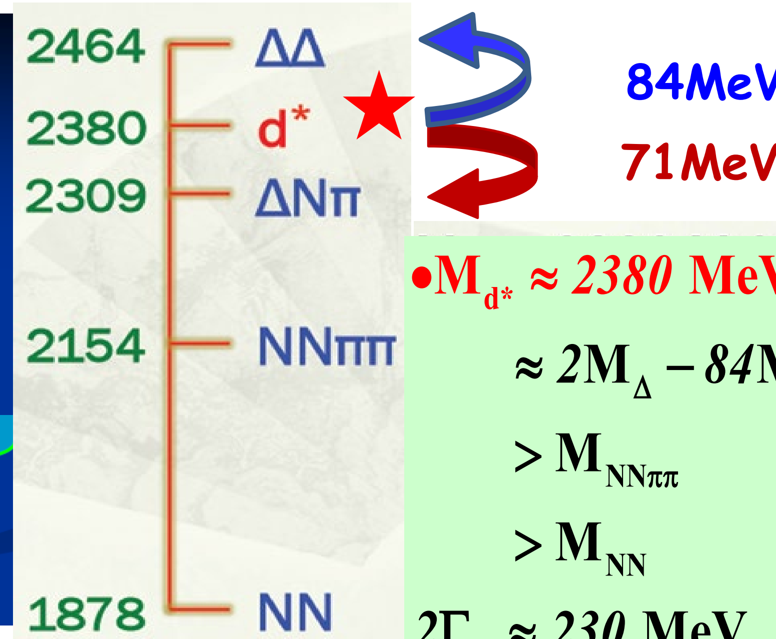
(2014)



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

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





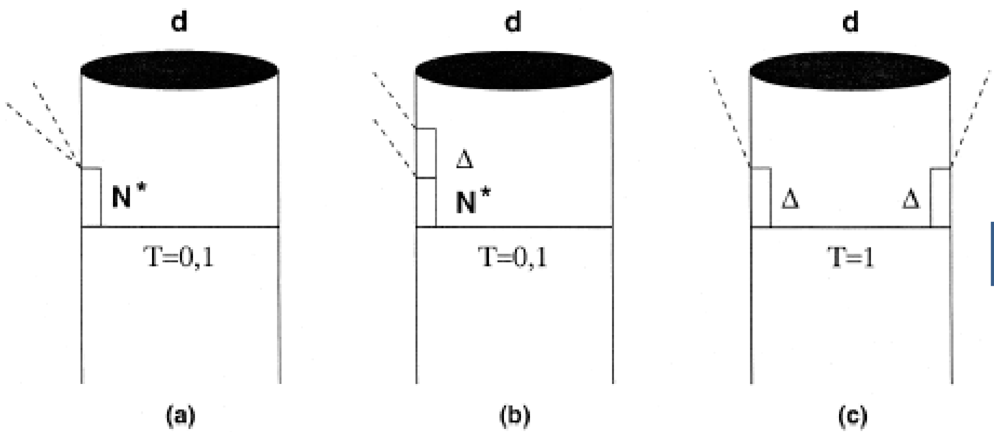
- $M_{d^*} \approx 2380$ MeV
  $\approx 2M_\Delta - 84$ MeV
  $> M_{NN\pi\pi}$
  $> M_{NN}$

$2\Gamma_\Delta \approx 230$ MeV

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

★Baryon number=2

★Unusual narrow width



Neither N*N (Roper), nor ΔΔ Intermediate state

They need this d*(2380)

