$\overline{D}$ meson and nucleon interaction: from exotic hadrons to charm nuclei

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

Shigehiro YASUI

∈ Sasaki Lab. ⊂ SKCM² ⊂ Hiroshima University

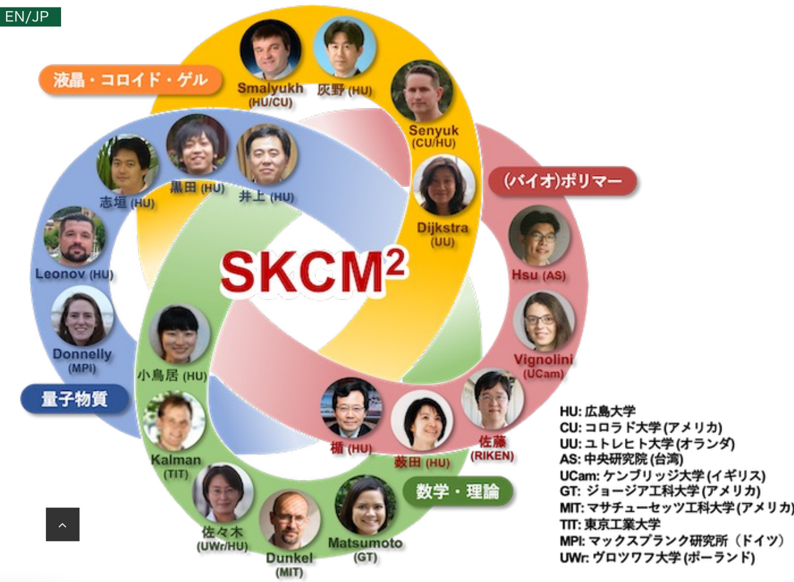
SKCM² WPI HIROSHIMA UNIVERSITY

wpi World Premier International Research Center Initiative

HADRON2023@Genova, 5-9 Jun. 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.)

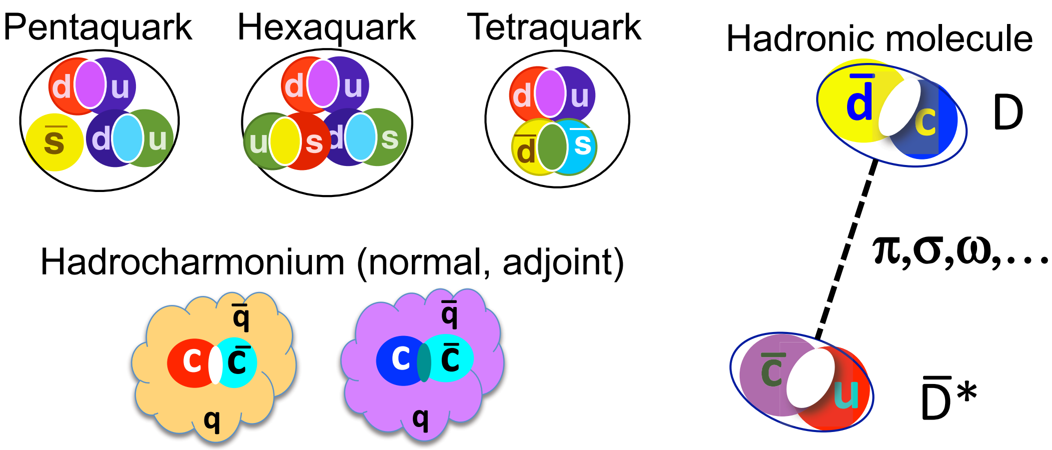
Contents

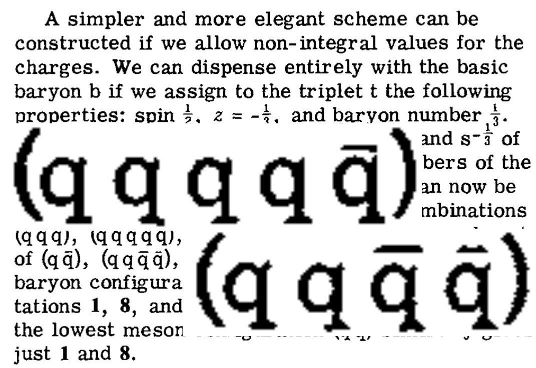
1. Introduction: Why $\bar{D}$ meson and nucleon?
2. $\bar{D}$ meson and nucleon potential
3. B meson and nucleon potential
4. Discussions
5. Summary

Contents

1. Introduction

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



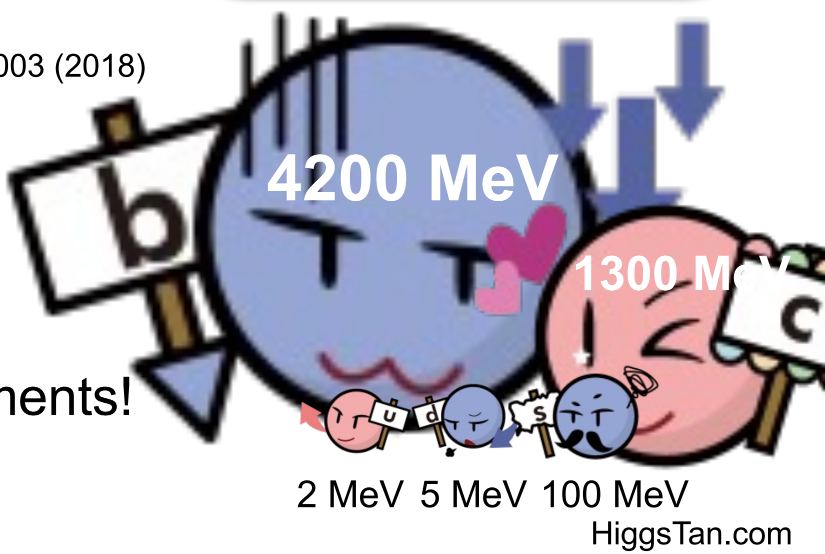

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{3}$, and baryon number $\frac{1}{3}$.
and $s^{-\frac{1}{3}}$ of
bers of the
an now be
mbinations
$(q\,q\,q\,q\,\bar{q})$
$(q\,q\,q)$, $(q\,q\,q\,q\,\bar{q})$,
of $(q\,\bar{q})$, $(q\,q\,\bar{q}\,\bar{q})$,
baryon configura
tations **1**, **8**, and
the lowest meson
just **1** and **8**.
$(q\,q\,\bar{q}\,\bar{q})$

