Exotic hadrons with charm and bottom flavors: X, Y, Z, P_c, T_{cc} and hadron interaction

- $\bar{D}$ meson and nucleon interaction and charm nuclei -

Y. Yamaguchi, S. Y., A. Hosaka, Phys. Rev. D106, 094001 (2022)

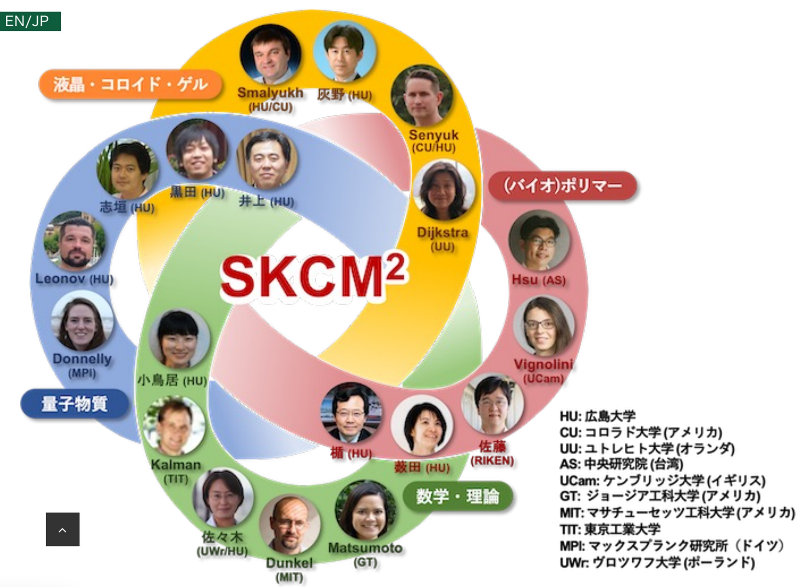
Shigehiro YASUI

∈ Sasaki Lab. ⊂ $SKCM^2$ ⊂ Hiroshima University

QCD theory seminar@online, 6 Jul. 2023

International Institute for Sustainability with Knotted Chiral Meta Matter/SKCM^2

World Premier International Research Center Initiative/WPI at Hiroshima University



✔ Cross-pollinates mathematical knot theory and chirality knowledge across disciplines and scales

✔ Creation of designable artificial knot-like particles that exhibit highly unusual and technologically useful properties

Hadron & nuclear physics group

PI: Kenta SHIGAKI (HU, ALICE member)

PI: Chihiro SASAKI (HU, Uni. of Wroclaw)

coPI: Chiho NONAKA (HU)

coPI: Muneto NITTA (HU, Keio Uni.)

Charm/bottom exotic hadrons

Contents

Contents

0. Introduction to exotic hadrons

1. Why $\bar{D}$ meson and nucleon?

2. $\bar{D}$ meson and nucleon potential

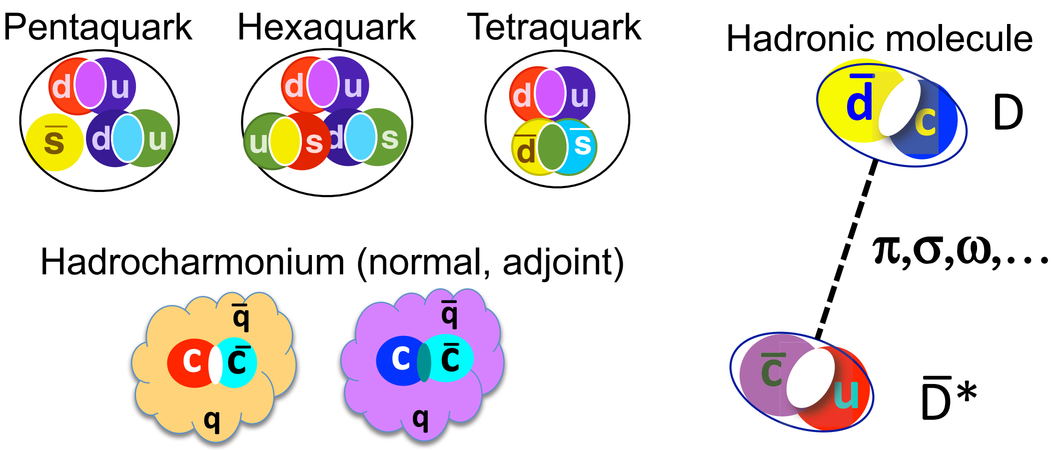
3. B meson and nucleon potential

4. Summary

0. Introduction to exotic hadrons

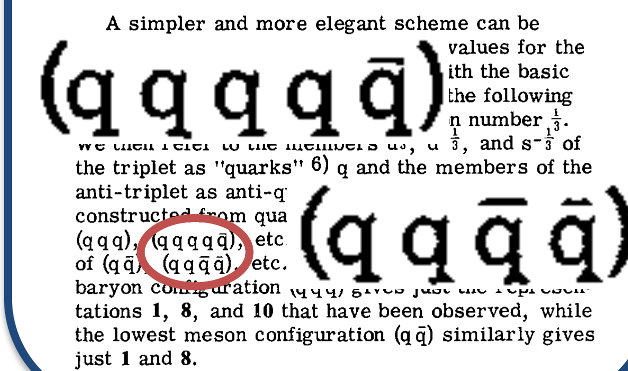
- Motivation to study exotic hadrons (multiquarks)
  - ✓ Color confinement (cf. Yang-Mills mass gap)
  - ✓ Flavor multiplets (unconventional assignment)
  - ✓ Multi-baryons (strange/charm/bottom nuclei)

Exotic hadrons: Diversity of hadrons



M. Gell-Mann
"Quarks"

Phys. Lett.
(1964)


A simpler and more elegant scheme can be ... values for the ... ith the basic ... the following ... n number $\frac{1}{3}$. ... and $s^{-\frac{1}{3}}$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-q ... constructed from qua ... (q q q), (q q q q q̄), etc. ... of (q q̄), (q q q̄ q̄), etc. ... baryon configuration (q q q) gives just the represen- tations **1**, **8**, and **10** that have been observed, while the lowest meson configuration (q q̄) similarly gives just **1** and **8**.

(q q q q q̄)

(q q q̄ q̄)

Cf. S. L. Olsen, T. Skwamicki, D. Ziemninska, Rev. Mod. Phys. 90, 015003 (2018)

- We focus on heavy quarks!
  - ✓ Charm (c) quark & bottom (b) quark
  - ✓ Mass hierarchy ($m_c, m_b \gg \Lambda_{\mathrm{QCD}}$)
  - ✓ Heavy quark spin symmetry
  - ✓ Many exotics have been found in experiments!

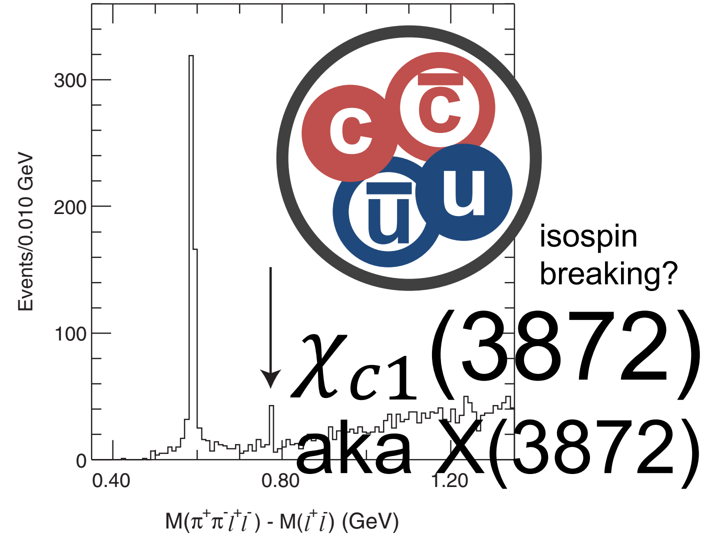
    $X, Y, Z, P_c, T_{cc}, \ldots$

0. Introduction to exotic hadrons

S. L. Olsen, T. Skwamicki, D. Ziemninska,
Rev. Mod. Phys. 90, 015003 (2018)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$	Belle (Choi et al., 2003, 2011), BABAR (Aubert et al., 2005c), LHCb (Aaij et al., 2013a, 2015d)
				$p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots$	CDF (Acosta et al., 2004; Abulencia et al., 2006; Aaltonen et al., 2009b), D0 (Abazov et al., 2004)
				$B \to K(J/\psi\pi^+\pi^-\pi^0)$	Belle (Abe et al., 2005), BABAR (del Amo Sanchez et al., 2010a)
				$B \to K(D^0\bar{D}^0\pi^0)$	Belle (Gokhroo et al., 2006; Aushev et al., 2010b), BABAR (Aubert et al., 2008c)
				$B \to K(J/\psi\gamma)$	BABAR (del Amo Sanchez et al., 2010a), Belle (Bhardwaj et al., 2011), LHCb (Aaij et al., 2012a)
				$B \to K(\psi'\gamma)$	BABAR (Aubert et al., 2009b), Belle (Bhardwaj et al., 2011), LHCb (Aaij et al., 2014a)
				$pp \to (J/\psi\pi^+\pi^-) + \cdots$	LHCb (Aaij et al., 2012a), CMS (Chatrchyan et al., 2013a), ATLAS (Aaboud et al., 2017)
				$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	BESIII (Ablikim et al., 2014d)
$X(3915)$	3918.4 ± 1.9	20 ± 5	0^{++}	$B \to K(J/\psi\omega)$	Belle (Choi et al., 2005), BABAR (Aubert et al., 2008b; del Amo Sanchez et al., 2010a)
				$e^+e^- \to e^+e^-(J/\psi\omega)$	Belle (Uehara et al., 2010), BABAR (Lees et al., 2012c)
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D})$	Belle (Pakhlov et al., 2008)
				$e^+e^- \to J/\psi(\cdots)$	Belle (Abe et al., 2007)
$X(4140)$	$4146.5^{+6.4}_{-5.3}$	83^{+27}_{-25}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen et al., 2009a), CMS (Chatrchyan et al., 2014), D0 (Abazov et al., 2014), LHCb (Aaij et al., 2017a, 2017d)
				$p\bar{p} \to (J/\psi\phi) + \cdots$	D0 (Abazov et al., 2015)
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$0^{-+}(?)$	$e^+e^- \to J/\psi(D^*\bar{D}^*)$	Belle (Pakhlov et al., 2008)
$Y(4260)$	See $Y(4220)$ entry		1^{--}	$e^+e^- \to \gamma(J/\psi\pi^+\pi^-)$	BABAR (Aubert et al., 2005a; Lees et al., 2012b), CLEO (He et al., 2006), Belle (Yuan et al., 2007; Liu et al., 2013)
$Y(4220)$	4222 ± 3	48 ± 7	1^{--}	$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (Ablikim et al., 2017c)
				$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim et al., 2017a)
				$e^+e^- \to (\chi_{c0}\omega)$	BESIII (Ablikim et al., 2015g)
				$e^+e^- \to (J/\psi\eta)$	BESIII (Ablikim et al., 2015c)
				$e^+e^- \to (\gamma X(3872))$	BESIII (Ablikim et al., 2014d)
				$e^+e^- \to (\pi^- Z_c^+(3900))$	BESIII (Ablikim et al., 2013a), Belle (Liu et al., 2013)
				$e^+e^- \to (\pi^- Z_c^+(4020))$	BESIII (Ablikim et al., 2013b)
$X(4274)$	4273^{+19}_{-9}	56^{+14}_{-16}	1^{++}	$B \to K(J/\psi\phi)$	CDF (Aaltonen et al., 2017), CMS (Chatrchyan et al., 2014), LHCb (Aaij et al., 2017a, 2017d)
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$(0/2)^{++}$	$e^+e^- \to e^+e^-(J/\psi\phi)$	Belle (Shen et al., 2010)
$Y(4360)$	4341 ± 8	102 ± 9	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$	BABAR (Aubert et al., 2007; Lees et al., 2014), Belle (Wang et al., 2007, 2015)
				$e^+e^- \to (J/\psi\pi^+\pi^-)$	BESIII (Ablikim et al., 2017c)
$Y(4390)$	4392 ± 6	140 ± 16	1^{--}	$e^+e^- \to (h_c\pi^+\pi^-)$	BESIII (Ablikim et al., 2017a)
$X(4500)$	4506^{+16}_{-19}	92^{+30}_{-21}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij et al., 2017a, 2017d)
$X(4700)$	4704^{+17}_{-26}	120^{+52}_{-45}	0^{++}	$B \to K(J/\psi\phi)$	LHCb (Aaij et al., 2017a, 2017d)
$Y(4660)$	4643 ± 9	72 ± 11	1^{--}	$e^+e^- \to \gamma(\psi'\pi^+\pi^-)$	Belle (Wang et al., 2007, 2015), BABAR (Aubert et al., 2007; Lees et al., 2014)
				$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle (Pakhlova et al., 2008)

← **Firstly discovered tetraquark**



S. K. Choi et al. [Belle Collaboration], Phys. Rev. Lett. 91, 262001 (2003)

← **Hybrid mesons (gluon excitation)**

Hybrid (string excitation)

$\psi(4230)$
aka Y(4260)