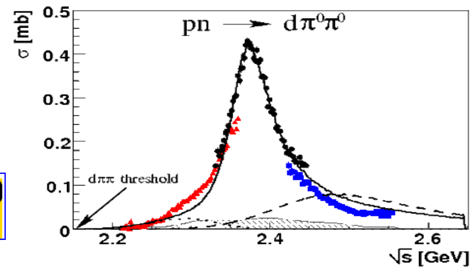
Signals in np processes WASA @ COSY

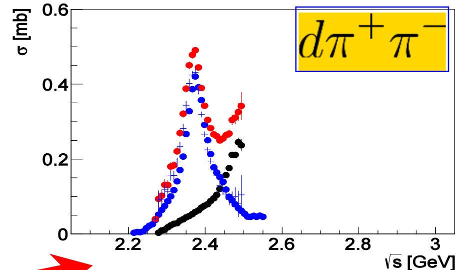
2π production processes

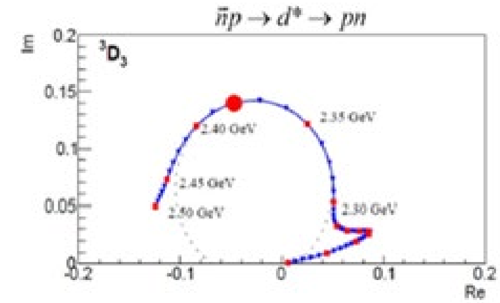
np scattering process

PRL 106 (2011) 242302
PLB 721 (2013) 229

● ● ● WASA data



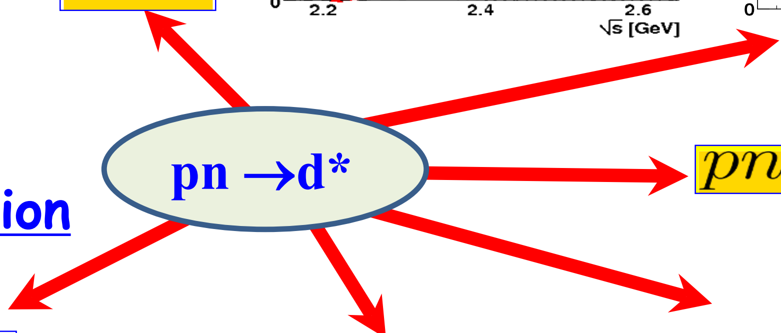


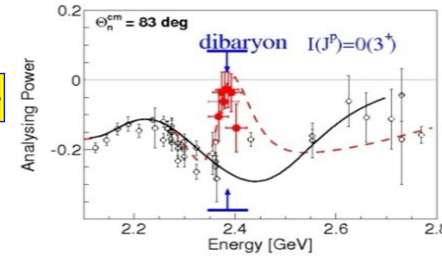


Fusion

$d\pi^0\pi^0$

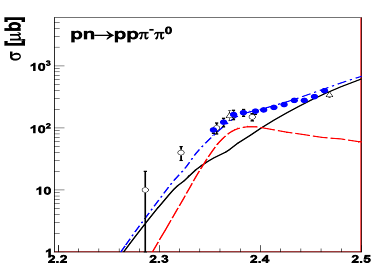
Non-fusion

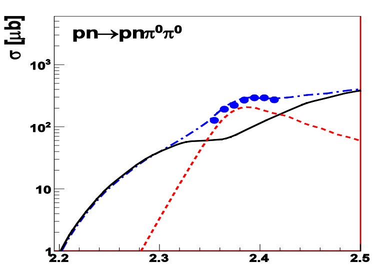


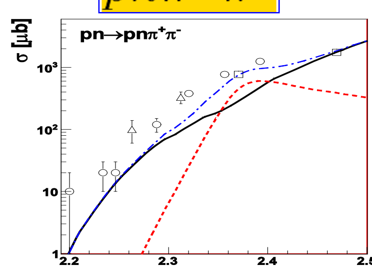


fusion 2π processes

$pp\pi^-\pi^0$ $pn\pi^0\pi^0$ $pn\pi^+\pi^-$







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 the d*(2380) 0(3⁺)

- d* locates between ΔΔ and ΔNπ thresholds

♥ Effect from threshold is expected to be small

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

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

$\Gamma_{d^*} \approx 80 MeV$

$M_{\Delta\Delta} = 2460\ MeV$

71MeV

84MeV

- d* narrow width → Possible 6q structure

Review article: by Heinz Clement,

Progress in Particle and Nuclear Physics,

93 (2017), 195-142

be different

from normal hadrons

★ Possible interpretation of d*(2380)

▲ **Before COSY's observation**

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)……

★ Possible interpretation of d*(2380) compact 6q dominated

▲ After COSY's observations

- **Quark model**

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

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

★ F.Huang, YBD, Zhang. (14-18)--ΔΔ+CC QM

→ A),a compact 6q dominated exotic state

- **Hadronic model**

Gal (14)---ΔNπ

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

→ B), a ΔNπ (or $D_{12}\pi$) resonant state

- Some Other interpretations

Bashkanov, Brodsky, H.Clement

Phys.Lett.B727 (2013) 438

Ansatz

According to M. Harvey [66]

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

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

- **d* narrow width**

$\Delta\Delta$ width:

$$\Gamma_{\Delta\Delta} = 230 MeV$$

Here $\Delta\Delta$ means the asymptotic $\Delta\Delta$ configuration and 6Q is the genuine "hidden color" six-quark configuration. The first solution denotes a S^6 quark structure (all six quarks in the S-shell).

Binding about 90MeV

$$\Gamma_{\Delta\Delta} = 160 MeV$$

- *Cluster*
- *Quark degrees of freedom*

The observed d*(2380) must be of
an unconventional
origin, probably 6q structure

★SU(3) chiral constituent quark model: SU(3) CCQM (Beijing Group)

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

- **Quark model framework**

SU(3) chiral QM + RGM approach (light flavor)

▲ **Interactions:** $V_{ij} = V_{ij}^{Conf.} + V_{ij}^{OGE} + V_{ij}^{ch} + V_{ij}^{chv}$

q-q potential $V_{ij}^{ch} = \sum_a (V_{ij}^{s(a)} + V_{ij}^{ps(a)})_{scalar+PS}$

Interactive Lagrangian

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

$$\begin{cases} \sigma_a : scalar\ nonet\ fields \\ \pi_a : psudoscalar\ nonet\ fields \end{cases}$$

★Extended SU(3) chiral constituent quark model: SU(3)ECCQM *in quark degrees of freedom*

$$\mathcal{L}_I = -\bar{\Psi}\left(g_{chv}\gamma_\mu \sum_a^8 \rho_a^\mu \lambda^a + \frac{f_{chv}}{2M_N}\sum_a^8 \sigma_{\mu\nu}\partial^\mu \rho_a^\nu \lambda^a\right)\Psi,$$

ρ_a : *vector nonet fields*

★Model parameters:

could well-reproduce and match the experimental data for the N-N scatterings

--- NN phase shifts;