Exotic hadrons: Diversity of hadrons

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

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

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

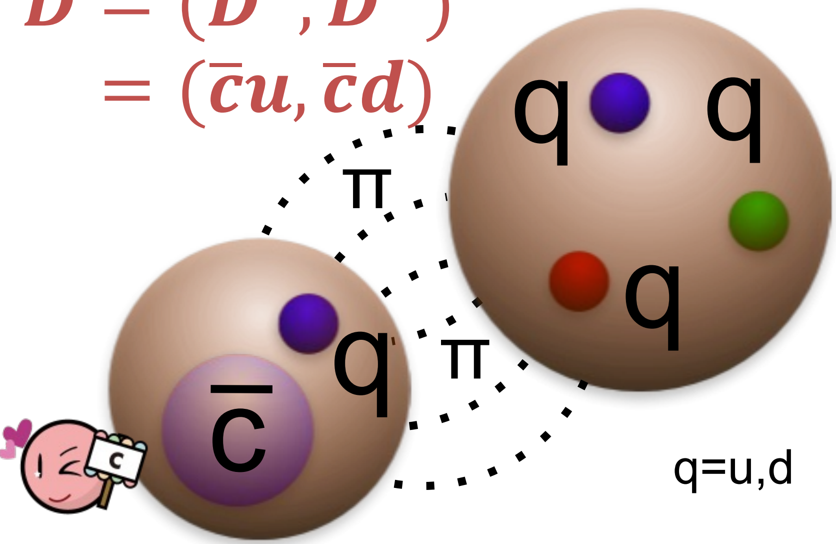


1. Introduction

No annihilation
→ (relatively) simple

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

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



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

(anti D meson)

*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)
etc.

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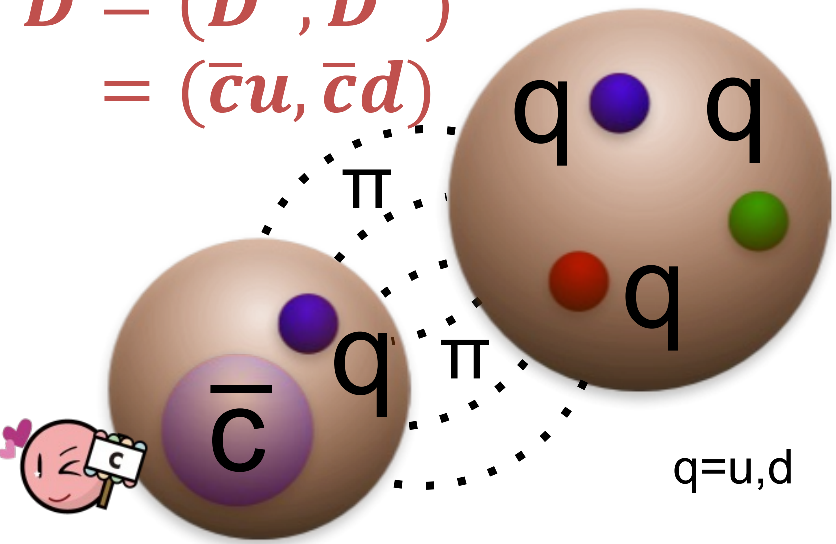


$\bar{D}$ meson
(anti D meson)

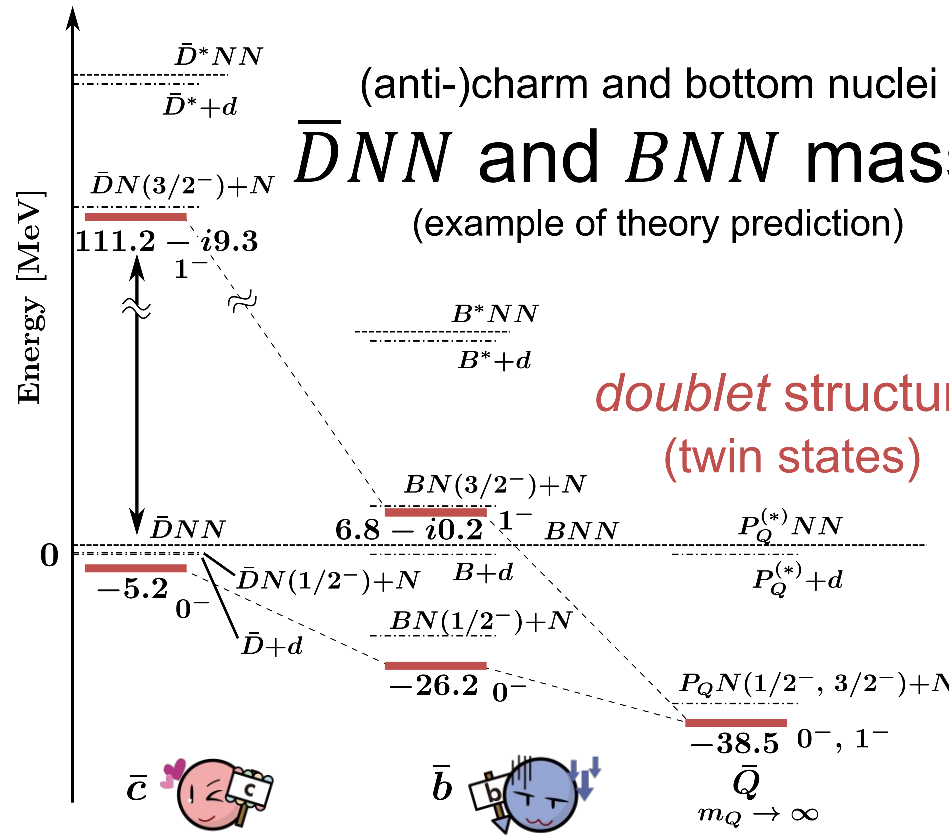
Nucleon

*penta*quark (5 quark)

(anti-)charm and bottom nuclei

$\bar{D}NN$ and BNN mass?