0. Introduction to exotic hadrons

S. L. Olsen, T. Skwamicki, D. Ziemninska, Rev. Mod. Phys. 90, 015003 (2018)

State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$Z_c^{+,0}(3900)$	3886.6 ± 2.4	28.1 ± 2.6	1^{+-}	$e^+e^- \to \pi^{-,0}(J/\psi\pi^{+,0})$	BESIII (Ablikim *et al.*, 2013a, 2015f), Belle (Liu *et al.*, 2013)
				$e^+e^- \to \pi^{-,0}(D\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2014b, 2015e)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0}(h_c\pi^{+,0})$	BESIII (Ablikim *et al.*, 2013b, 2014c)
				$e^+e^- \to \pi^{-,0}(D^*\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2014a, 2015d)
$Z^+(4050)$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4200)$	4196^{+35}_{-32}	370^{+99}_{-149}	1^+	$B \to K(J/\psi\pi^+)$	Belle (Chilikin *et al.*, 2014)
				$B \to K(\psi'\pi^+)$	LHCb (Aaij *et al.*, 2014b)
$Z^+(4250)$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$B \to K(\chi_{c1}\pi^+)$	Belle (Mizuk *et al.*, 2008), *BABAR* (Lees *et al.*, 2012a)
$Z^+(4430)$	4477 ± 20	181 ± 31	1^+	$B \to K(\psi'\pi^+)$	Belle (Choi *et al.*, 2008; Mizuk *et al.*, 2009), Belle (Chilikin *et al.*, 2013), LHCb (Aaij *et al.*, 2014b, 2015b)
				$B \to K(J\psi\pi^+)$	Belle (Chilikin *et al.*, 2014)
$P_c^+(4380)$	4380 ± 30	205 ± 88	$(\frac{3}{2}/\frac{5}{2})^{\mp}$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$P_c^+(4450)$	4450 ± 3	39 ± 20	$(\frac{5}{2}/\frac{3}{2})^{\pm}$	$\Lambda_b^0 \to K(J/\psi p)$	LHCb (Aaij *et al.*, 2015c)
$Y_b(10860)$	$10891.1^{+3.4}_{-3.8}$	$53.7^{+7.2}_{-7.8}$	1^{--}	$e^+e^- \to (\Upsilon(nS)\pi^+\pi^-)$	Belle (Chen *et al.*, 2008; Santel *et al.*, 2016)
$Z_b^{+,0}(10610)$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$Y_b(10860) \to \pi^{-,0}(\Upsilon(nS)\pi^{+,0})$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015), Belle (Krokovny *et al.*, 2013)
				$Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$	Belle (Bondar *et al.*, 2012)
				$Y_b(10860) \to \pi^-(B\bar{B}^*)^+$	Belle (Garmash *et al.*, 2016)
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$Y_b(10860) \to \pi^-(\Upsilon(nS)\pi^+)$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015)
				$Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$	Belle (Bondar *et al.*, 2012)
				$Y_b(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle (Garmash *et al.*, 2016)

← **Genuine tetraquark**

Electrically charged state (+)

← **Pentaquark**

Is that all ?

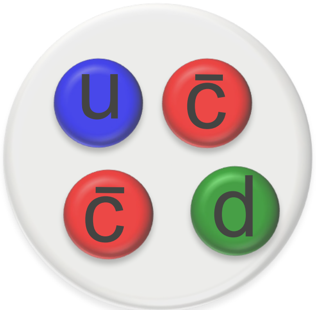
New type discovered!

0. Introduction to exotic hadrons

J.P. Ader, J.M. Richard and P. Taxil,
Phys. Rev. D25, 2370 (1982)

T_{cc}

Double charm tetraquark



0. Introduction to exotic hadrons

T_{cc}

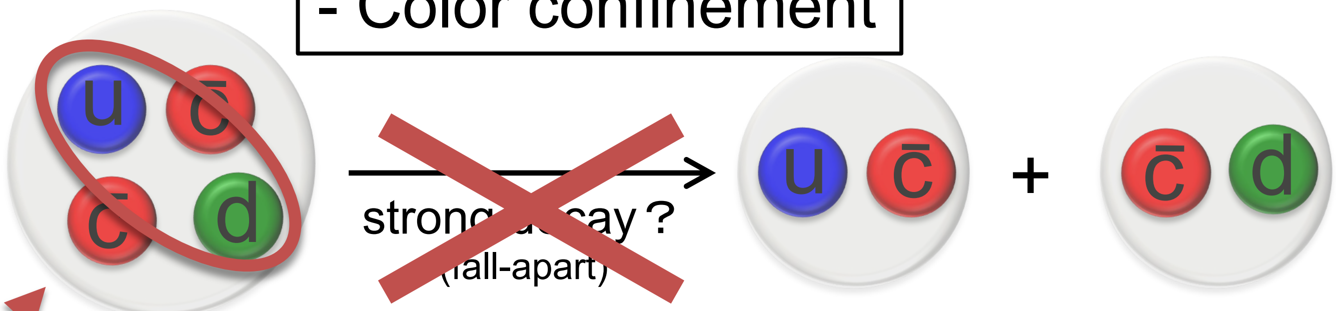
Double charm tetraquark

J.P. Ader, J.M. Richard and P. Taxil, Phys. Rev. D25, 2370 (1982)

- Diquark
- Color confinement

almost uniquely determined

$I(J^P)=0(1^+)$



T_{cc} can be stable!

strong ud attraction

Gluon exchange force induces color-spin interaction

$$H_{int} = \sum_{i>j} \frac{C_H}{m_i m_j} \vec{s}_i \cdot \vec{s}_j \qquad C_H = v_0 \vec{\lambda}_i \cdot \vec{\lambda}_j \langle \delta(r_{ij}) \rangle$$

ud pair ~1 dominant attraction ($\bar{3}_c$, I=0, $^1S_0$)

c̄u pair $\sim 1/m_c$ suppressed

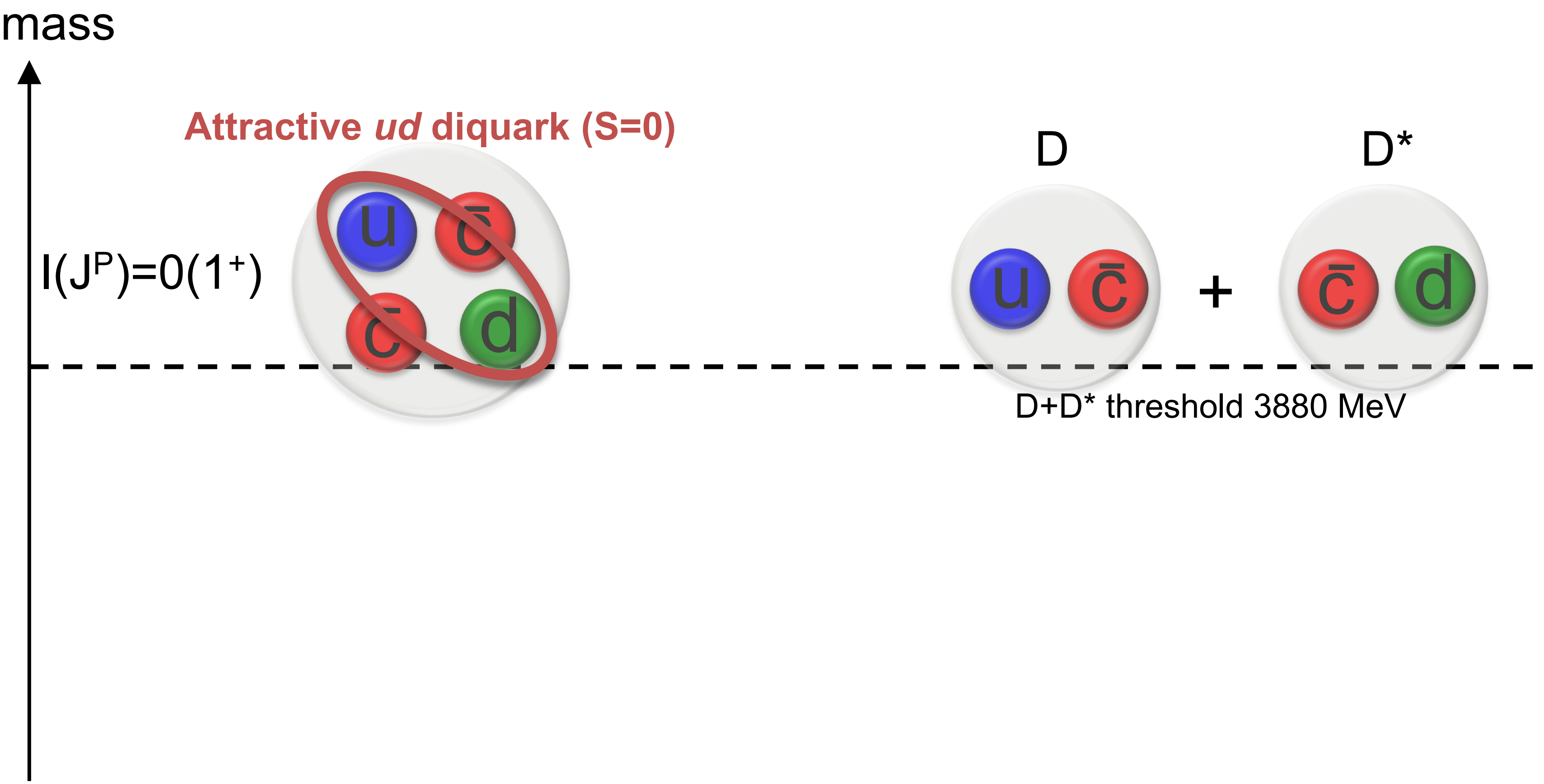
c̄c̄ pair $\sim 1/m_c^2$ more suppressed ($\bar{3}_c$, $^3S_1$)

0. Introduction to exotic hadrons

T_{cc}

Double charm tetraquark

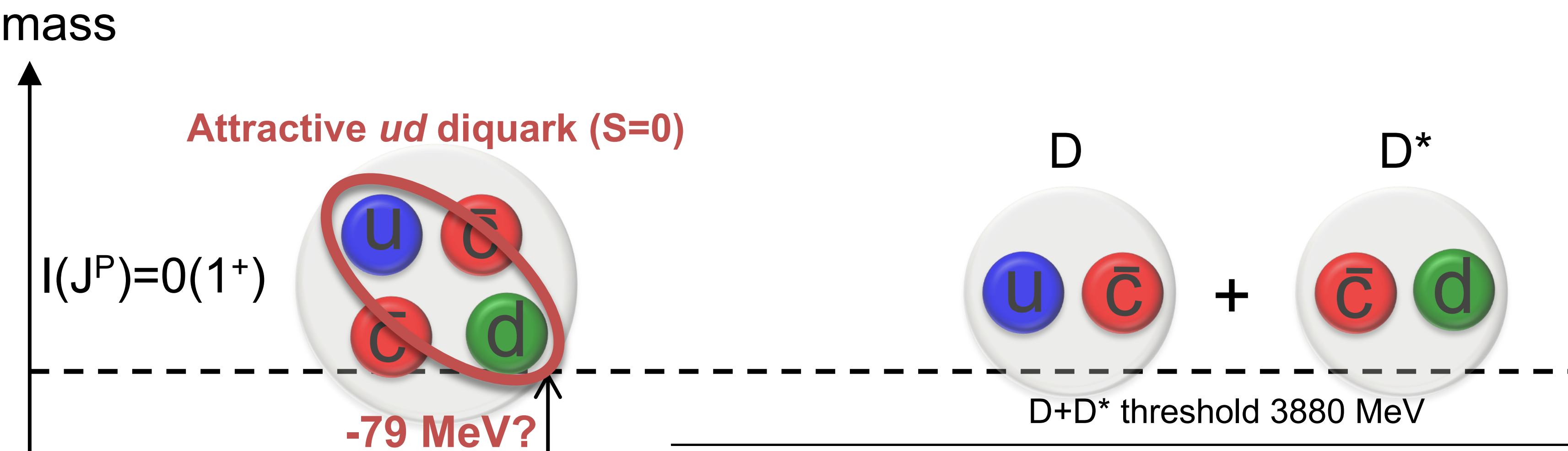
J.P. Ader, J.M. Richard and P. Taxil, Phys. Rev. D25, 2370 (1982)

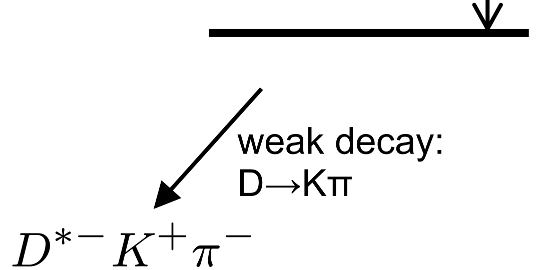


0. Introduction to exotic hadrons

T_{cc}
Double charm tetraquark

J.P. Ader, J.M. Richard and P. Taxil, Phys. Rev. D25, 2370 (1982)