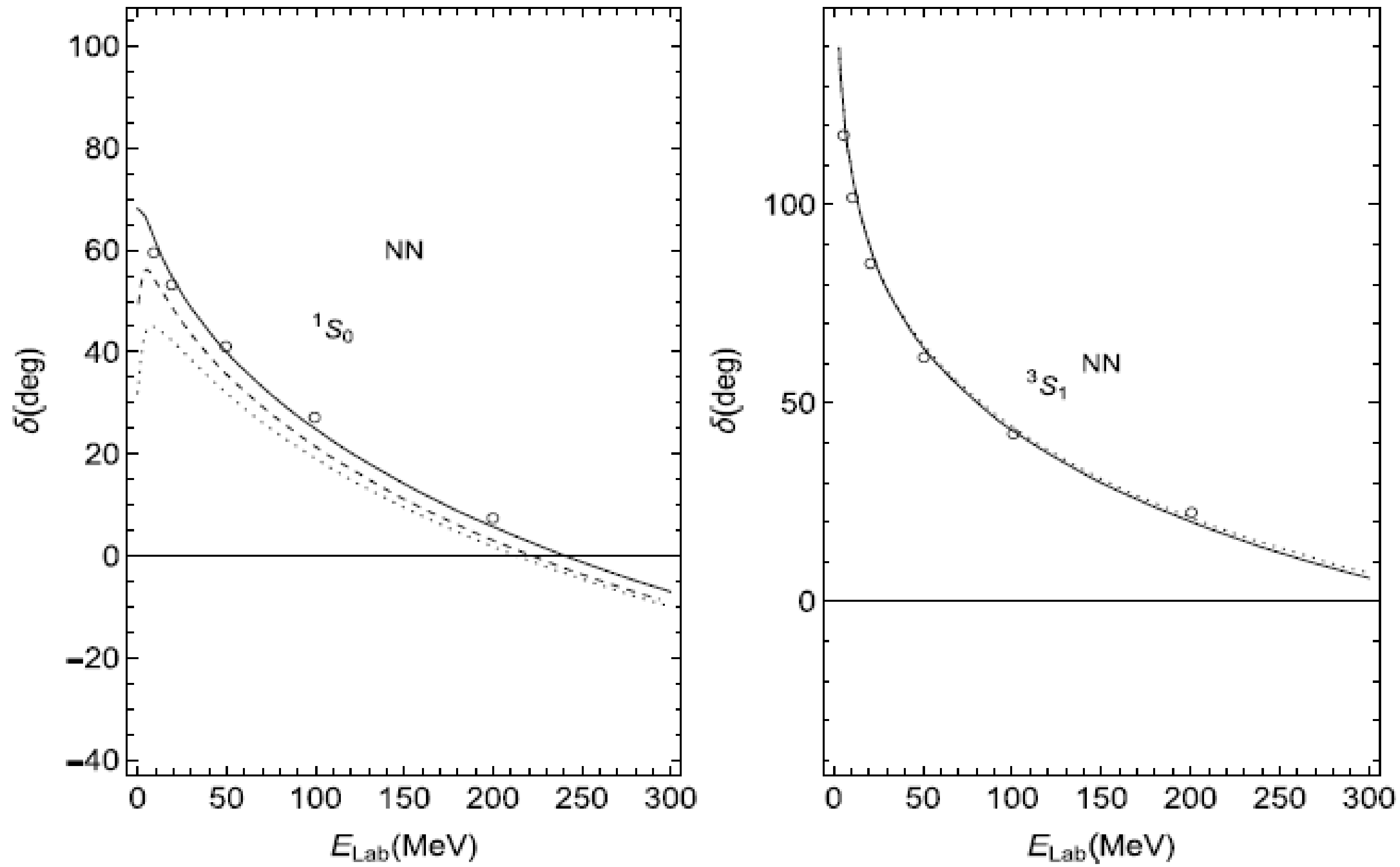
& hyper-nucleon interaction

+ deuteron properties { *bingding*, *size* }

Binding Energy $(BE)_d^{Expt} = 2.22 MeV$

Values of model parameters in *SU*(3)CCQM and *SU*(3)ECCQM

	SU(3)CCQM	*SU*(3)ECCQM	
		Set I	Set II
b_u (fm)	0.5	0.45	0.45
$g_{NN\pi}$	13.67	13.67	13.67
g_{ch}	2.621	2.621	2.621
g_{chv}	0	2.351	1.973
f_{chv}/g_{chv}	0	0	2/3
m_σ (MeV)	595	535	547
g_u	0.875	0.237	0.363
α_s (g_u^2)	0.766	0.056	0.132
a_{uu}^c (MeV/fm^2)	46.6	44.5	39.1
a_{uu}^{c0} (MeV)	−42.4	−72.3	−62.9
$B_{deuteron}$ (MeV)	2.09	2.24	2.20



The S-Wave phase shifts of the N-N scattering in SU(3)CCQM and SU(3) ECCQM. Dotted, dashed and solid curves: (f/g=0, 2/3).

▲ Trial wave function of d*

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

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

★ 6-quark two clusters + 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)

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

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

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

●**the two components orthogonal**

★**the quark exchange effect included**

On d*(2380) Properties

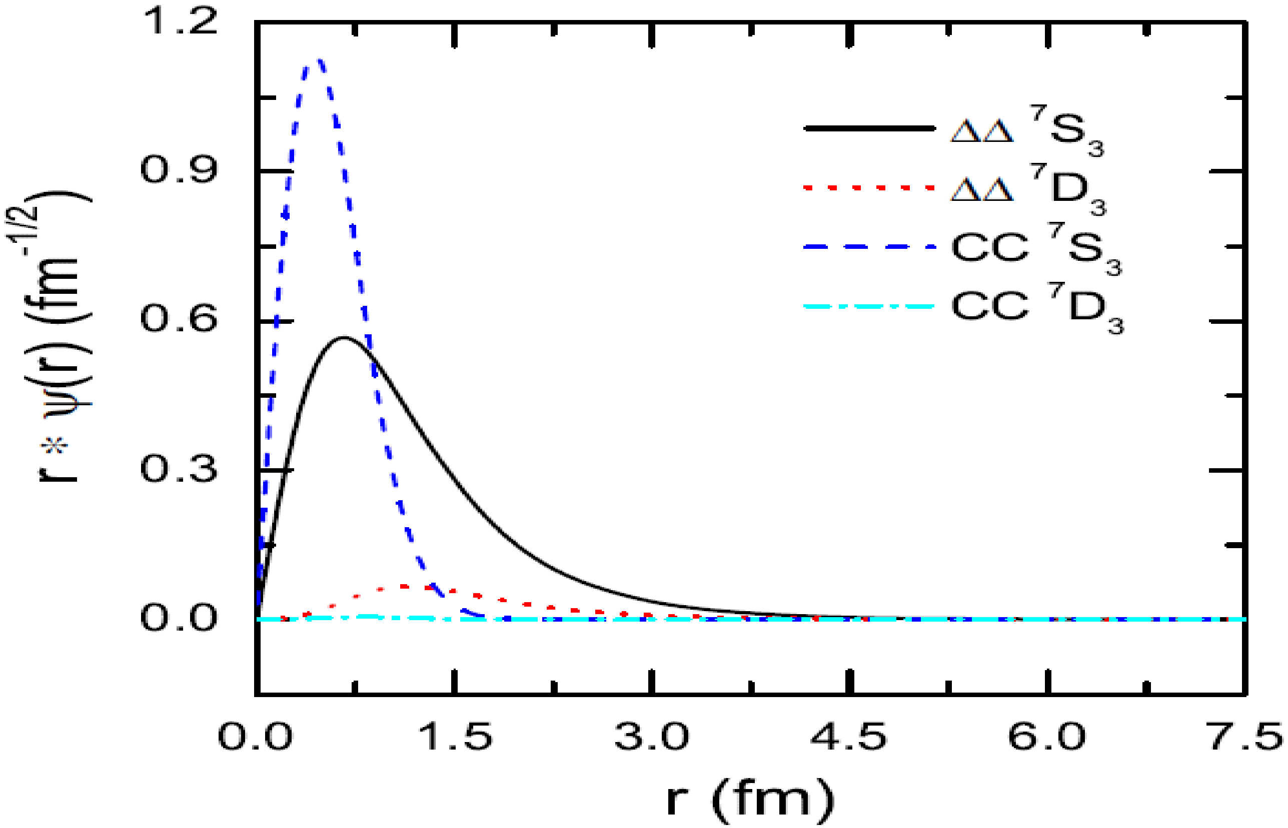
a, Mass & wave function of d*(2380)