(example of theory prediction)



doublet structure
(twin states)

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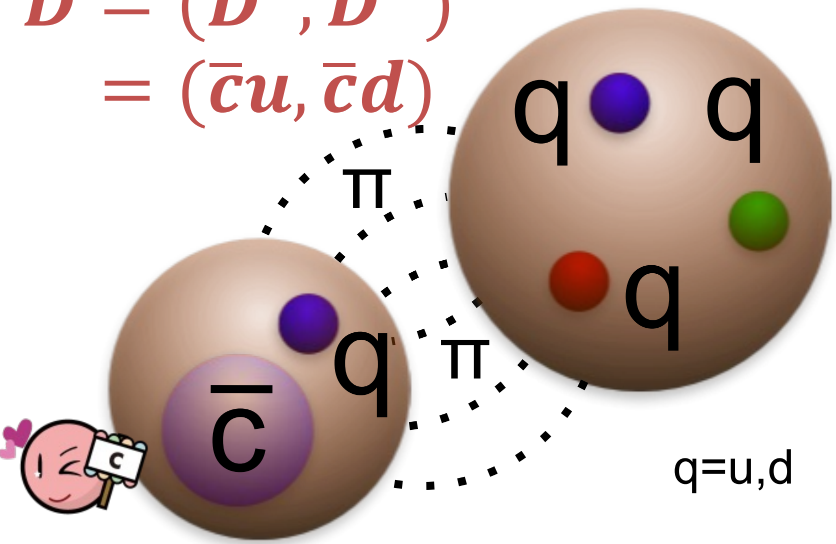

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(anti-)charm and bottom nuclei

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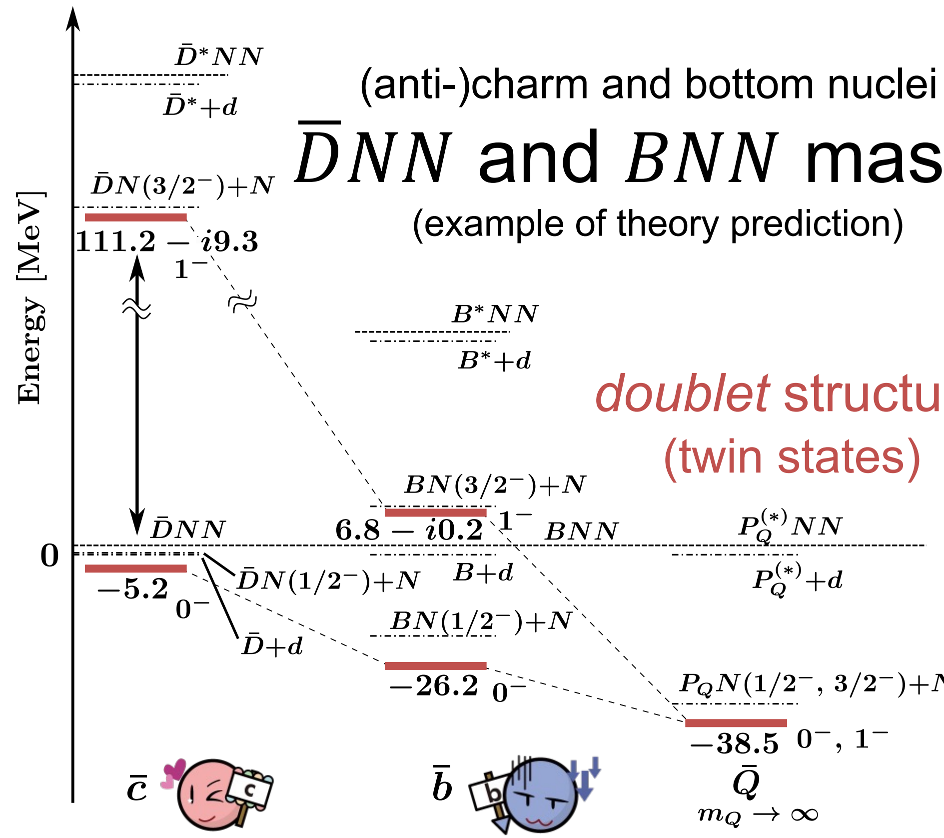


doublet structure
(twin states)

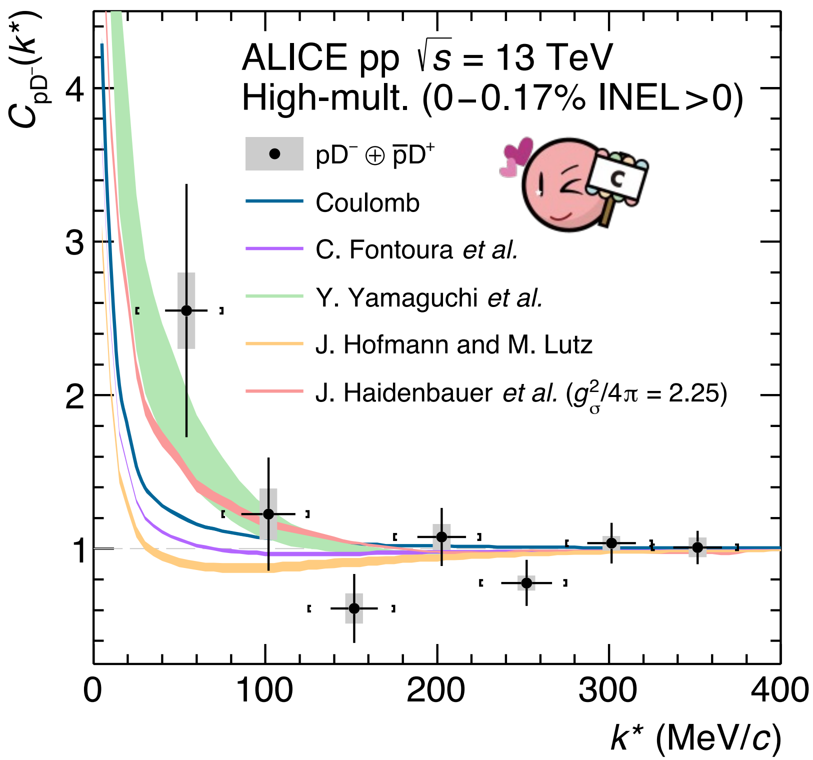
Can (anti-)charm nuclei exist in our nature?