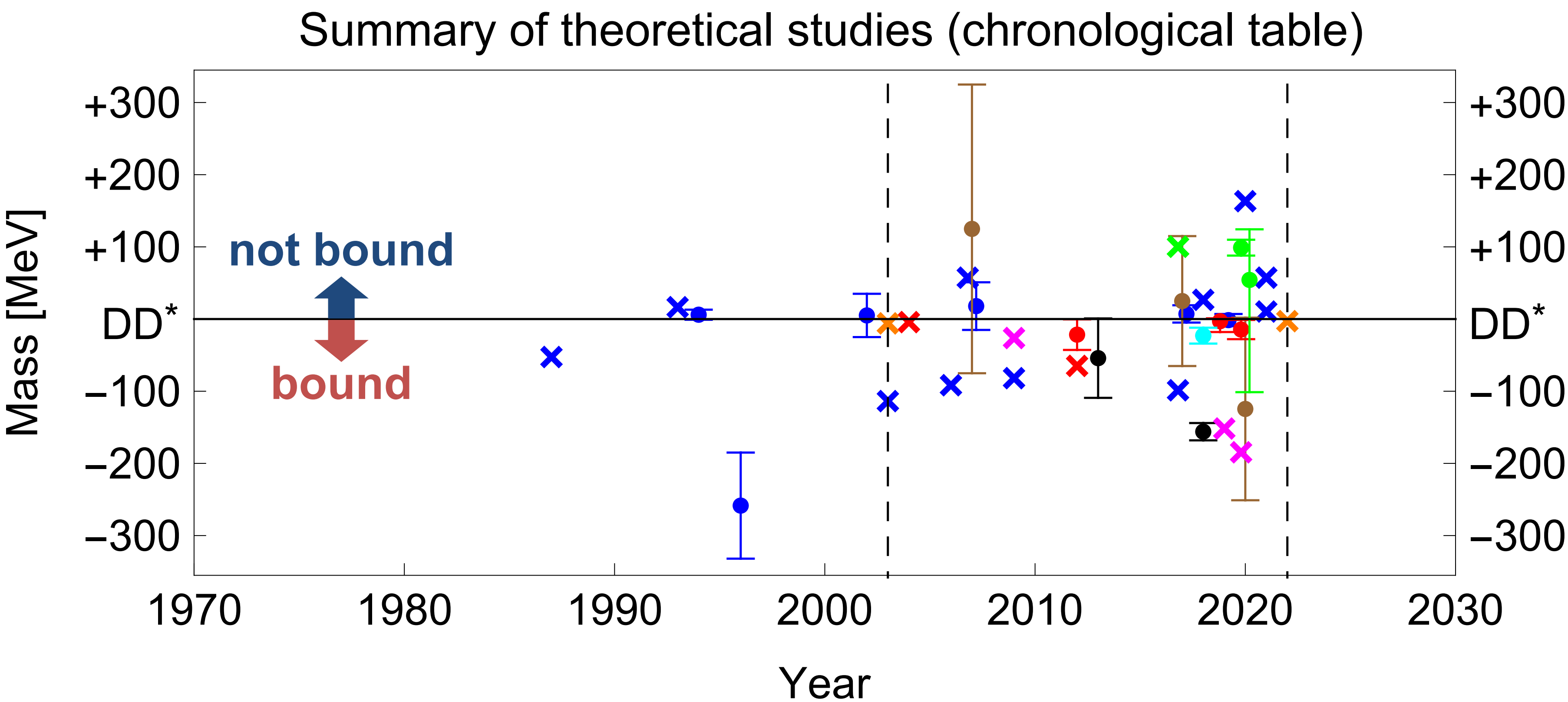
	$ud\bar{c}\bar{c}$	$us\bar{c}\bar{c}$	$ds\bar{c}\bar{c}$
T^1_{cc}	-79.3	-8.7	-8.7
	$\bar{D}^0 + D^{*-}$, $\bar{D}^{*0} + D^-$	$\bar{D}^0 + D_s^{*-}$	$D^- + D_s^{*-}$
	$ud\bar{b}\bar{b}$	$us\bar{b}\bar{b}$	$ds\bar{b}\bar{b}$
T^1_{bb}	-124.3	-62.3	-62.3
	$B^+ + B^{*0}$, $B^{*+} + B^0$	$B^+ + B_s^{*0}$	$B^0 + B_s^{*0}$
	$ud\bar{c}\bar{b}$	$us\bar{c}\bar{b}$	$ds\bar{c}\bar{b}$
T^1_{cb}	-59.0	$+2.9$	$+2.9$
	$B^{*+} + D^-$, $B^{*0} + \bar{D}^0$	$B_s^{*0} + D^0$	$B_s^{*0} + D^-$

S.-H. Lee, S. Yasui, Eur. Phys. J. C64,283 (2009)
S.-H. Lee, S. Yasui, W. Liu, C.-M. Ko, Eur. Phys. J. C54, 259 (2008)

0. Introduction to exotic hadrons

Recent review:
H.-X. Chen, W. Chen, X. Liu, Y.-R. Liu, S.-L. Zhu, 2204.02649 [hep-ph]

T_{cc}
Double charm tetraquark



bound or **not bound**？

0. Introduction to exotic hadrons

T_{cc}

Double charm tetraquark

PRL **119,** 202002 (2017) PHYSICAL REVIEW LETTERS week ending 17 NOVEMBER 2017

Heavy-Quark Symmetry Implies Stable Heavy Tetraquark Mesons $Q_iQ_j\bar{q}_k\bar{q}_l$

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Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois 60510, USA

(Received 8 August 2017; published 15 November 2017)

~100 MeV **above** DD* threshold

State	J^P	j_ℓ	$m(Q_iQ_jq_m)$ (c.g.)	HQS relation	$m(Q_iQ_j\bar{q}_k\bar{q}_l)$	Decay channel	$\mathcal{Q}$ (MeV)
$\{cc\}[\bar{u}\bar{d}]$	1^+	0	3663[b]	$m(\{cc\}u)+315$	3978	D^+D^{*0} 3876	102
$\{cc\}[\bar{q}_k\bar{s}]$	1^+	0	3764[c]	$m(\{cc\}s)+392$	4156	$D^+D_s^{*-}$ 3977	179
$\{cc\}\{\bar{q}_k\bar{q}_l\}$	$0^+,1^+,2^+$	1	3663	$m(\{cc\}u)+526$	4146,4167,4210	D^+D^0, D^+D^{*0} 3734,3876	412,292,476
$[bc][\bar{u}\bar{d}]$	0^+	0	6914	$m([bc]u)+315$	7229	B^-D^+/B^0D^0 7146	83
$[bc][\bar{q}_k\bar{s}]$	0^+	0	7010[d]	$m([bc]s)+392$	7406	B_sD 7236	170
$[bc]\{\bar{q}_k\bar{q}_l\}$	1^+	1	6914	$m([bc]u)+526$	7439	B^*D/BD^* 7190/7290	249
$\{bc\}[\bar{u}\bar{d}]$	1^+	0	6957	$m(\{bc\}u)+315$	7272	B^*D/BD^* 7190/7290	82
$\{bc\}[\bar{q}_k\bar{s}]$	1^+	0	7053[d]	$m(\{bc\}s)+392$	7445	DB_s^* 7282	163
$\{bc\}\{\bar{q}_k\bar{q}_l\}$	$0^+,1^+,2^+$	1	6957	$m(\{bc\}u)+526$	7461,7472,7493	BD/B^*D 7146/7190	317,282,349
$\{bb\}[\bar{u}\bar{d}]$	1^+	0	10 176	$m(\{bb\}u)+306$	10 482	$B^-\bar{B}^{*0}$ 10 603	−121
$\{bb\}[\bar{q}_k\bar{s}]$	1^+	0	10 252[c]	$m(\{bb\}s)+391$	10 643	$\bar{B}\bar{B}_s^*/\bar{B}_s\bar{B}^*$ 10 695/10 691	−48
$\{bb\}\{\bar{q}_k\bar{q}_l\}$	$0^+,1^+,2^+$	1	10 176	$m(\{bb\}u)+512$	10 674,10 681,10 695	B^-B^0, B^-B^{*0} 10 559,10 603	115,78,136

No bound state for T_{cc} ?

0. Introduction to exotic hadrons

nature physics
LETTERS
https://doi.org/10.1038/s41567-022-01614-y
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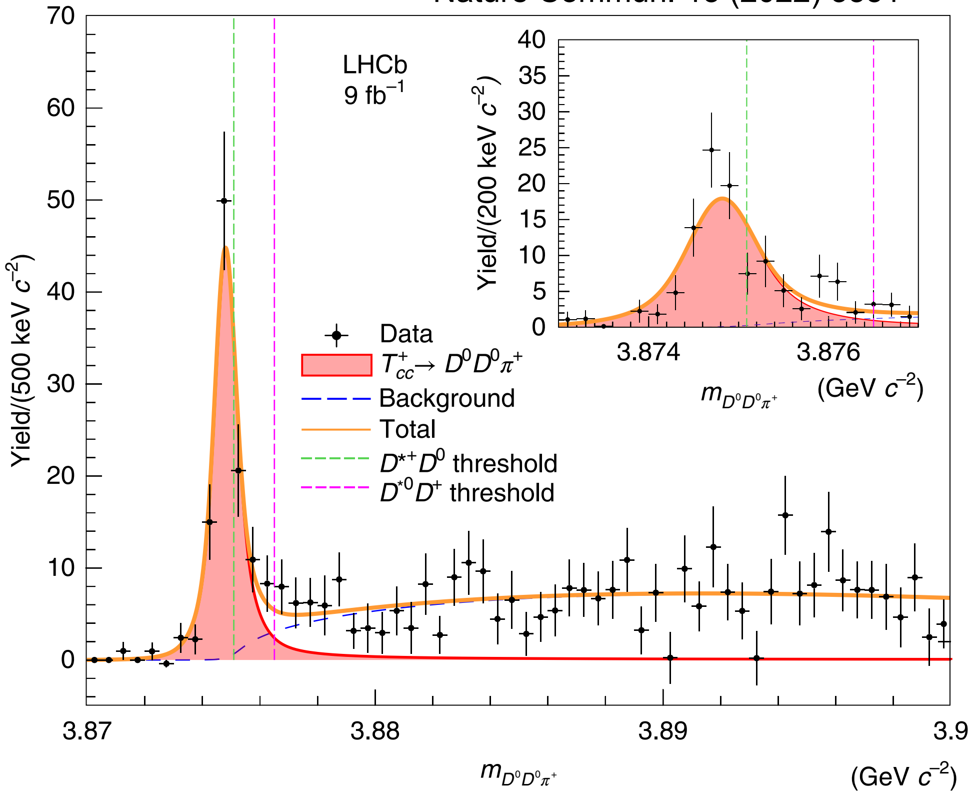
Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

LHCb, Nature Phys. 18 (2022) 751,
Nature Commun. 13 (2022) 3351



Bound state below $D^{*+}D^0$ threshold

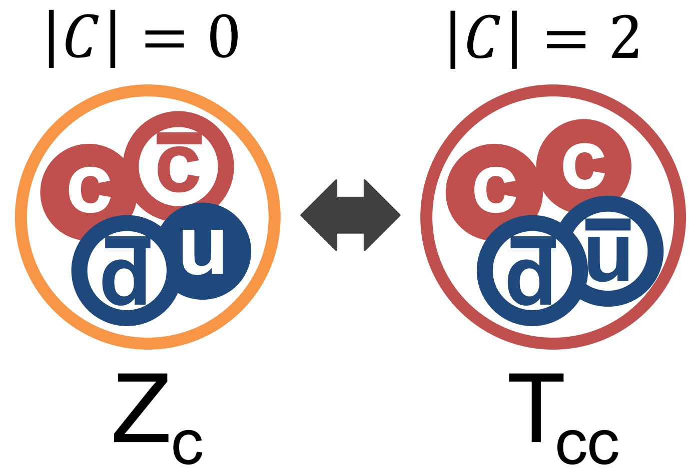
$$\delta m_{\rm BW} = -273 \pm 61 \pm 5\,^{+11}_{-14}\ \text{keV}\,c^{-2},$$

$$\Gamma_{\rm BW} = 410 \pm 165 \pm 43\,^{+18}_{-38}\ \text{keV},$$

Note: Above $D^0D^0\pi^+$ threshold 3869.25 MeV: “resonance(?)”

New type of exotics!

T_{cc}: doubly charmed tetraquark



T_{cc} has four quarks at least: genuinely exotic.