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

▲ **Results:**

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

d* (WFs)



- Binding energy (BE)

$$(BE)_{d*}\begin{cases}Expt.\sim\ 84\,MeV\\ Theor.\sim 84\,MeV\end{cases}$$

$I(J^P)=0(3^+)$		Ext. SU(3) (f/g=0)	
PRC 60 (1999) 045203		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

■1, Intrinsic character of d*

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

■ 2, Dynamical effect

(IS=03) ， OGE & vector meson exchange induced Δ-Δ short range interaction is attractive

**d* deep bound & narrow width

The observed d*(2380) must be of an unconventional origin

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

Reason for large component of CC (67%) — Due to quark exchange effect

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

exchange effect in spin-flavor-color spaces

intrinsic	$(\Delta\Delta)_{SI=30}$ $(\Delta\Delta)_{SI=30}$	$(\Delta\Delta)_{SI=30}$ $(CC)_{SI=30}$	$(CC)_{SI=30}$ $(CC)_{SI=30}$
$<P^{sfc}_{36}>$	$-\frac{1}{9}$	$-\frac{4}{9}$	$-\frac{7}{9}$

$<P^{r}_{36}>$ 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.

⟶ Two clusters ΔΔ closer,

1) d* special characters
spin-flavor-color spaces exchange effect

should also large

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

Dynamical effect ⟷ Model independent

d* might be a 6q dominant state

P_{36} Effect large, large CC component

⟶ d* deep bounded and narrow width

b, Strong decay_I:

▲ 2π decay widths

PRC91 064002, PRC94 014003

Three-body decay

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

$d^* \rightarrow d\pi^0\pi^0$

$d^* \rightarrow d\pi^+\pi^-$

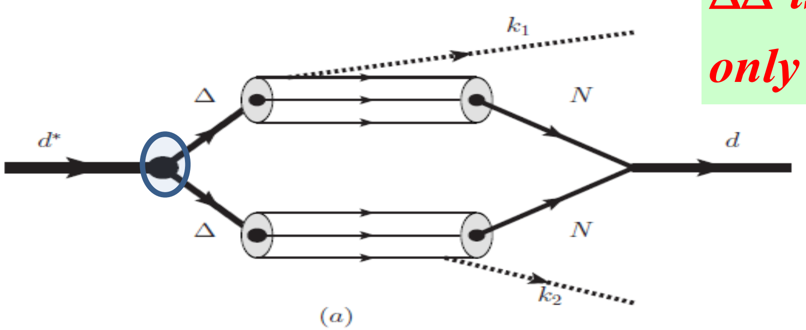
Typical diagram

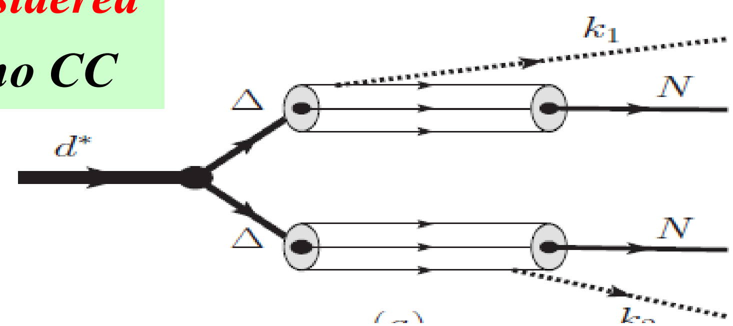
ΔΔ is considered only and no CC

Four-body decay

$d^* \rightarrow pn\pi^0\pi^0 (pn\,\pi^+\pi^-)$

$d^* \rightarrow nn\pi^0\pi^+ (pp\pi^0\pi^-)$





Parameters:

$\Delta \rightarrow N\pi$

$qq\pi$

Interaction

Coupling & form factor

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

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

Our interpretation of d*_Compact 6q dominated exotic state

(wave function of SU(3) (CQM+ECQM))

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

PRC91,064002(15), PRC94,014003(16) $I(J^P) = 0(3^+)$

	Theor.(MeV)	Expt.(MeV)
$d^* \rightarrow d\pi^+\pi^-$	16.8	16.7
$d^* \rightarrow d\pi^0\pi^0$	9.2	10.2
$d^* \rightarrow pn\pi^+\pi^-$	20.6	21.8
$d^* \rightarrow pn\pi^0\pi^0$	9.6	8.7
$d^* \rightarrow pp\pi^0\pi^-$	3.5	4.4
$d^* \rightarrow nn\pi^0\pi^+$	3.5	4.4
$d^* \rightarrow pn$	8.7	8.7
Total	71.9	74.9

▲ **2π decay widths**

* **All partial and total widths agree with data reasonably**

$$\begin{cases} \Gamma^{Expt} = 70 \sim 75\text{MeV} \\ \Gamma^{Theor.} \approx 72\text{MeV} \end{cases}$$