HiggsTan.com

1. Introduction

- 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]			
	$-\ g^2_\sigma/4\pi = 1$	0.14	−0.28	(1.2–1.5)
	$-\ g^2_\sigma/4\pi = 2.25$	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***!

1. Introduction

My few 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

www.elsevier.com/locate/physletb

ELSEVIER

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

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

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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. Introduction

$\bar{D}N$ (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.

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

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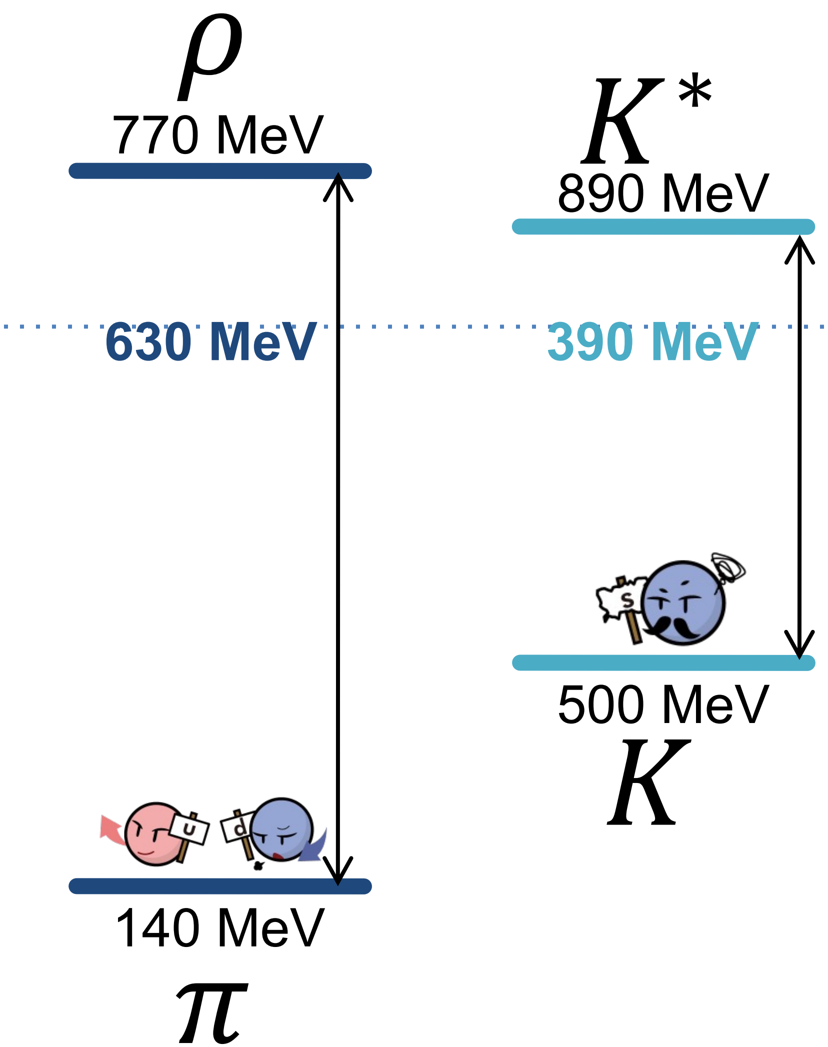
2. $\bar{D}$ meson and nucleon potential

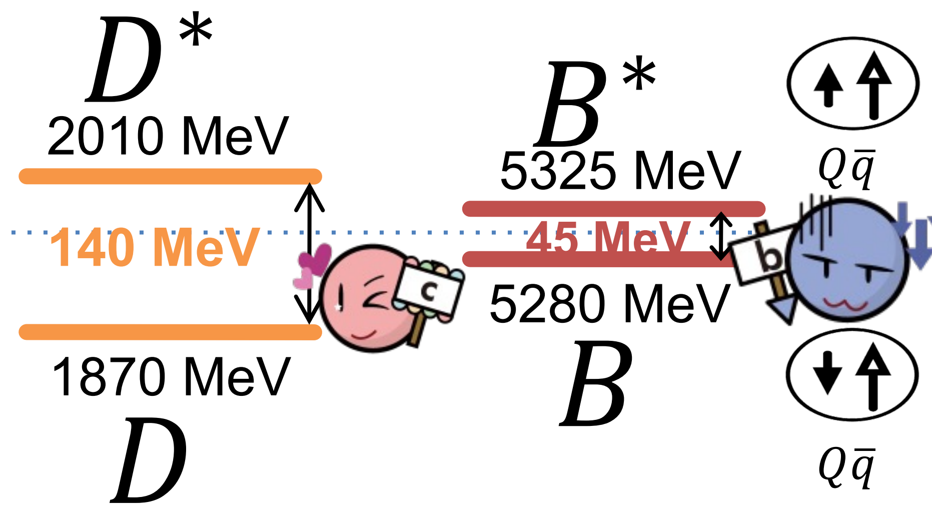
- Structure of $\bar{D}$ meson: Heavy quark spin symmetry (HQS)
  - ✓ HQS: $Q \to SQ$ with $S \in \mathrm{SU}(2)_{\text{heavy quark spin}}$
  - ✓ D and D^* mesons as HQS doublet
  - ✓ B and B^* mesons also

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

$$\boldsymbol{B} = (\boldsymbol{B}^+, \boldsymbol{B}^0) = (\bar{\boldsymbol{b}}\boldsymbol{u}, \bar{\boldsymbol{b}}\boldsymbol{d})$$