0. Introduction to exotic hadrons

nature physics LETTERS
https://doi.org/10.1038/s41567-022-01614-y
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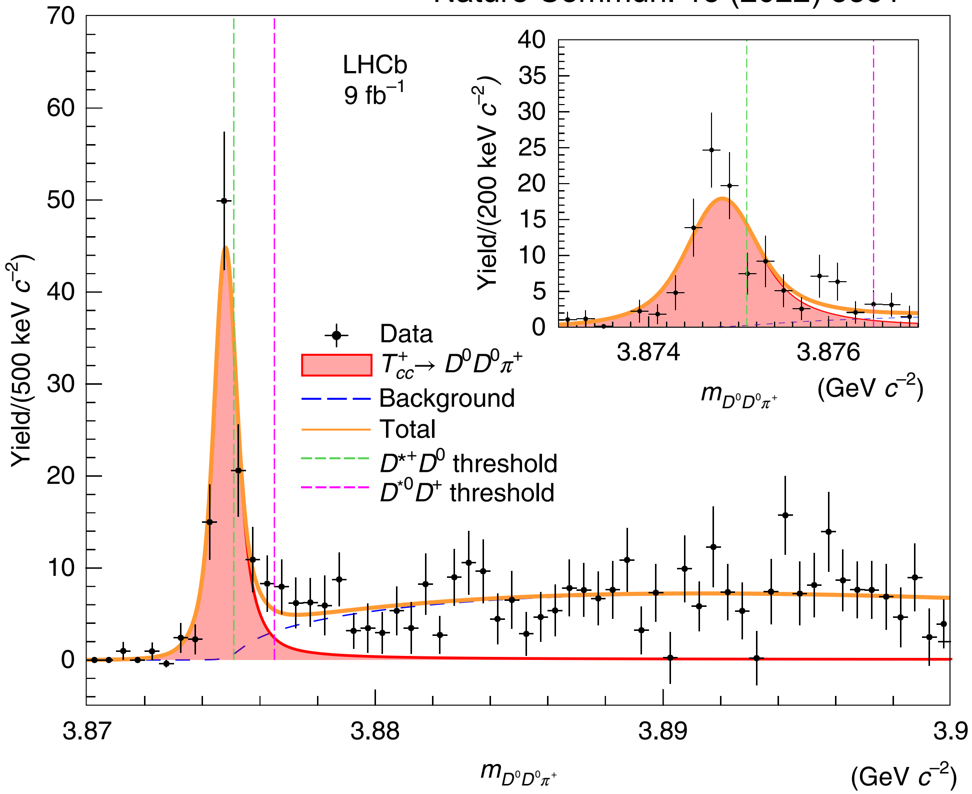

Bound state below $D^{*+}D^0$ threshold

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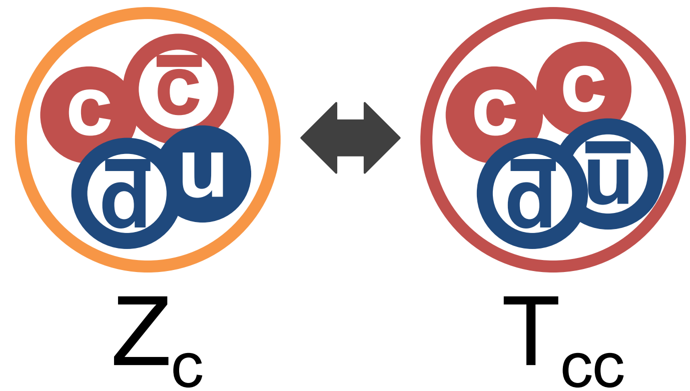
Note: Above $D^0D^0\pi^+$ threshold 3869.25 MeV: "resonance(?)"

New type of exotics!

T_{cc}: doubly charmed tetraquark

$|C| = 0$ $|C| = 2$



T_{cc} has four quarks at least: genuinely exotic.

Important questions:

1. strong ud diquark attraction ?
2. $D(c\bar{u})D^*(c\bar{d})$ molecule ?
3. Are there other T_{cc} ?
4. Are there T_{bb} (double bottom) ?

etc.

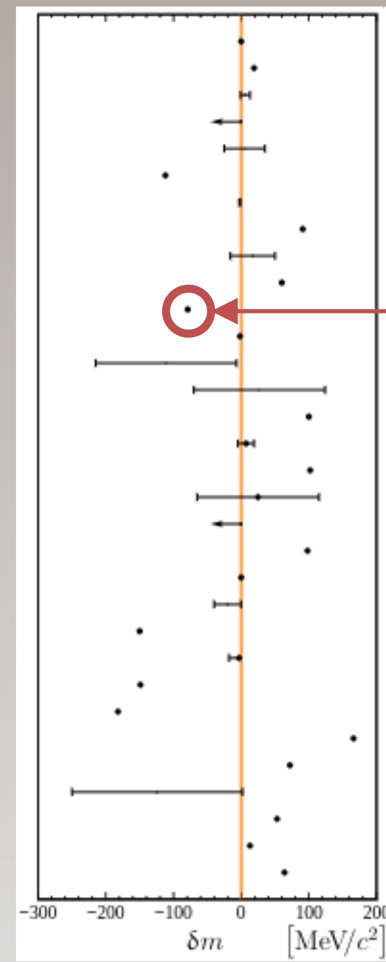
0. Introduction to exotic hadrons

T_{cc} has been studied over **35 years** in theories!

Ivan Polyakov (2021)

Theory predictions

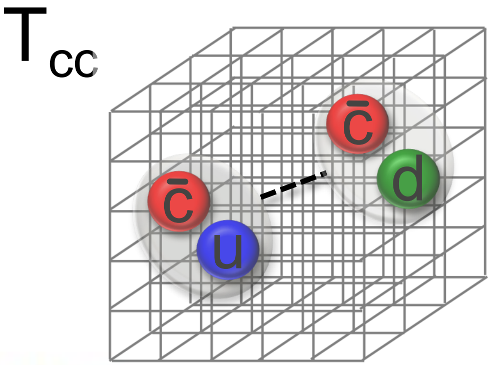
Reference		Year	$\delta' m$ [MeV/c^2]
J. Carlson, L. Heller and J. A. Tjon	36	1987	~ 0
B. Silvestre-Brac and C. Semay	37	1993	$+19$
C. Semay and B. Silvestre-Brac	38	1994	$[-1, +13]$
S. Pepin, F. Stancu, M. Genovese and J. M. Richard	39	1996	< 0
B. A. Gelman and S. Nussinov	40	2002	$[-25, +35]$
J. Vijande, F. Fernandez, A. Valcarce, A. and B. Silvestre-Brac	41	2003	-112
D. Janc and M. Rosina	42	2004	$[-3, -1]$
F. Navarra, M. Nielsen and S. H. Lee	43	2007	$+91$
J. Vijande, E. Weissman, A. Valcarce	44	2007	$[-16, +50]$
D. Ebert, R. N. Faustov, V. O. Galkin and W. Lucha	45	2007	$+60$
S. H. Lee and S. Yasui	46	2009	-79
Y. Yang, C. Deng, J. Ping and T. Goldman	47	2009	-1.8
G.-Q. Feng, X.-H. Guo and B.-S. Zou	48	2013	-215
Y. Ikeda, B. Charron, S. Aoki, T. Doi, T. Hatsuda, T. Inoue, N. Ishii, K. Murano, H. Nemura and K. Sasaki	49	2013	$[-70, +124]$
S.-Q. Luo, K. Chen, X. Liu, Y.-R. Liu and S.-L. Zhu	50	2017	$+100$
M. Karliner and J. Rosner	51	2017	$7 \pm 12 \to 1$
E. J. Eichten and C. Quigg	52	2017	$+102$
Z. G. Wang	53	2017	$+25 \pm 90$
G. K. C. Cheung, C. E. Thomas, J. J. Dudek and R. G. Edwards	54	2017	$\lesssim 0$
W. Park, S. Noh and S. H. Lee	55	2018	$+98$
A. Francis, R. J. Hudspith, R. Lewis and K. Maltman	56	2018	~ 0
P. Junnarkar, N. Mathur and M. Padmanath	57	2018	$[-40, 0]$
C. Deng, H. Chen and J. Ping	58	2018	-150
M.-Z. Liu, T.-W. Wu, V. Pavon Valderrama, J.-J. Xie and L.-S. Geng	59	2019	-3^{+4}_{-15}
G. Yang, J. Ping and J. Segovia	60	2019	-149
Y. Tan, W. Lu and J. Ping	61	2020	-182
Q.-F. Lü, D.-Y. Chen and Y.-B. Dong	62	2020	$+166$
E. Braaten, L.-P. He and A. Mohapatra	63	2020	$+72$
D. Gao , D. Jia, Y.-J. Sun, Z. Zhang, W.-N. Liu and Q. Mei	64	2020	$[-250, +2]$
J.-B. Cheng, S.-Y. Li, Y.-R. Liu, Z.-G. Si, T. Yao	65	2020	$+53$
S. Noh, W. Park and S. H. Lee	66	2021	$+13$
R. N. Faustov, V. O. Galkin and E. M. Savchenko	67	2021	$+64$



me!

https://indico.desy.de/event/28202/contributions/105627/attachments/67806/84639/EPS-HEP_2021_Polyakov_v5.pdf

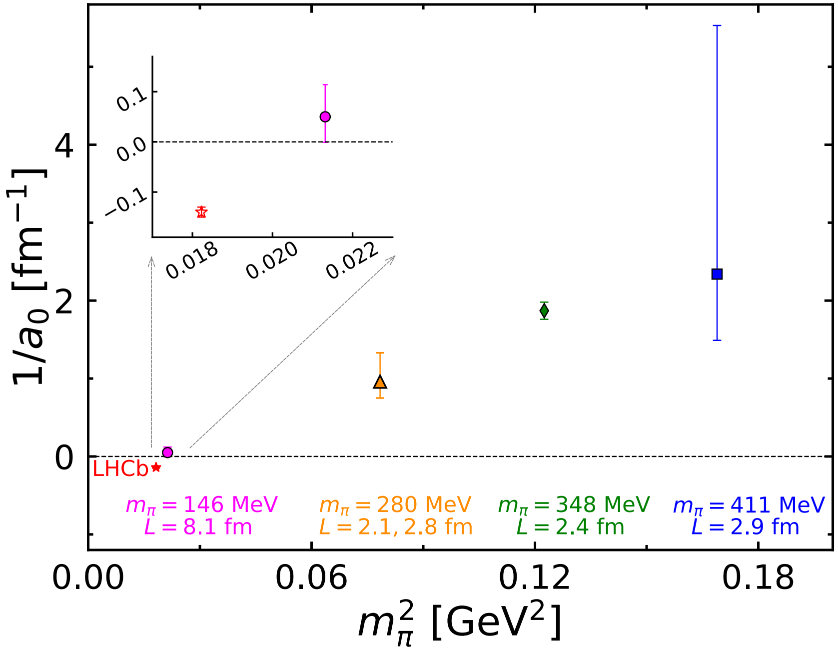
0. Introduction to exotic hadrons

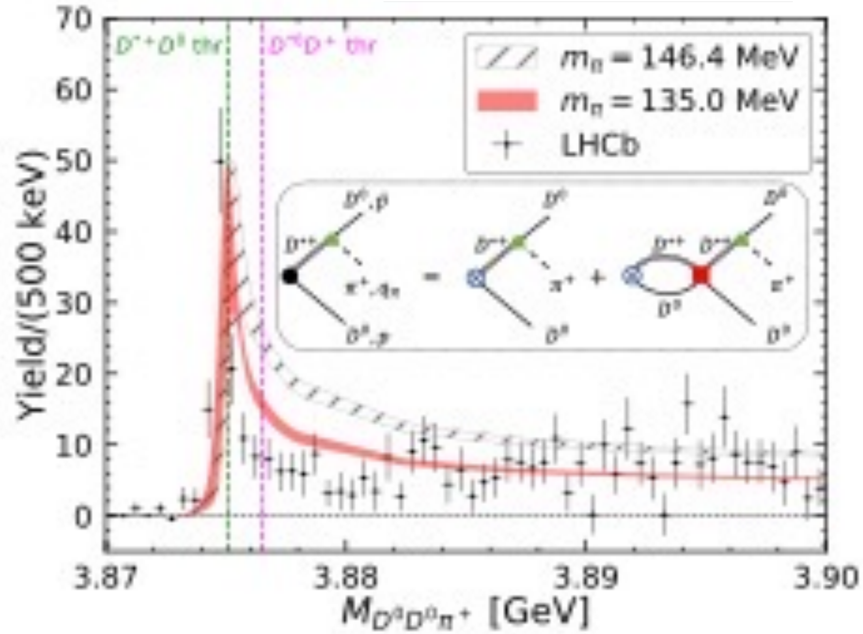


Lattice QCD study of T_{cc} near physical point

Y. Ikeda, et al. (HAL Collaboration), PLB729, 85 (2014) : $m_\pi = 410, 700$ MeV

Y. Lyu, et al. (HAL Collaboration), 2302.04505: $m_\pi = 135$ MeV (near physical point)





$E_{\text{pole}} = -45$ keV

"virtual state"