The narrow width is due to large CC component

①, *Compact structure: size~~0.8fm*

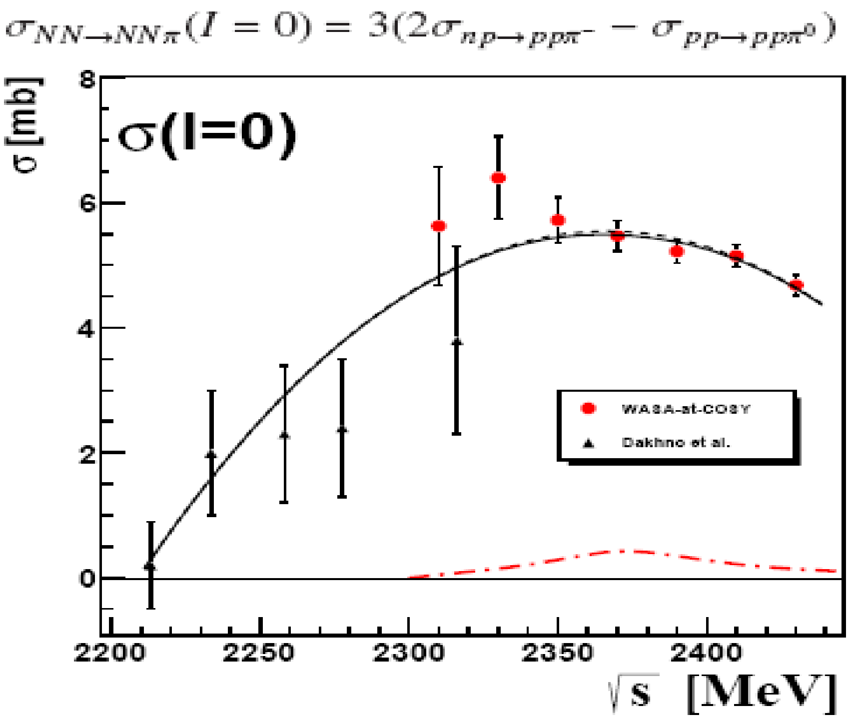
②, *Components*

$$|d^*> \sim \sqrt{\frac{1}{3}}|\Delta\Delta> + \sqrt{\frac{2}{3}}|CC>,$$

③, *ΔΔ component plays of the most important role in the calculations*

c, Strong decay_II: Single-pion decay

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



- **Experimental status**

  The WASA-@-COSY Collaborations,

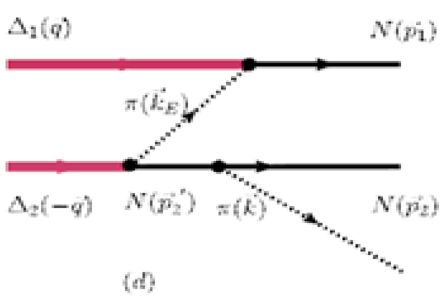
  PLB774 (2017), 599-607

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

Upper limit of branching ratio for "d*(2380)→NNπ" <u>is around 9%.</u>

This channel might serve as a test!

One of Typical diagrams



ΔΔ is considered only and no CC

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

Comparison of two interpretations

(A) Compact quark model: (deeply) (B) $\Delta\pi N$ three-body system:

Good √ Quarks

Mass, energy and Double-pion strong decays

Good √ Hadrons

d*(2380) single-π decay

Our prediction 1% which is compatible with the experimental up-limits

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

The result of three-body ($\Delta\pi N$) scenario is about 18%.

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

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

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

Exp. gives 9% up-limit

Recently (PLB769) In order to match the up-limit of exp.

EM Form Factors:

Photo-absorption on deuteron by *d*(2380)*

More sophisticated admixture

$$|d^*> \approx \sqrt{\frac{5}{7}}\,|\Delta\Delta> + \sqrt{\frac{2}{7}}\,|N\Delta\pi>$$

Cloud

d, Form factors of d*

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

Form factors: 2S+1 relative to size

arXiv:1704.01253, PRD96,094001

Nucleon(s-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 (s-1): $J_{jk}^\mu(p',p) = \epsilon_j^{\prime *\alpha}(p')S_{\alpha\beta}^\mu\epsilon_k^\beta(p)$

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

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

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

Breit frame

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

EM current (7 form factors, S=3)

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

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

$$q_\mu \mathcal{M}^\mu_{\alpha'\beta'\gamma',\alpha\beta\gamma} = 0$$

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

Electric multi-poles

$$G^E_l(Q^2) = \frac{(2M_{d^*})^l}{e}\sqrt{\frac{4\pi}{2l+1}}\frac{(2l+1)!!}{l!Q^l}\mathcal{I}_{El}(Q^2),$$

with e being the unit of charge and

$$\begin{aligned}
\mathcal{I}_{El}(Q^2) &= \langle d^*|\sum_{i=1}^{6}\int d^3r[d^3X]e_i j_l(Q|\vec{r}_i - \vec{R}|)Y_{l0}(\Omega_{r_i})|d^*\rangle \\
&= 3\langle d^*|\int d^3r[d^3X][e_3 j_l(Q|\vec{r}_3 - \vec{R}|)Y_{l0}(\Omega_{\vec{r}_3-\vec{R}}) \\
&\quad + e_6 j_l(Q|\vec{r}_6 - \vec{R}|)Y_{l0}(\Omega_{\vec{r}_6-\vec{R}})]|d^*\rangle,
\end{aligned}$$

Magnetic multi-poles

$$\langle d^*|\rho^M(\vec{q})|d^*\rangle = e\sum_{l=0}^{+\infty} i^l\tau^{l/2}\frac{l+1}{\tilde{C}^{l-1}_{2l-1}}G_{Ml}(Q^2)Y_{l0}(\Omega_q), \quad (10)$$

where $\rho^M(\vec{q})$ denotes the magnetic density of the system with $\tau = \frac{Q^2}{4M^2_{d^*}}$, and

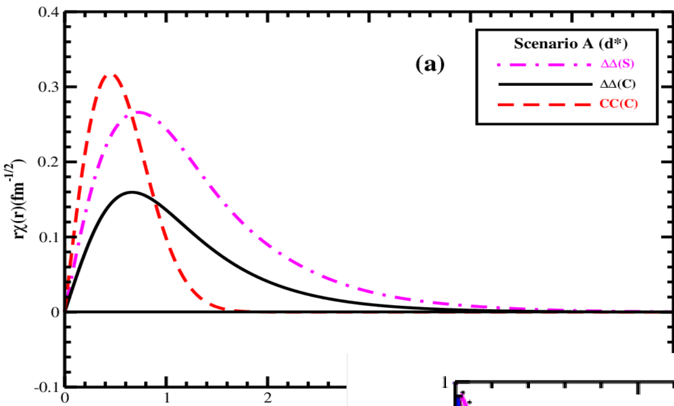
If we only consider the quark-photon coupling, we can write the magnetic density as $\rho^M(\vec{r}) = \sum_{i=1}^6 \vec{\nabla}\cdot(\vec{j}_i(r)\times\vec{r}_i)$ with $\vec{j}_i(r)$ and $\vec{r}_i$ being the current and position vectors for the ith quark in the coordinate space, and $\rho^M(\vec{q}) = \sum_{i=1}^6 \vec{\nabla}\cdot[(e_i\vec{\sigma}_i\times\vec{q})\times\vec{q}] = 2\sum_{i=1}^6 e_i\vec{\sigma}_i\cdot\vec{q}$ with $\vec{\sigma}_i$, e_i, and $\vec{q}$ being the Pauli matrix, the charge for the ith quark and the transferred momentum, respectively.