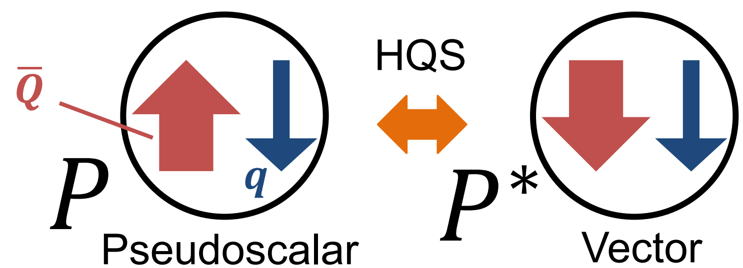
u	c	t
d	s	b





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

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



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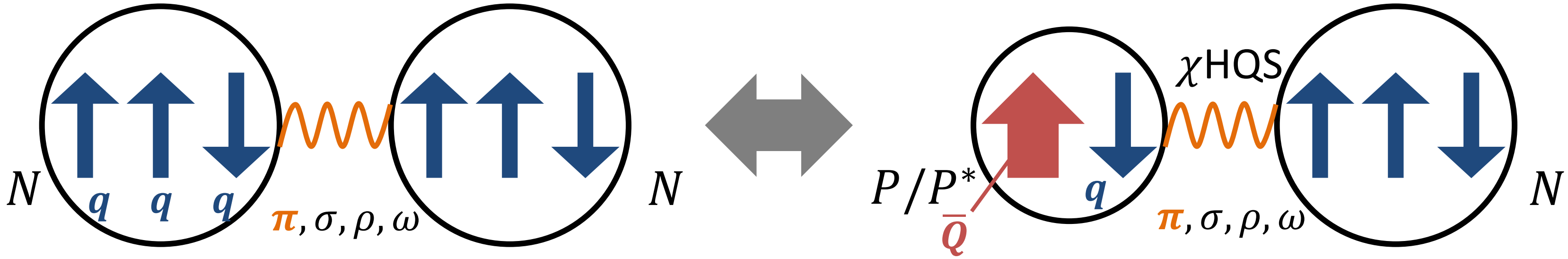
2. $\overline{D}$ meson and nucleon potential

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



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

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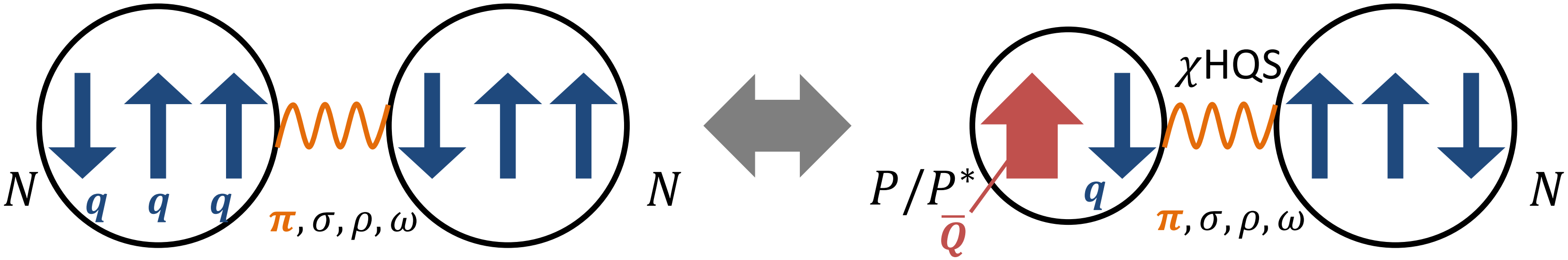

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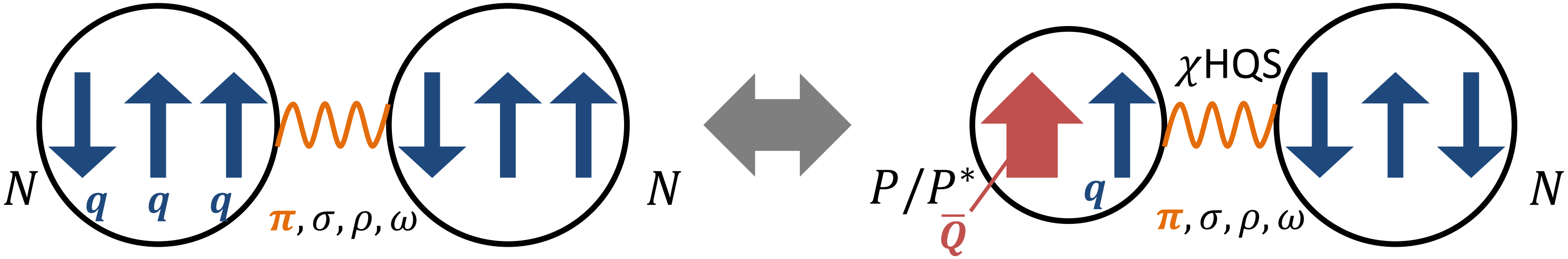

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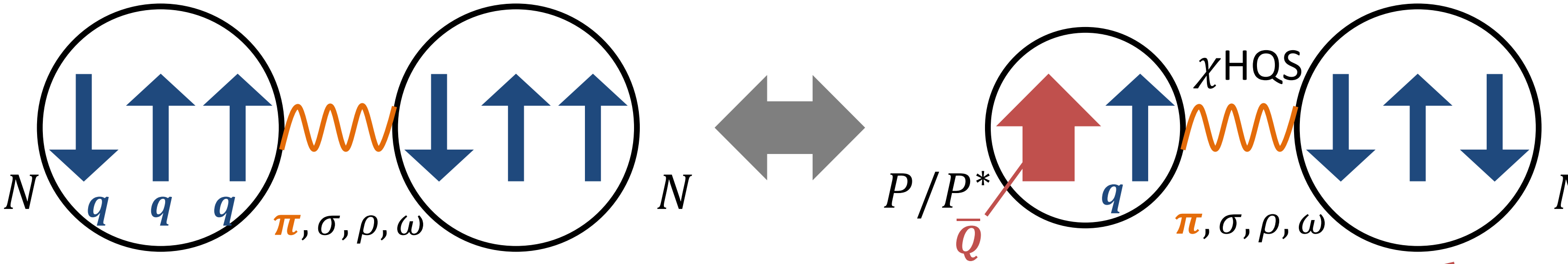
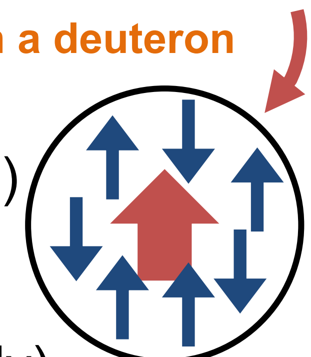
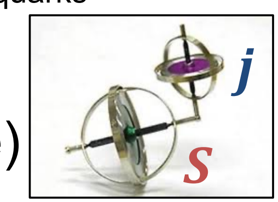