Mass spectrum

Cf. LHCb (2022): below $D^{*+}D^0$ threshold

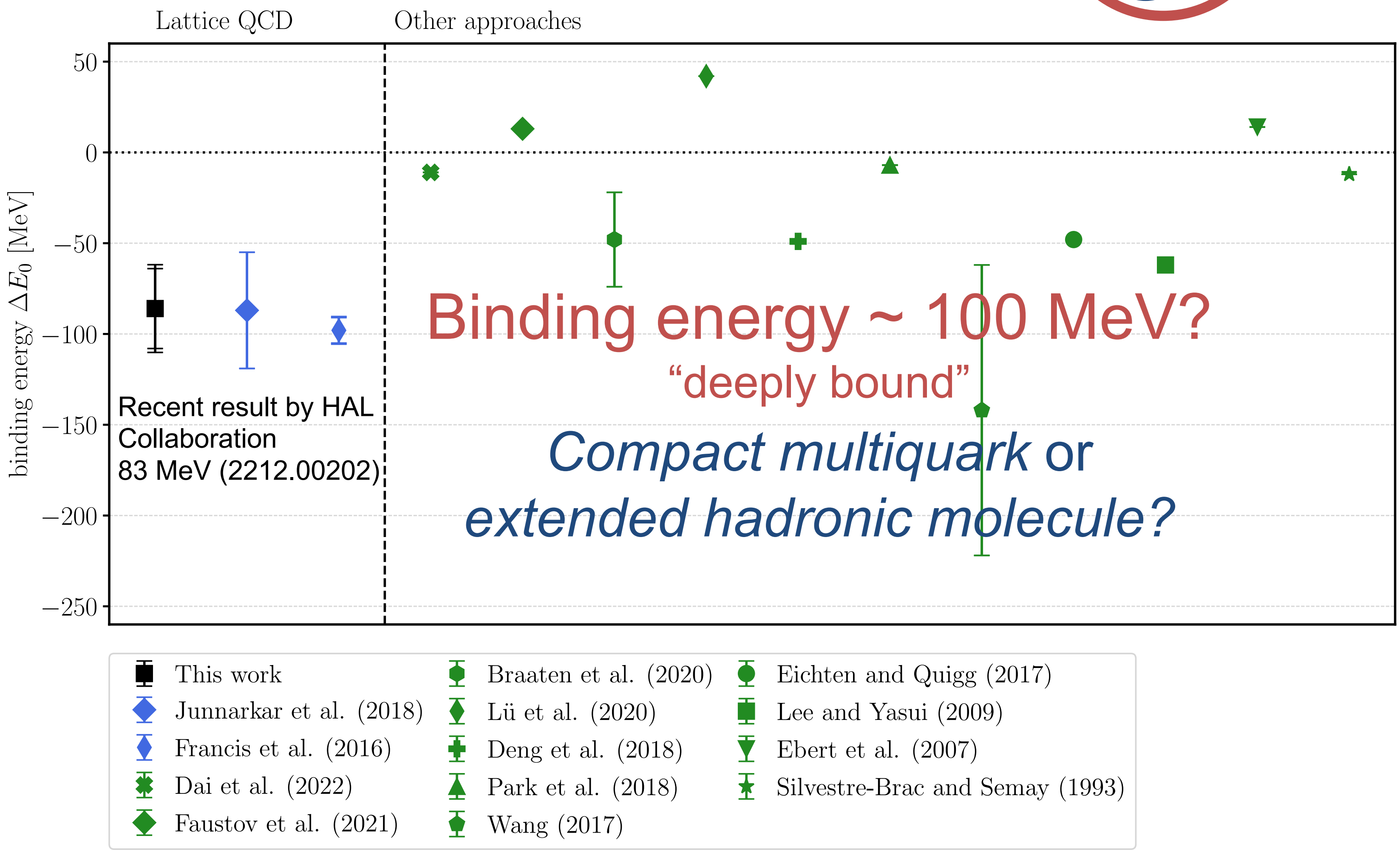
$$\delta m_{\text{BW}} = -\underline{273} \pm 61 \pm 5\,^{+11}_{-14}\,\underline{\text{keV}}\,c^{-2},$$

$$\Gamma_{\text{BW}} = \underline{410} \pm 165 \pm 43\,^{+18}_{-38}\,\underline{\text{keV}},$$

0. Introduction to exotic hadrons

Recent lattice QCD study on T_{bb}
Meinel, Pflaumer, Wagner,
Phys. Rev. D106, 034507 (2022)

T_{bb}
*Doubly **bottom** tetraquark*



Recent result by HAL Collaboration
83 MeV (2212.00202)

Binding energy ~ 100 MeV?
"deeply bound"

Compact multiquark or
extended hadronic molecule?

Let us research T_{bb} in future experiments!

0. Introduction to exotic hadrons

Personal view on

significance of T_{cc} (possibly T_{bb})

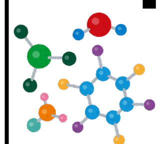
Before…

“Taxonomy”

分類学

Classification of exotic hadrons

After…



“Molecular biology”

High-precision data of exotic hadrons

When (nearly) stable exotic states exist, studies for internal structures will become possible at high-precision for exotic hadrons in experiments, lattice QCD and phenomenology!

Internal property: charge radius, form factor, magnetic moment, quadrupole moment, parton structure, spin decomposition, …

0. Introduction to exotic hadrons

1. Why $\bar{D}$ meson and nucleon?

2. $\bar{D}$ meson and nucleon potential

3. B meson and nucleon potential

4. Summary

0. Introduction to exotic hadrons

1. Why $\bar{D}$ meson and nucleon?

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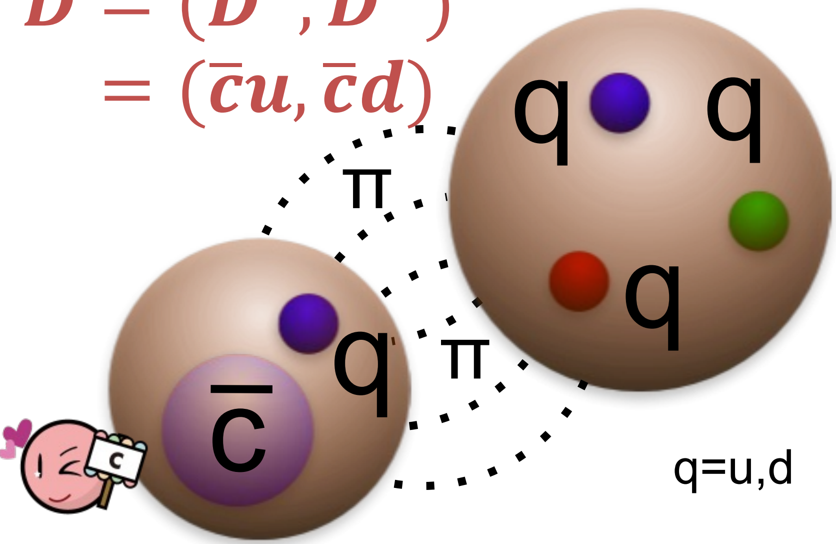
4. Summary

1. Why $\bar{D}$ meson and nucleon?

- $\bar{D}$ meson and nucleon (pentaquark)
  - ✓ $\bar{c}qqqq$ $(q = u, d)$: no annihilation
  - ✓ (Anti-)charm nuclei? Cf. Review paper: Hosaka, Hyodo, Sudoh, Yamaguchi, Yasui, PPNP 96, 88 (2017)
  - ✓ Extension to B meson and nucleon

① No $\bar{q}q$ annihilation
② No NG boson emission
→ High-precision data

$$\bar{D} = (\bar{D}^0, D^-) = (\bar{c}u, \bar{c}d)$$



$\bar{D}$ meson
(anti D meson)

Nucleon

*penta*quark (5 quark)

chiral + HQS symmetries:
Cohen, Hohler, Lebed, PRD72, 074010 (2005)
Yasui, Sudoh, PRD80, 034008 (2009)
Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84, 014032 (2011), ibid. 85, 054003 (2012)
Cf. compact quarks: Gignoux, Silvestre-Brac, Richard, PLB193, 323 (1987), Lipkin, PLB195, 484 (1987)

1. Why $\bar{D}$ meson and nucleon?

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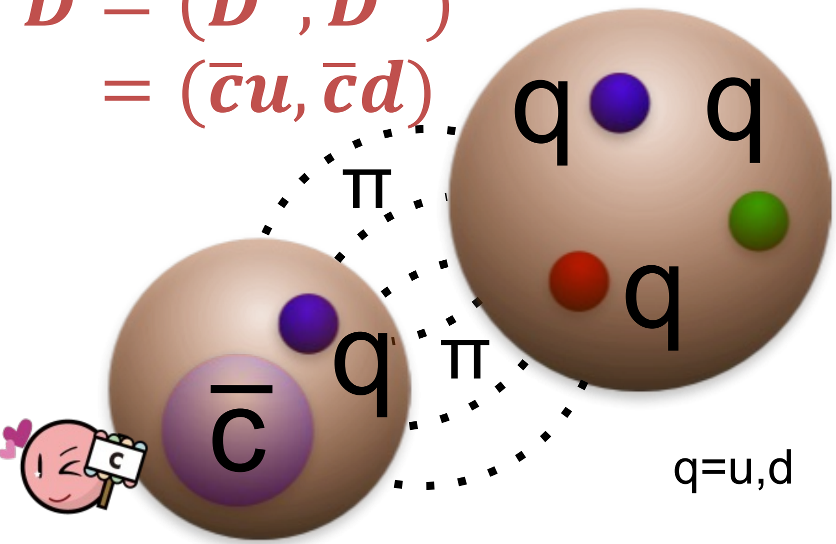

q=u,d

$\bar{D}$ meson **Nucleon**

(anti D meson)

*penta*quark (5 quark)

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Cohen, Hohler, Lebed, PRD72, 074010 (2005)
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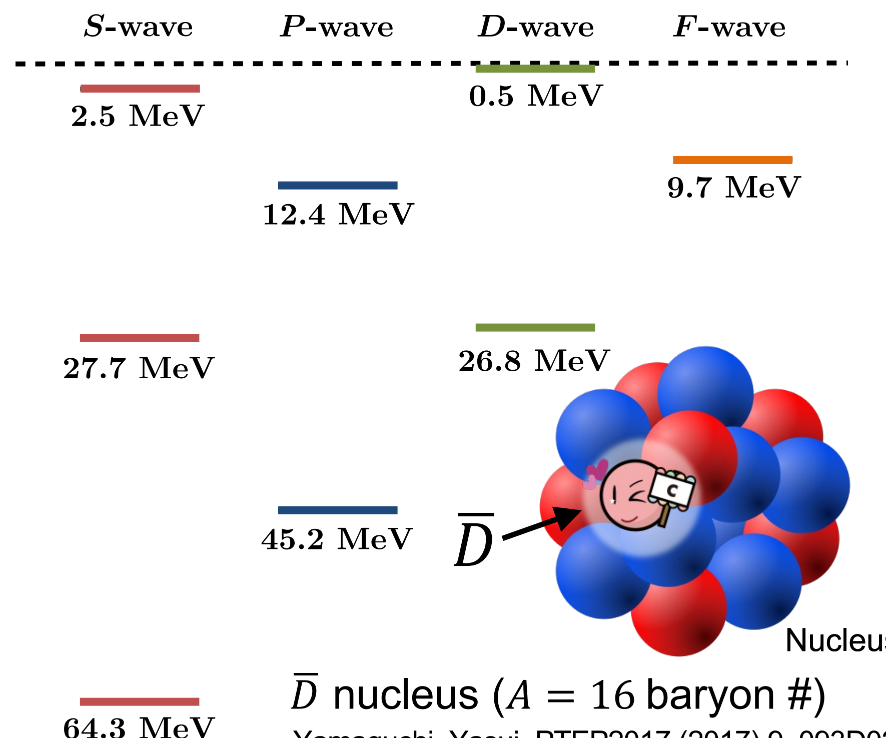
Cf. compact quarks: Gignoux, Silvestre-Brac, Richard, PLB193, 323 (1987), Lipkin, PLB195, 484 (1987)

(anti-)charm and bottom nuclei

$\bar{D}$ meson bound nuclei?

(example of theory prediction)



$\bar{D}$ nucleus ($A = 16$ baryon #)
Yamaguchi, Yasui, PTEP2017 (2017) 9, 093D02

Accessible to high-precision data of charm exotic hadrons and nuclei, if exist.

1. Why $\bar{D}$ meson and nucleon?

- $\bar{D}$ meson and nucleon (pentaquark)
  - ✓ $\bar{c}qqqq$ ($q = u, d$): no annihilation
  - ✓ (Anti-)charm nuclei? Cf. Review paper: Hosaka, Hyodo, Sudoh, Yamaguchi, Yasui, PPNP 96, 88 (2017)
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→ High-precision data

$\bar{D} = (\bar{D}^0, D^-)$
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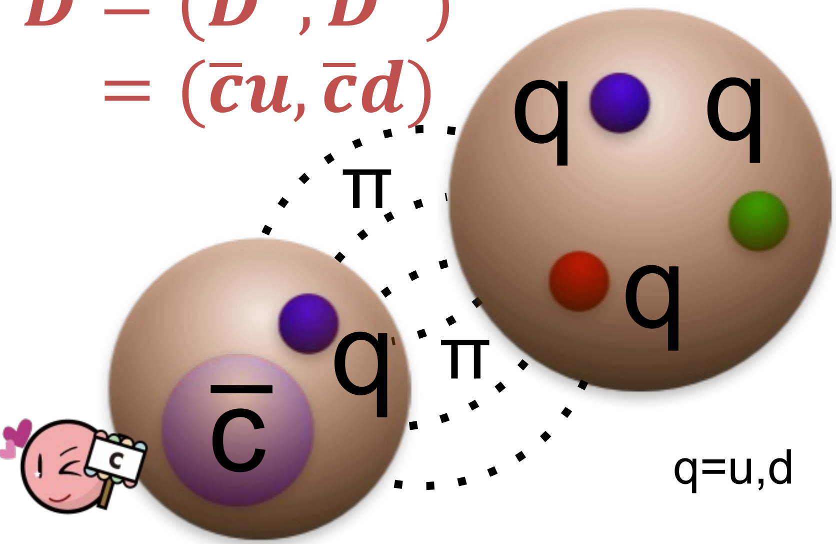

$\bar{D}$ meson **Nucleon**
(anti D meson)

*penta*quark (5 quark)

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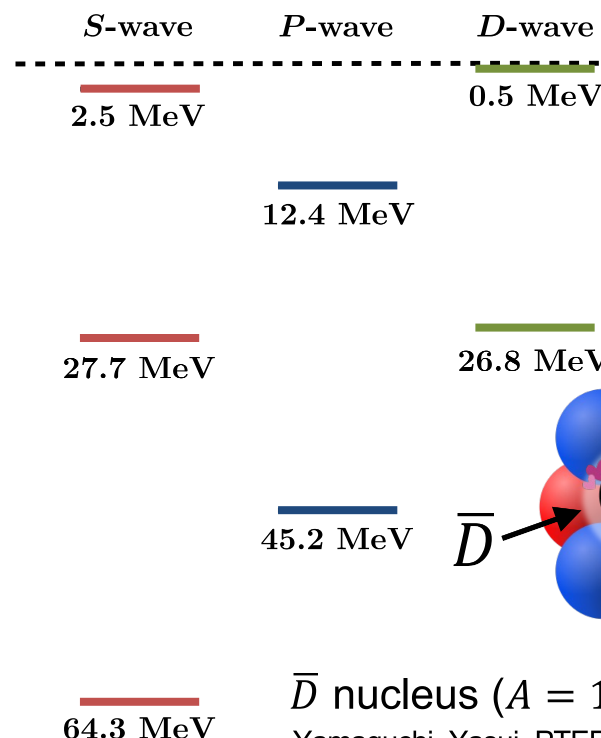
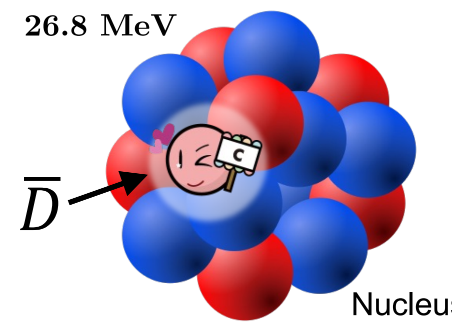
Cohen, Hohler, Lebed, PRD72, 074010 (2005)
Yasui, Sudoh, PRD80, 034008 (2009)
Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84, 014032 (2011), ibid. 85, 054003 (2012)
Cf. compact quarks: Gignoux, Silvestre-Brac, Richard, PLB193, 323 (1987), Lipkin, PLB195, 484 (1987)

(anti-)charm and bottom nuclei

$\bar{D}$ meson bound nuclei?