(a) Compact quark model

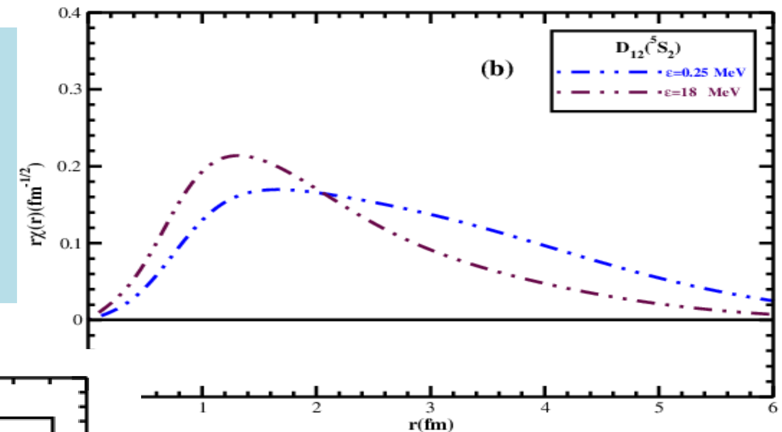
(b) πΔN three-body system

d*(2380) charge distributions

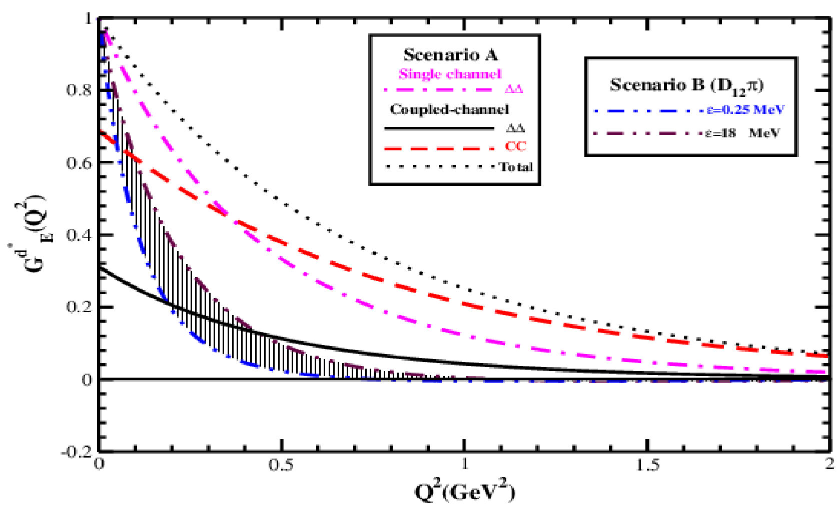
Cases	$d^*(2380)$		D_{12}
	A1	A2	
$rms \quad (fm)$	1.09	0.78	2.39



Wave functions



both ΔΔ and CC are considered



Magnetic Moment

Naïve quark model

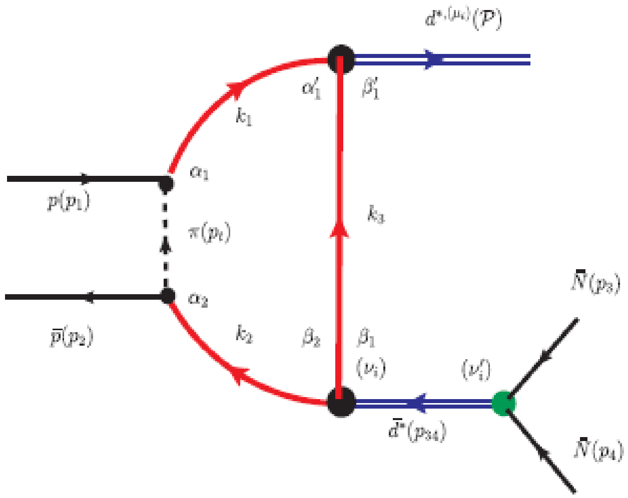
Nucleon $\frac{\mu_p}{\mu_n} = -\frac{3}{2} \rightarrow -\frac{2.79}{1.91}_{EXPT.}$

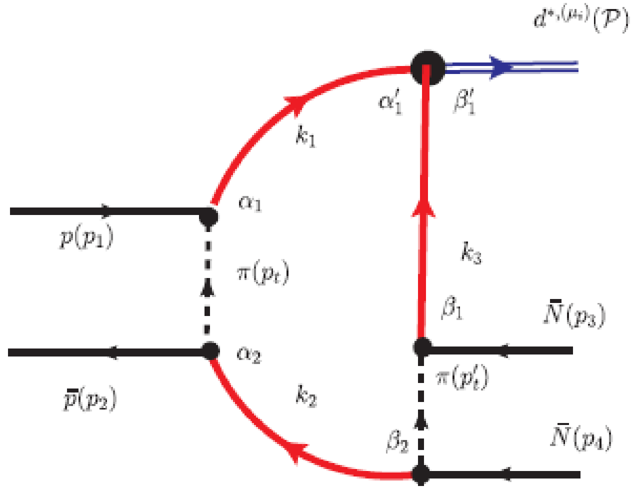
d*(2380) ΔΔ+CC $\mu_{d^*} = \frac{M_{d^*}}{m_q} \approx 7.6$