π exchange → spin flipping (P, P^* mixing) like in a deuteron

- 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)
    - **HQS doublet**: $q + N$ with $j = 1$ (total $J = 1/2, 3/2$ degenerate)



"brown muck"
light spin j
Spin decomposition by light quarks and gluons from heavy quarks



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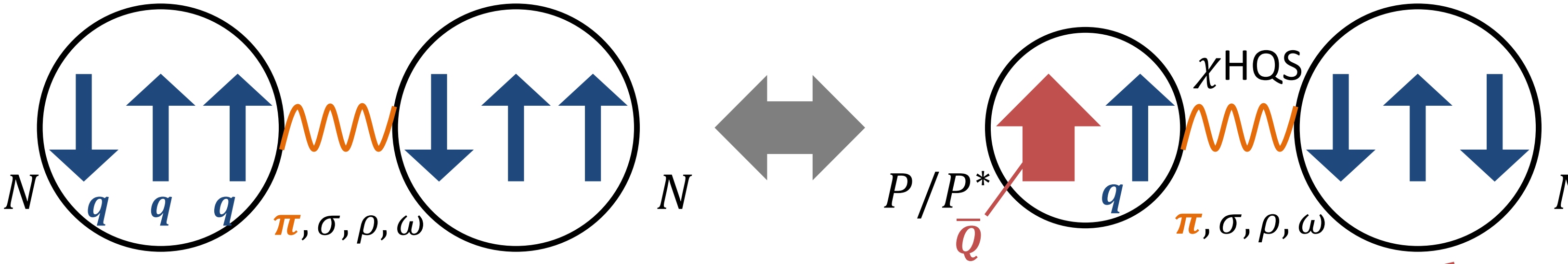

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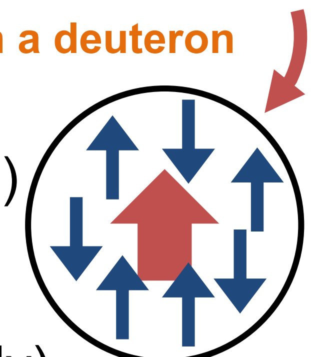

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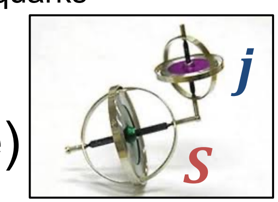

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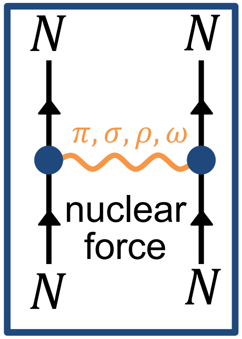
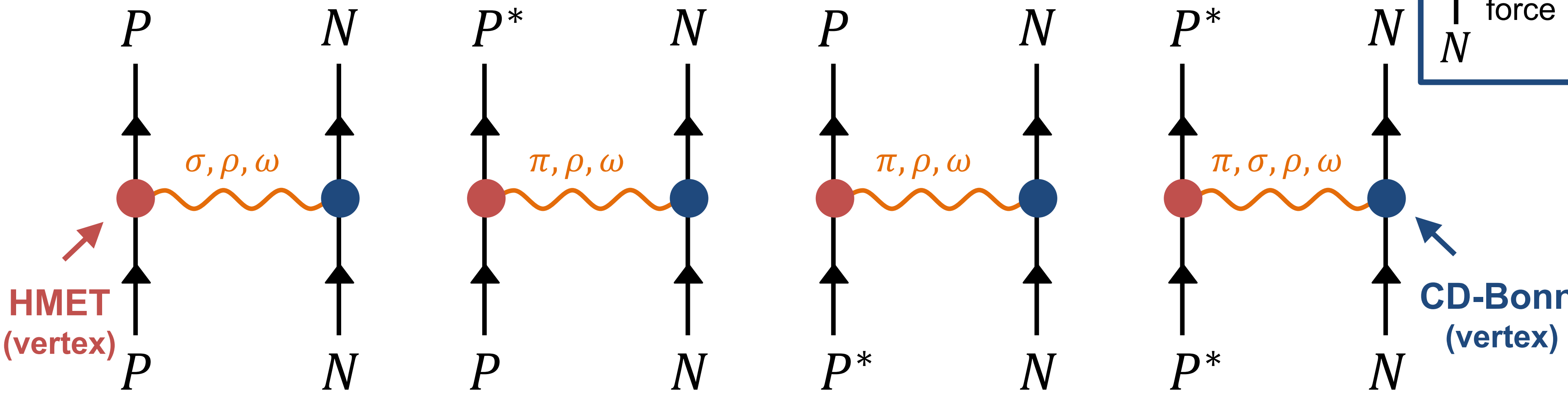
    - **HQS doublet**: $q + N$ with $j = 1$ (total $J = 1/2, 3/2$ degenerate)
- We need to solve QCD in order to get the potential, but it's difficult.
  - ✓ We still rely on model calculations.