(example of theory prediction)





$\bar{D}$ nucleus ($A = 16$ baryon #)
Yamaguchi, Yasui, PTEP2017 (2017) 9, 093D02

Can (anti-)charm nuclei exist in our nature?

1. Why $\bar{D}$ meson and nucleon?

- Charm (bottom) nuclei? **Flavor nuclei (diversity of matter)**
  - ✓ Can charm (bottom) nuclei exist as stable states?
  - ✓ Binding energy of $\bar{D}$ mesons in nuclear medium?

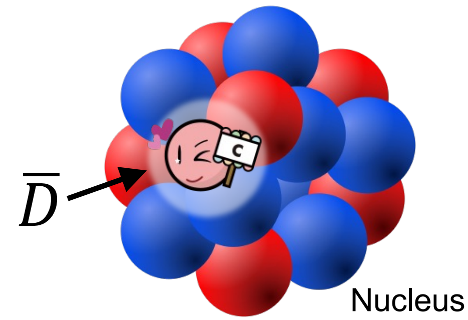


TABLE I. List of the mass shifts of the $\bar{D}$ meson in nuclear medium in previous works: quark meson coupling (QMC) model, QCD sum rule, coupled channel analysis, and chiral effective model.

Analysis	Ref.	Mass shift of $\bar{D}$ (MeV)	Density ρ (fm^{-3})
QMC model (QMC: quark-meson coupling)	[18]	–62 **attractive**	0.15
QCD sum rule	[19]	-48 ± 8 **attractive**	0.17
	[23]	+45 (averaged mass shift of D and $\bar{D}$) **repulsive**	0.15
	[28]	-46 ± 7 (averaged mass shift of D and $\bar{D}$) **attractive**	0.17
	[30]	−72 (averaged mass shift of D and $\bar{D}$) **attractive**	0.17
	[31]	+38 **repulsive**	0.17
Coupled channel analysis	[21]	+18 **repulsive**	0.17
	[22]	+(11–20) **repulsive**	0.16
	[26]	+35 **repulsive**	0.17
	[15]	$\simeq -(20–27)$ **attractive**	0.17
Chiral effective model	[20]	$\simeq -(30–180)$ **attractive**	0.15
	[25]	−27.2 **attractive**	0.15
	[16]	−35.1 **attractive**	0.17
	[37]	+97 (parity doublet model), +120 (skyrmion crystal) **repulsive**	0.16
	~~Our~~ result*	+74 **repulsive**	0.095

*D. Suenaga, S. Yasui., M. Harada, Phys. Rev. C96, 015204 (2017) [See this paper for the reference numbers.]

(Anti-)charm nuclei:
Is $\bar{D}N$ interaction *attractive* or *repulsive*?

1. Why $\bar{D}$ meson and nucleon? My contributions since 2009…

PHYSICAL REVIEW D **80**, 034008 (2009)

Exotic nuclei with open heavy flavor mesons

Shigehiro Yasui[1,*] and Kazutaka Sudoh[2,†]

PHYSICAL REVIEW D **84**, 014032 (2011)

Exotic baryons from a heavy meson and a nucleon: Negative parity states

Yasuhiro Yamaguchi,[1] Shunsuke Ohkoda,[1] Shigehiro Yasui,[2] and Atsushi Hosaka[1]

PHYSICAL REVIEW D **85**, 054003 (2012)

Exotic baryons from a heavy meson and a nucleon: Positive parity states

Yasuhiro Yamaguchi,[1] Shunsuke Ohkoda,[1] Shigehiro Yasui,[2] and Atsushi Hosaka[1]

Physics Letters B 727 (2013) 185–189

Contents lists available at ScienceDirect

Physics Letters B

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www.elsevier.com/locate/physletb

Spin degeneracy in multi-hadron systems with a heavy quark

CrossMark

Shigehiro Yasui[a,*], Kazutaka Sudoh[b], Yasuhiro Yamaguchi[c], Shunsuke Ohkoda[c], Atsushi Hosaka[c], Tetsuo Hyodo[d,1]

PHYSICAL REVIEW D **91**, 034034 (2015)

Heavy quark symmetry in multihadron systems

Yasuhiro Yamaguchi,[1] Shunsuke Ohkoda,[1] Atsushi Hosaka,[1,2] Tetsuo Hyodo,[3] and Shigehiro Yasui[4,5,*]

CrossMark

PHYSICS A

ELSEVIER

Nuclear Physics A 927 (2014) 110–118

www.elsevier.com/locate/nuclphysa

Exotic dibaryons with a heavy antiquark

Yasuhiro Yamaguchi[a,*], Shigehiro Yasui[b], Atsushi Hosaka[a,c]

PTEP

Prog. Theor. Exp. Phys. **2017**, 093D02 (14 pages)

DOI: 10.1093/ptep/ptx112

Mesic nuclei with a heavy antiquark

Yasuhiro Yamaguchi[1,2,*] and Shigehiro Yasui[3]

PHYSICAL REVIEW C **87**, 015202 (2013)

$\bar{D}$ and B mesons in a nuclear medium

S. Yasui[*]

KEK Theory Center, Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization, 1-1 Oho, Ibaraki 305-0801, Japan

K. Sudoh

PHYSICAL REVIEW C **89**, 015201 (2014)

Probing gluon dynamics by charm and bottom mesons in nuclear theory with $1/M$ corrections

S. Yasui[1,*] and K. Sudoh[2]

Progress in Particle and Nuclear Physics 96 (2017) 88–153

Contents lists available at ScienceDirect

Progress in Particle and Nuclear Physics

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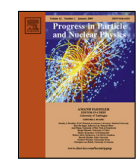
journal homepage: www.elsevier.com/locate/ppnp



Review

Heavy hadrons in nuclear matter

CrossMark

Atsushi Hosaka[a,b], Tetsuo Hyodo[c], Kazutaka Sudoh[d], Yasuhiro Yamaguchi[c,e], Shigehiro Yasui[f,*]

1. Why $\bar{D}$ meson and nucleon?

$\bar{D}N$ (BN) potential; the *latest* version

PHYSICAL REVIEW D **106,** 094001 (2022)

Open charm and bottom meson-nucleon potentials *à la* the nuclear force

Yasuhiro Yamaguchi[*]
Department of Physics, Nagoya University, Nagoya 464-8602, Japan
and Advanced Science Research Center, Japan Atomic Energy Agency (JAEA),
Tokai 319-1195, Japan

Shigehiro Yasui[†]
Research and Education Center for Natural Sciences, Keio University,
Hiyoshi 4-1-1, Yokohama, Kanagawa 223-8521, Japan

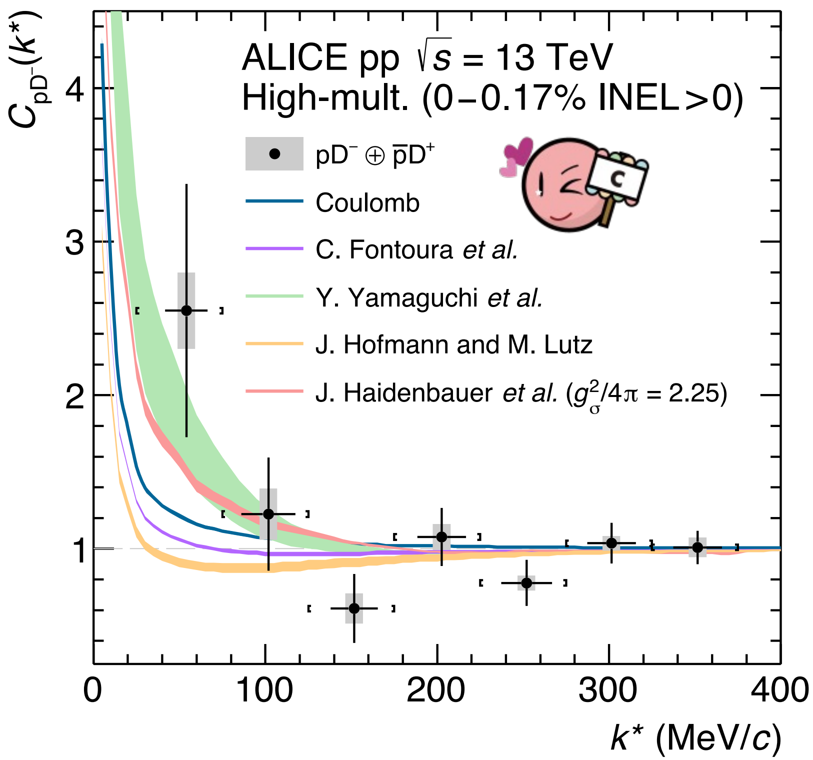
Atsushi Hosaka[‡]
Research Center for Nuclear Physics (RCNP), Ibaraki, Osaka 567-0047, Japan;
Advanced Science Research Center, Japan Atomic Energy Agency, Tokai, Ibaraki 319-1195, Japan
and Theoretical Research Division, Nishina Center, RIKEN, Hirosawa, Wako, Saitama 351-0198, Japan

I talk on this.

1. Why $\bar{D}$ meson and nucleon?

- 2022: First experiment for $\bar{D}N$ interaction!
  - ✓ ALICE at LHC Phys. Rev. D106, 052010 (2022) ← analysis by Kamiya, Hyodo, **Ohnishi**
  - ✓ D^-p ($\bar{D}N$) correlation function from proton-proton collisions
  - ✓ Attraction suggested? (Cf. KN is repulsive.)

Cf. Hyperon interaction: Ohnishi et al., Nucl. Phys. A954, 294 (2016)



	Model	f_0 (I = 0)	f_0 (I = 1)	n_σ
	Coulomb			(1.1–1.5)
attraction	Haidenbauer et al. [21]			
	$-\ g_\sigma^2/4\pi = 1$	0.14	−0.28	(1.2–1.5)
	$-\ g_\sigma^2/4\pi = 2.25$	0.67	0.04	(0.8–1.3)
repulsion	Hofmann and Lutz [22]	−0.16	−0.26	(1.3–1.6)
attraction (bound)	Yamaguchi et al. [24]	−4.38	−0.07	(0.6–1.1)
attraction	Fontoura et al. [23]	0.16	−0.25	(1.1–1.5)

[21] Haidenbauer, Krein, Meißner, Sibirtsev, EPJ. A33, 107 (2007)
[22] Hofmann, Lutz, NPA763, 90 (2005)
[24] Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84, 014032 (2011)
[23] Fontoura, Krein, Vizcarra, PRC87, 025206 (2013)

We should explore $\bar{D}$ meson and nucleon interaction ***more seriously***!