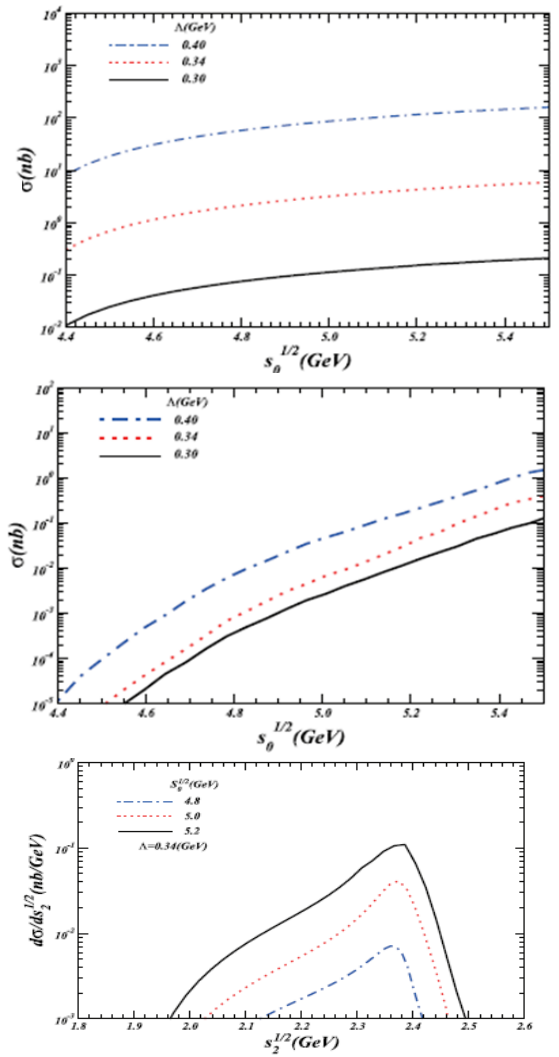
d*(2380) D12π $\mu_{d^*} = \frac{2M_{d^*}}{3m_q} \approx 5.1$

e, Productions at other facilities

$$p+\bar{p}\rightarrow d^*(2380)+(\bar{p}+\bar{n})$$







$$\mathcal{L}_{d^*pn} = g_{d^*pn} q_{\mu_1}^{(pn)} q_{\mu_2}^{(pn)} \bar{\psi}_N \gamma_{\mu_3} \psi_N^C \times (d^*(\mathcal{P}))^{(\mu_i)} + \text{h.c.},$$

★1, *ΔΔ Contribution*
★2, *Compact system*
★3, *Breit-Wigner form considered*

Panda

LM: $2\times10^{32}cm^{-2}/s$

$\sqrt{s_0}=(4.8, 5.0, 5.2, 5.4)GeV$

$(3.6, 5.6, 7.2, 9.3)\times10^4{}_{evens}$

$(20, 100, 600, 3200)_{evens}$

♣ Discussions: for d*(2380)

★ ① Our SU(3)(CCQM & ECCQM) approaches, in quark degrees of freedom, are employed to study the mass, and wave function of [d*(2380), 3^+]. These approaches could well reproduce the experimental data for the N-N scatterings as well as the properties of deuteron and hyperon-nucleon interaction, and the model parameters are fixed.

★ ② Within the approaches and by employing the same set of parameters, the mass of d*(2380) is well-reproduced and its wave function is expressed as ΔΔ+CC, hidden color parts dominated.

$$|d^* > \sim \sqrt{\frac{1}{3}}|\Delta\Delta > + \sqrt{\frac{2}{3}}|CC >,$$

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

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

novel

★ ③ It is a compact 6-quark state with some portions |ΔΔ> and |cc> components, due to its spin and quark exchange effect.

★④ We also obtained channel wave function for the two channels and they are orthogonal. Then, the channel wave function are employed to calculate the strong decays of d*(2380). Double pion decays are well reproduced comparing the available measurement, and the single pion decay is expected to be much small.

★⑤ The electromagnetic form factors of d*(2380) are also calculated and its charge radius, magnetic moments, quadupole moments are obtained. The scenarios of compact and loosely bounded are compared.

★⑥ More experimental information of this dibaryon is necessary to confirm its existence. Some possible observation is predicted.

- ***Suggest other possible experimental searchings for it***

and study for possible dibaryon signals (non-strange):

① *Process* (*Mainz, Jlab., ELPH, BGOOD*): $\gamma + d$

② *Process* (*Belle*), *Y-decays*: $\Upsilon \to \overline{d}^* + X$, $BR(\Upsilon \to \overline{d} + X)_{已知} \sim 2.9 \times 10^{-5}$

③ *Processes* (*BEPC, Babar, Belle?*) : $e^+ + e^- \to \overline{d}^* + p + n$

④ *Processes* (*Panda*) : $p + \overline{p} \to \overline{d}^* d^* + X$

Other Than WASA@COSY NICA: $p+n$, $p+d$, $d+d$

- ***Theoretical study of other dibaryon candidates:***

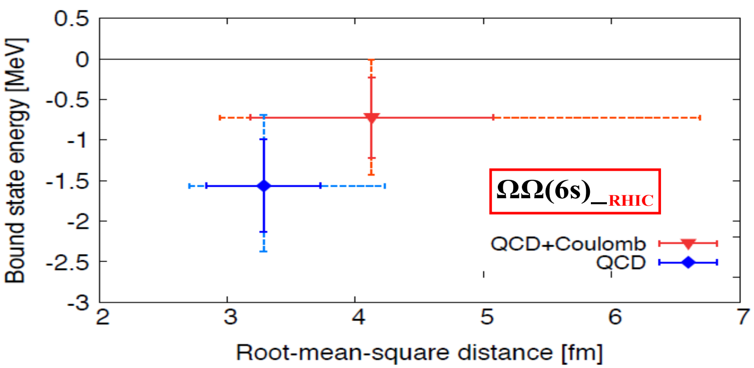
[★ $d_{(S=3,I=0)}$*(2380): $|d^*> \sim \sqrt{\frac{1}{3}}|\Delta\Delta> + \sqrt{\frac{2}{3}}|CC>$, $d_{(S=0,I=3)}$*(???)],