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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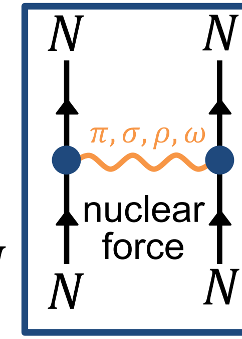

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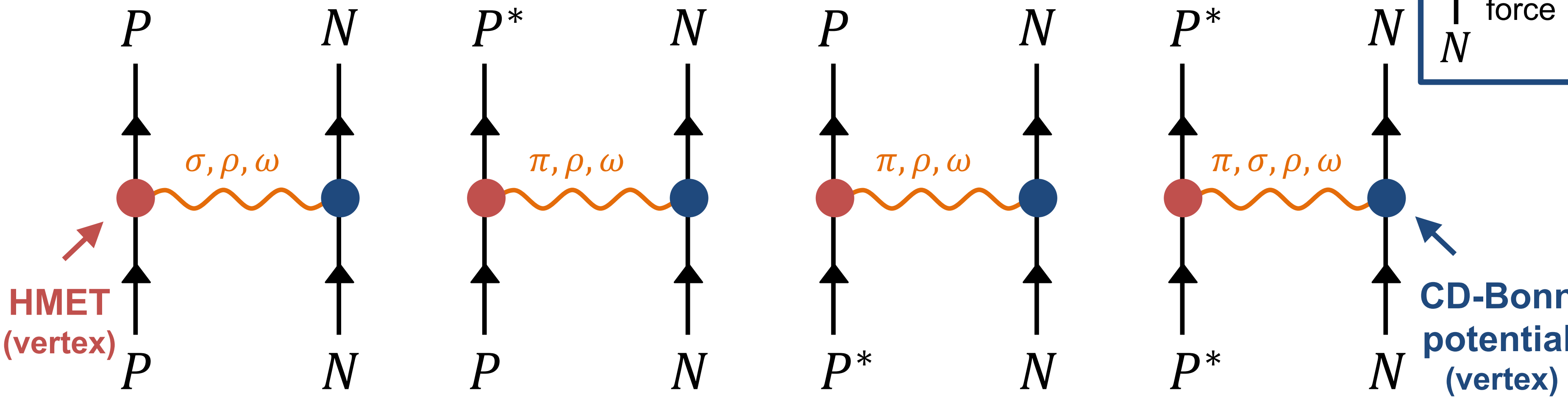


- **Heavy Meson Effective Theory (HMET)** Luke, Manohar, Wise, Casalbuoni, …
  ✓ Hadronic effective theory based on χ+HQS symmetries for P and P^*
  ✓ Effective field: $H_\alpha = \left(P^{*\mu}_\alpha \gamma_\mu + P_\alpha \gamma_5\right)\frac{1-\not{v}}{2}$ $\quad H_\alpha \to \underset{\text{HQS}}{S}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

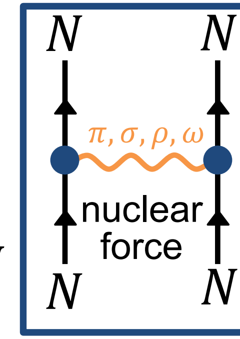
$$\mathcal{L}_{\pi HH} = i g_\pi \mathrm{tr}\left(H_\alpha \bar{H}_\beta \gamma_\mu \gamma_5 A^\mu_{\beta\alpha}\right)$$

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

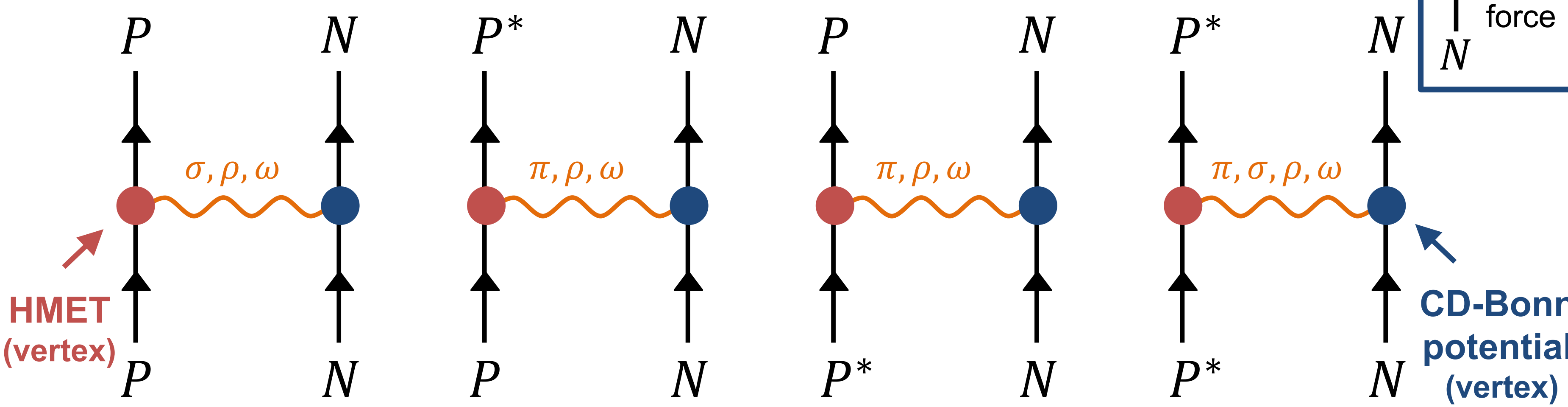
$$\mathcal{L}_{vHH} = -i\beta \mathrm{tr}\left(H_b v^\mu (\rho_\mu)_{ba} \bar{H}_a\right) + i\lambda \mathrm{tr}\left(H_b \sigma^{\mu\nu} (F_{\mu\nu}(\rho))_{ba} \bar{H}_a\right)$$

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

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)



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

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

$$\mathcal{L}_{\sigma_I HH} = g_{\sigma_I} \mathrm{tr}\left(H \sigma_I \bar{H}\right) \longleftarrow \boldsymbol{\sigma} \textbf{ is new!}$$

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

σ is important for NN ($I = 0, 1$ channels):
σ_0 (weak coupling) for NN with $I = 0$
σ_1 (strong coupling) for NN with $I = 1$