0. Introduction to exotic hadrons

1. Why $\bar{D}$ meson and nucleon?

2. $\bar{D}$ meson and nucleon potential

3. B meson and nucleon potential

4. Summary

0. Introduction to exotic hadrons

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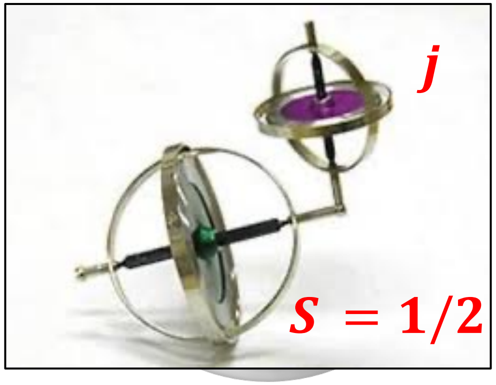
2. $\bar{D}$ meson and nucleon potential

- Structure of $\bar{D}$ meson: Heavy quark spin symmetry (HQS)
  - ✓ HQS: $Q \to SQ$ with $S \in \mathrm{SU}(2)_{\text{heavy quark spin}}$
  - ✓ D and D^* mesons as HQS doublet
  - ✓ B and B^* mesons also



HQS ($S = 1/2$) conserved ⇦ Spin J conserved ⇨ Light spin j **conserved!**

$$\vec{J} = \vec{S} + \vec{j}$$

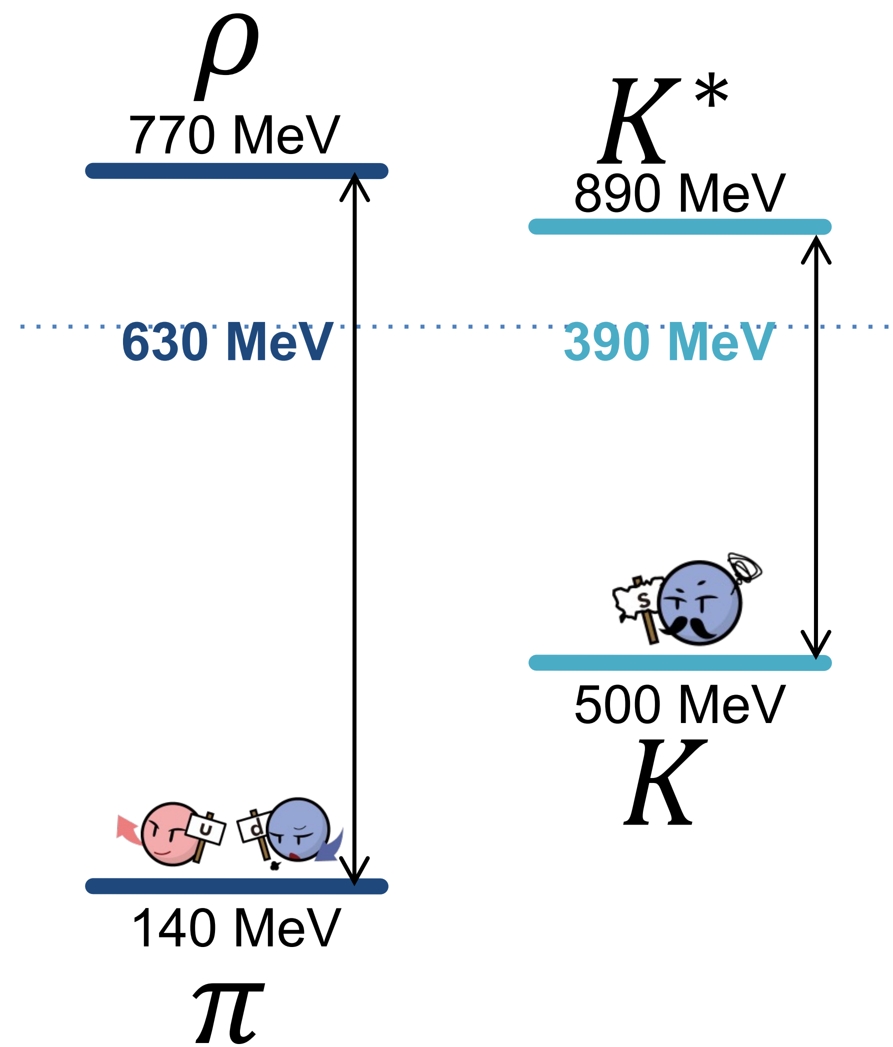
→ **Mass degeneracy for $J = j \pm 1/2$**

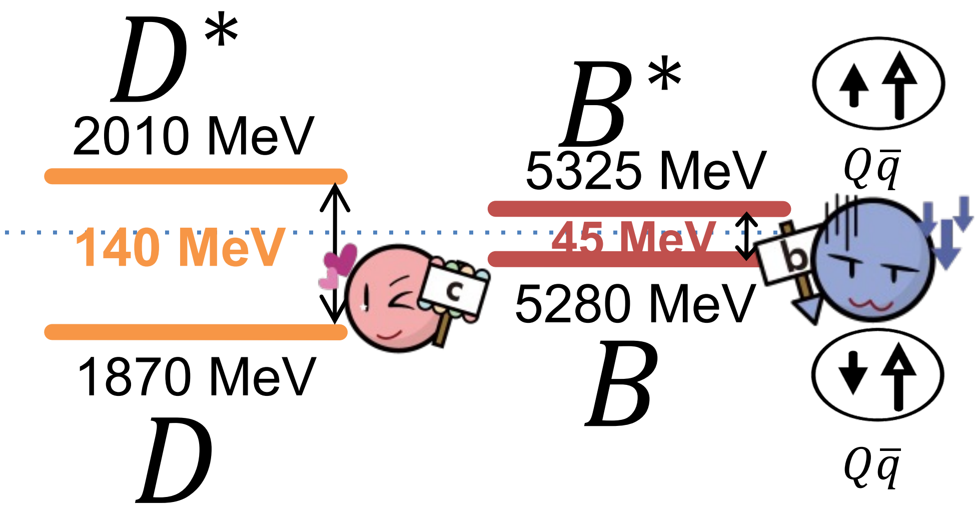
2. $\bar{D}$ meson and nucleon potential

- Structure of $\bar{D}$ meson: Heavy quark spin symmetry (HQS)
  - ✓ HQS: $Q \to SQ$ with $S \in \mathrm{SU}(2)_{\text{heavy quark spin}}$
  - ✓ D and D^* mesons as HQS doublet
  - ✓ B and B^* mesons also

$$\bar{\boldsymbol{D}} = \left(\bar{\boldsymbol{D}}^0, \boldsymbol{D}^-\right) = (\bar{\boldsymbol{c}}\boldsymbol{u}, \bar{\boldsymbol{c}}\boldsymbol{d}) \qquad \boldsymbol{u} \quad \boldsymbol{c} \quad \boldsymbol{t}$$

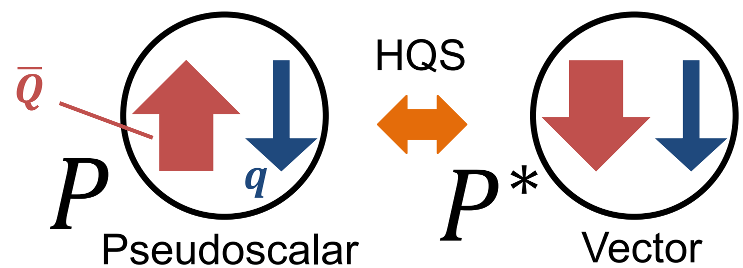
$$\boldsymbol{B} = \left(\boldsymbol{B}^+, \boldsymbol{B}^0\right) = (\bar{\boldsymbol{b}}\boldsymbol{u}, \bar{\boldsymbol{b}}\boldsymbol{d}) \qquad \boldsymbol{d} \quad \boldsymbol{s} \quad \boldsymbol{b}$$





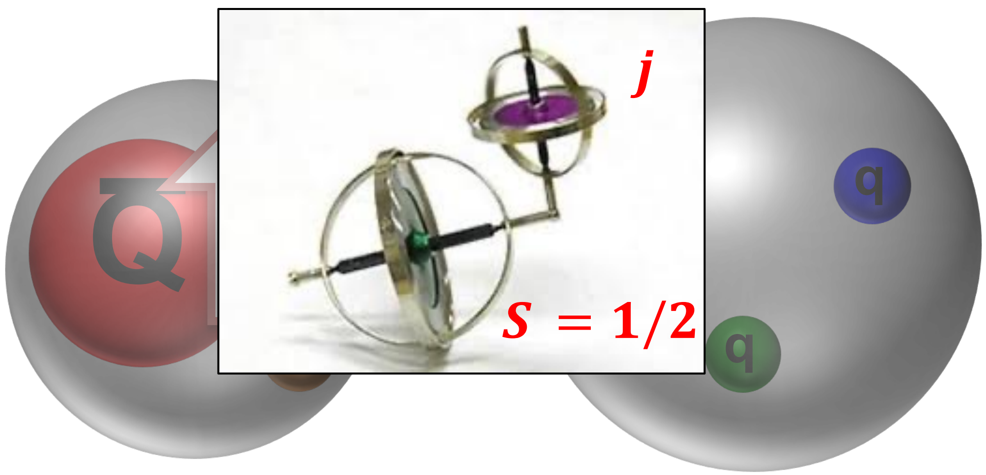
Pseudoscalar and vector mesons (P and P^*) become degenerate in heavy quark limit.

P and P^* should be considered **simultaneously**.



2. $\bar{D}$ meson and nucleon potential

- Structure of $\bar{D}$ meson: Heavy quark spin symmetry (HQS)
  - ✓ HQS can be applied to arbitrary (exotic) heavy hadrons.
  - ✓ Pentaquark $\bar{Q}qqqq$ $(= \bar{Q}q + qqq)$



HQS ($S = 1/2$) conserved ⟵ **Spin J** conserved ⟶ Light spin j **conserved!**

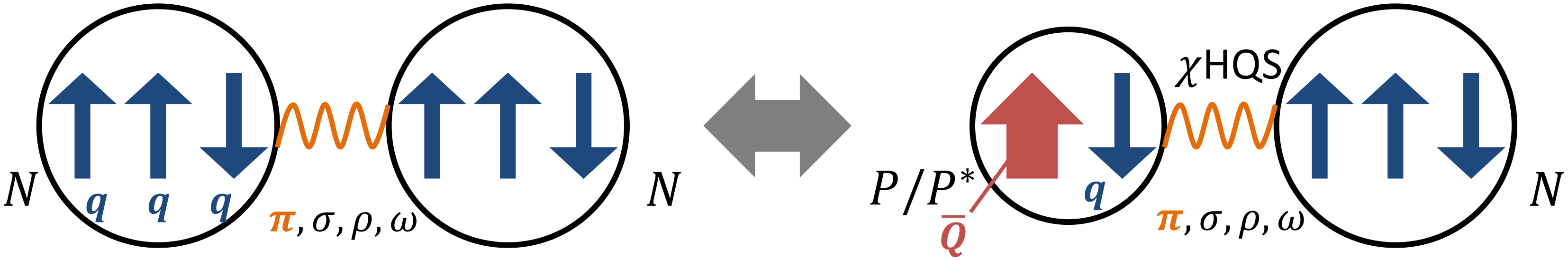
$$\vec{J} = \vec{S} + \vec{j}$$

→ Mass degeneracy for $J = j \pm 1/2$

We will see single-heavy hadronic molecules.

2. $\bar{D}$ meson and nucleon potential

- $\bar{D}$ meson and nucleon potential ($P = \bar{D}$, $P^* = \bar{D}^*$)
  - ✓ $PN - P^*N$ mixing (P and P^* are interchangeable.)
  - ✓ **Chiral (χ) symmetry** + **Heavy-quark spin (HQS) symmetry**
  - ✓ OPEP (one-pion exchange potential) ← χ+HQS
  - ✓ Scalar (σ), vector (ρ, ω) exchanges
  - ✓ Analogy to nucleon-nucleon (NN) pot. (Note: $1/\sqrt{2}$ factor for $P^{(*)}P^{(*)}m$)



π exchange → spin flipping (P, P^* mixing) like in a deuteron

2. $\bar{D}$ meson and nucleon potential

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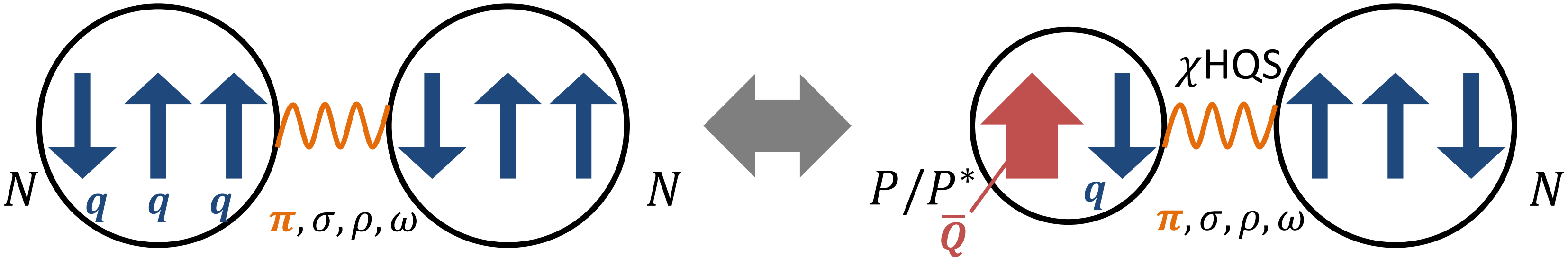

π exchange $\rightarrow$ spin flipping (P, P^* mixing) like in a deuteron

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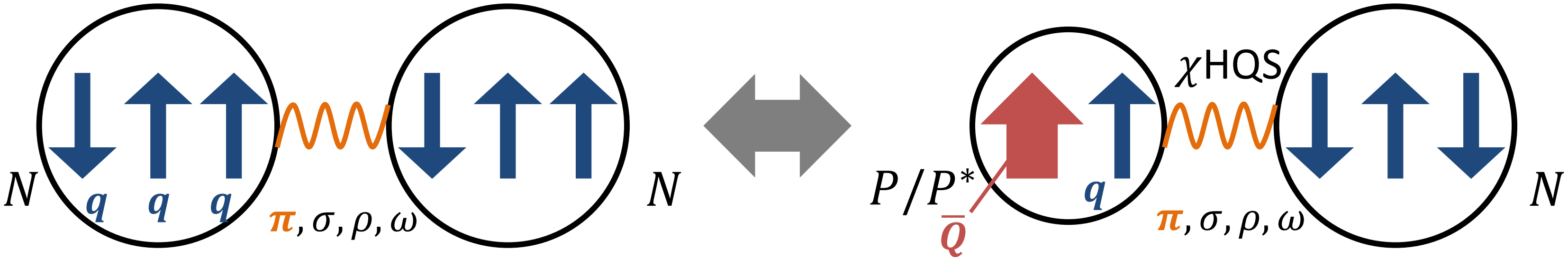