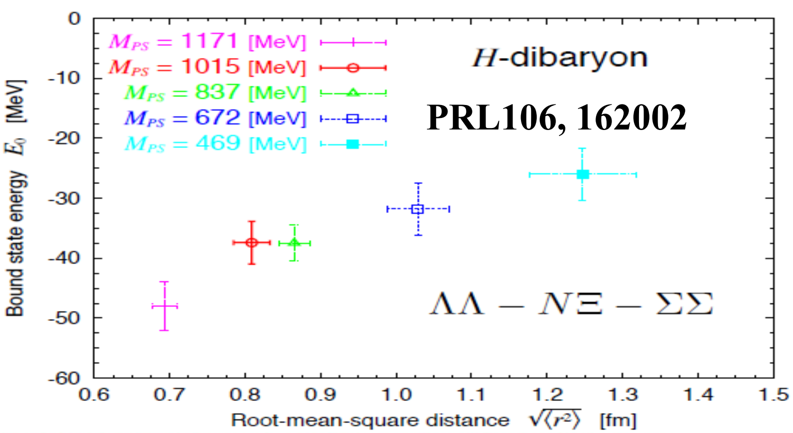
[$D_{(S=2,I=1)}$, $D_{(S=1,I=2)}$], [Roper+Δ]_Wasa@Cosy

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

Some Lattice Calculations (HALQCD)

Binding energy

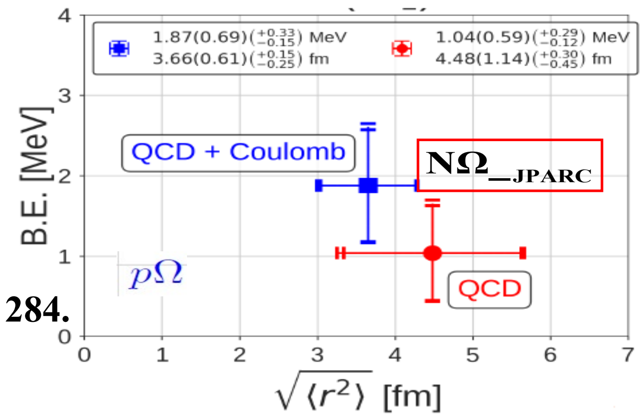




An H-dibaryon exists in the flavor SU(3) limit.
Binding energy = 25-50 MeV at this range of quark mas
A mild quark mass dependence.

Other Di-baryons_Lattice

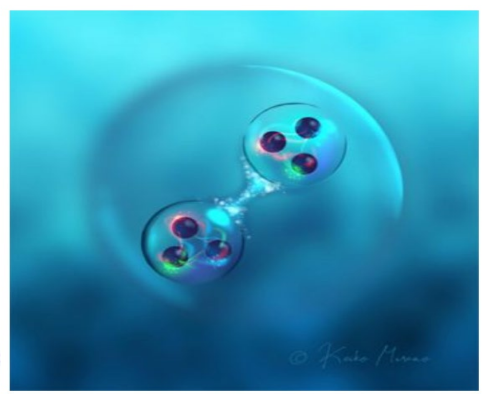
Preliminary !



PLB 792, 284.

Dibaryon with Highest Charm Number near Unitarity from Lattice QCD

Yan Lyu, Hui Tong, Takuya Sugiura, Sinya Aoki, Takumi Doi, Tetsuo Hatsuda, Jie Meng, and Takaya Miyamoto
Phys. Rev. Lett. **127**, 072003 – Published 11 August 2021



チャームダイオメガ（ΩcccΩccc）のイメージ図

Some others: deuteron-like (shallow bounded) heavy dibaryons, PRL123,162003

4. Summaries and Discussions

- The study of XYZ hadronic exotics and other possible dibaryons (multiquark) structures are essential for our understanding of hadron structures.

- It opens a window of the interpretations of those exotics.

- No definite conclusion has been drawn for the structures of those exotics. Some possible explanations: molecular scenario or compact picture seem to be successful for some sophisticated structures and for struetures.

- More efforts are still needed in both theoretical study and experimental measurements.

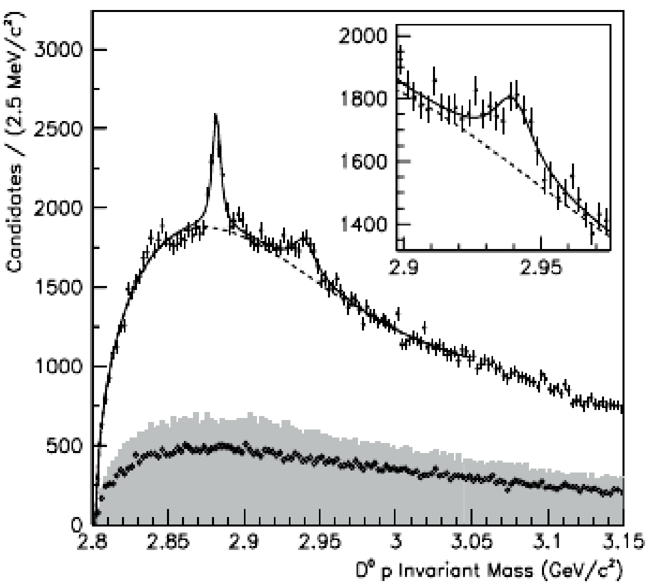
Thanks for your attention!

$\Lambda_c(2940)^+$ $\Sigma_c(2800)$

PRL 98, 012001 (2007) PHYSICAL REVIEW LETTERS week ending 5 JANUARY 2007

Observation of a Charmed Baryon Decaying to D^0p at a Mass Near 2.94 GeV/c^2

(BABAR Collaboration)



The results for the $\Lambda_c(2940)^+$ baryon are

$$m = [2939.8 \pm 1.3(\text{stat}) \pm 1.0(\text{syst})]\ \text{MeV}/c^2,$$

$$\Gamma = [17.5 \pm 5.2(\text{stat}) \pm 5.9(\text{syst})]\ \text{MeV}.$$

For the $\Lambda_c(2880)^+$ baryon the results are

$$m = [2881.9 \pm 0.1(\text{stat}) \pm 0.5(\text{syst})]\ \text{MeV}/c^2,$$

$$\Gamma = [5.8 \pm 1.5(\text{stat}) \pm 1.1(\text{syst})]\ \text{MeV}.$$