π exchange $\rightarrow$ spin flipping (P, P^* mixing) like in a deuteron

2. $\bar{D}$ meson and nucleon potential

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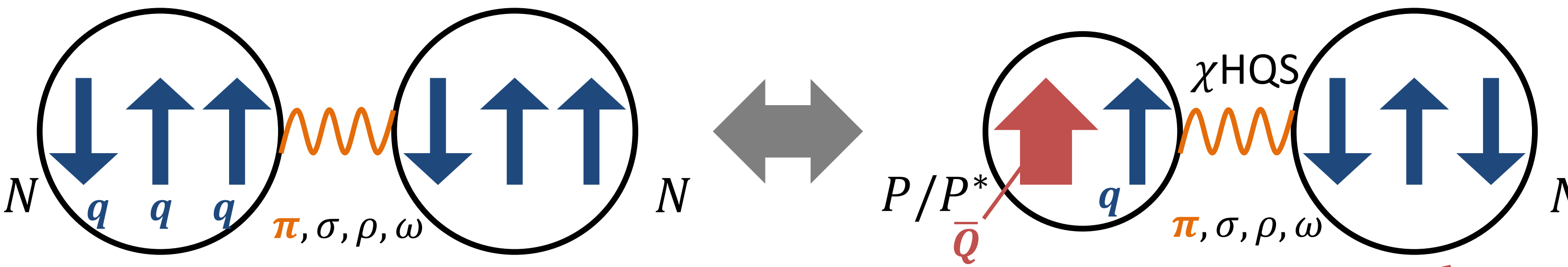

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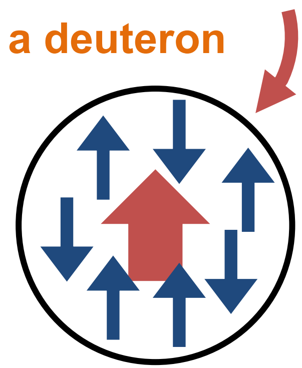
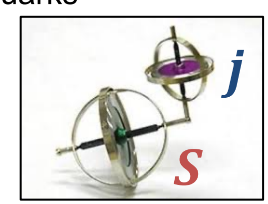


"brown muck"

light spin j

Spin decomposition by light quarks and gluons from heavy quarks



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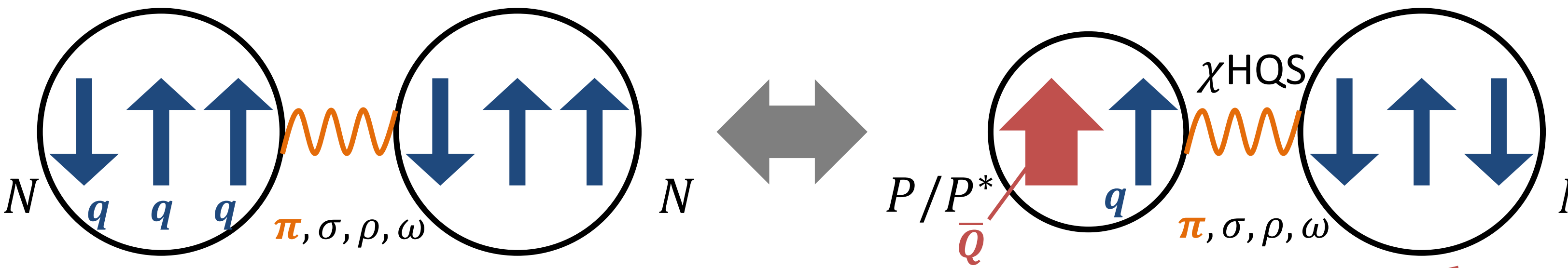

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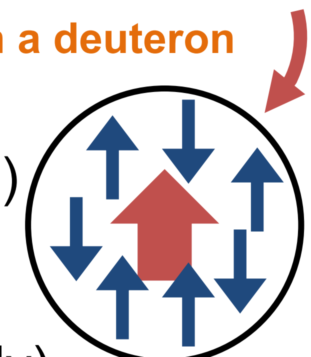

“brown muck”
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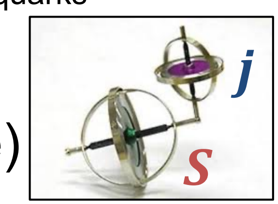

- Generality: spin-structure (q: light quark, N: nucleon)
  - ✓ Recombination: $[\bar{Q}q]N = \bar{Q}[qN]$
  - ✓ HQS multiplets: ***which is realized in QCD?***
    - **HQS singlet**: $q + N$ with $j = 0$ (total $J = 1/2$ only)
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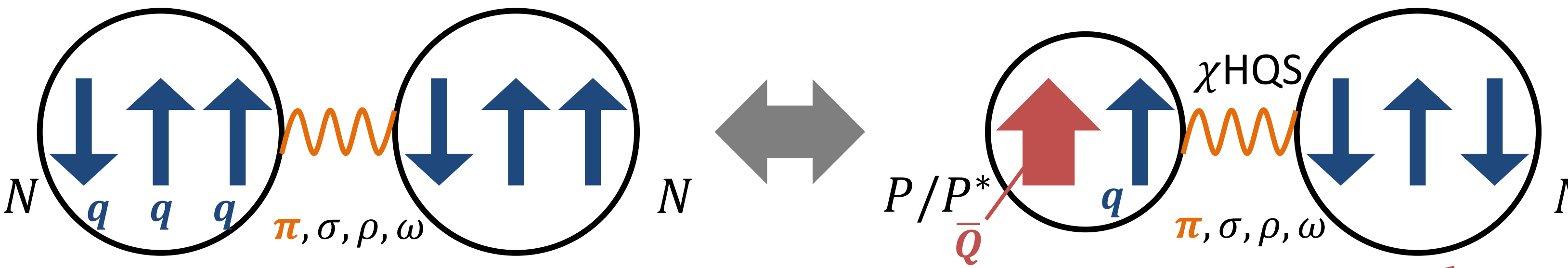

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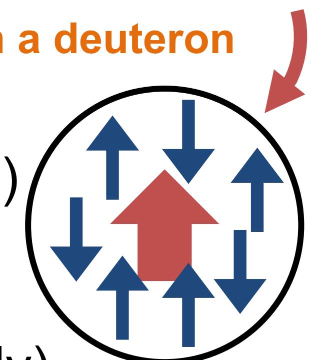

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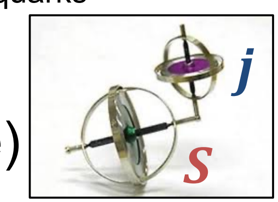

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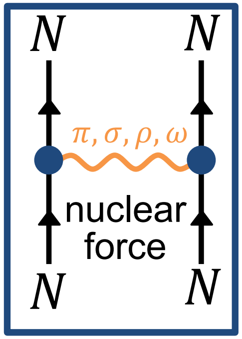
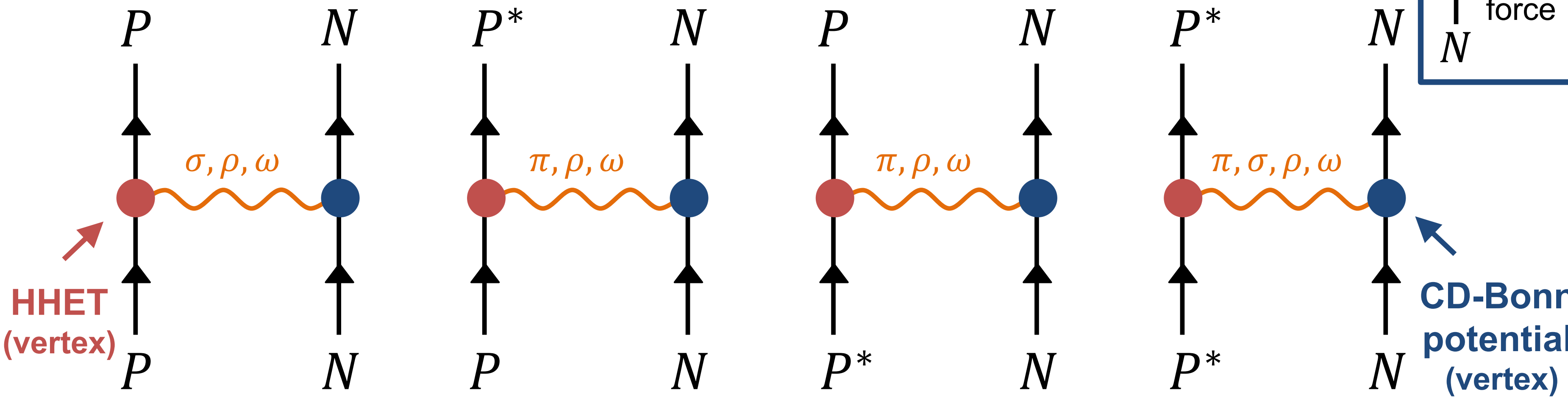
- We need to solve QCD in order to get the potential, but it's difficult.
  - ✓ We still rely on model calculations.

2. $\bar{D}$ meson and nucleon potential

- $P^{(*)}N$ potential ($P = \bar{D}, B$ meson; $P^* = \bar{D}^*, B^*$ meson, N nucleon)
  - ✓ $PN - P^*N$ channel mixing (multi-channel)





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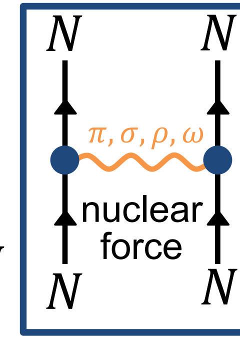

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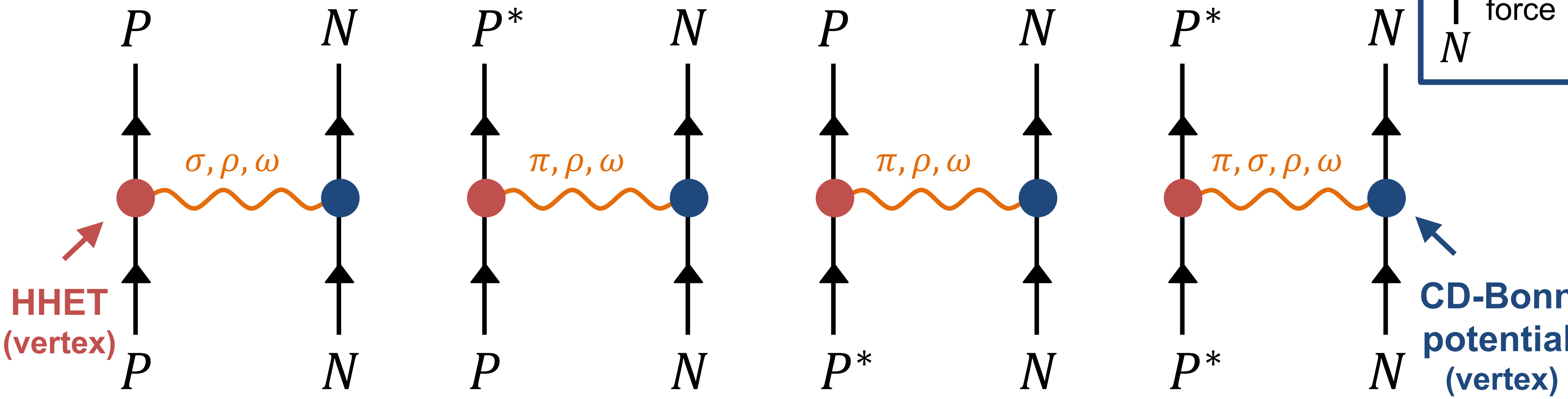

- **Heavy Hadron Effective Theory (HHET)** Luke, Manohar, Wise, Casalbuoni, …
  - ✓ Hadronic effective theory based on χ+HQS symmetries for P and P^*
  - ✓ Effective field: $H_\alpha = \left(P^{*\mu}_\alpha \gamma_\mu + P_\alpha \gamma_5\right)\frac{1-\not{v}}{2} \quad H_\alpha \to \underset{\text{HQS}}{S} H_\beta \underset{\chi\text{ sym.}}{U^\dagger_{\beta\alpha}}$
  - ✓ $P^{(*)}P^{(*)}m$ vertices are uniquely determined ($m = \pi, \boldsymbol{\sigma}, \rho, \omega$)

$$\mathcal{L}_{\pi HH} = i g_\pi \mathrm{tr}\left(H_\alpha \bar{H}_\beta \gamma_\mu \gamma_5 A^\mu_{\beta\alpha}\right)$$

$$\mathcal{L}_{\sigma_I HH} = g_{\sigma_I} \mathrm{tr}\left(H \sigma_I \bar{H}\right)$$

$$\mathcal{L}_{vHH} = -i\beta \mathrm{tr}\left(H_b v^\mu (\rho_\mu)_{ba} \bar{H}_a\right) + i\lambda \mathrm{tr}\left(H_b \sigma^{\mu\nu} (F_{\mu\nu}(\rho))_{ba} \bar{H}_a\right)$$

Previous works:
π only: Yasui, Sudoh, PRD80, 034008 (2009)
π, ρ, ω: Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84 014032 (2011), ibid. 054003 (2012)