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

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

- $P^{(*)}N$ state ($J^P = 1/2^-$, $I = 0$ or 1) Note: applicable to $J^P = 3/2^-$ (HQS partner)
  - ✓ Particle basis: $\boldsymbol{PN(^2S_{1/2}), P^*N(^2S_{1/2}), P^*N(^4D_{1/2})}$ **← 3 channels**
  - ✓ HQS basis: $\bar{Q}_{S=1/2}[qN]_{j=0,1}$ Cf. Yasui, Sudoh, Yamaguchi, Ohkoda, Hosaka, Hyodo, PLB727, 185 (2013); PRD91, 034034 (2015)

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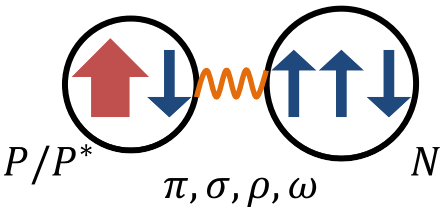
- $P^{(*)}N(1/2^-)$ Hamiltonian $H_{J^P} = K_{J^P} + V^{\pi}_{J^P} + V^{\sigma_I}_{J^P} + V^{\rho}_{J^P} + V^{\omega}_{J^P}$
  - ✓ Kinetic term $K_{1/2^-} = \mathrm{diag}\left(K_0, K_0^*, K_2^*\right)$ (S-wave, S-wave, D-wave)
  - ✓ $\pi, \sigma, v(= \rho, \omega)$ pot. term ($1/\sqrt{2}$ factor included)



$$V^{\pi}_{1/2^-} = \begin{pmatrix} 0 & \sqrt{3}\,C_\pi & -\sqrt{6}\,T_\pi \\ \sqrt{3}\,C_\pi & -2\,C_\pi & -\sqrt{2}\,T_\pi \\ -\sqrt{6}\,T_\pi & -\sqrt{2}\,T_\pi & C_\pi - 2\,T_\pi \end{pmatrix} \qquad V^{\sigma_I}_{1/2^-} = \begin{pmatrix} C_{\sigma_I} & 0 & 0 \\ 0 & C_{\sigma_I} & 0 \\ 0 & 0 & C_{\sigma_I} \end{pmatrix}$$

$$V^{v}_{1/2^-} = \begin{pmatrix} C'_v & 2\sqrt{3}C_v & \sqrt{6}T_v \\ 2\sqrt{3}C_v & C'_v - 4C_v & \sqrt{2}T_v \\ \sqrt{6}T_v & \sqrt{2}T_v & C'_v + 2C_v + 2T_v \end{pmatrix}$$

including **HQS singlet/doublet**

- ✓ **Tensor force** (T_π, T_v) induces strong mixing among 3 channels

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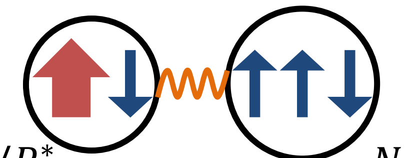


$$V^{\pi}_{1/2^-} = \begin{pmatrix} 0 & \sqrt{3}\,C_\pi & -\sqrt{6}\,T_\pi \\ \sqrt{3}\,C_\pi & -2\,C_\pi & -\sqrt{2}\,T_\pi \\ -\sqrt{6}\,T_\pi & -\sqrt{2}\,T_\pi & C_\pi - 2\,T_\pi \end{pmatrix} \quad V^{\sigma_I}_{1/2^-} = \begin{pmatrix} C_{\sigma_I} & 0 & 0 \\ 0 & C_{\sigma_I} & 0 \\ 0 & 0 & C_{\sigma_I} \end{pmatrix}$$

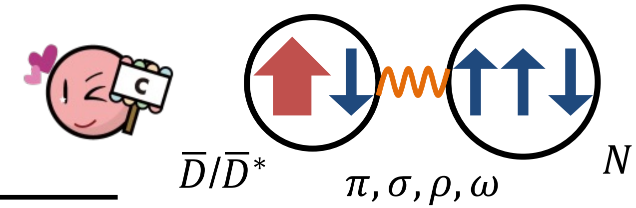
$$V^{v}_{1/2^-} = \begin{pmatrix} C'_v & 2\sqrt{3}C_v & \sqrt{6}T_v \\ 2\sqrt{3}C_v & C'_v - 4C_v & \sqrt{2}T_v \\ \sqrt{6}T_v & \sqrt{2}T_v & C'_v + 2C_v + 2T_v \end{pmatrix}$$

including **HQS singlet/doublet**

- ✓ **Tensor force** (T_π, T_v) induces strong mixing among 3 channels
- ✓ Model parameters
  - π pot. coupling ($D^* \to D\pi$)
  - $v = \rho, \omega$ pot. couplings (universal couplings)
  - σ pot. coupling ~ 1/3 of NN (# of light quarks in $P^{(*)}$ meson)
  - Momentum cutoffs (size ratios of $\bar{D}$ (B) and N from quark model)

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

- Results ($\overline{D}$ and N)
  - ✓ bound states ($I = 0, 1$)

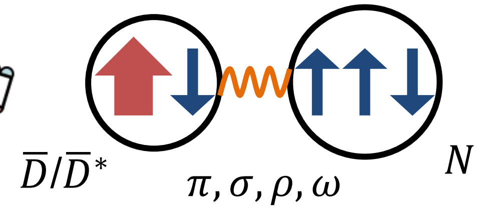


$\bar{D}N$	B.E. [MeV]	Mixing ratio [%]	
$I(J^P) = 0(1/2^-)$	1.38 "shallow"	$\bar{D}N(^2S_{1/2})$	96.1
		$\bar{D}^*N(^2S_{1/2})$	1.94
		$\bar{D}^*N(^4D_{1/2})$	1.93
$I(J^P) = 1(1/2^-)$	5.99 "deep"	$\bar{D}N(^2S_{1/2})$:	88.9
		$\bar{D}^*N(^2S_{1/2})$:	10.9
		$\bar{D}^*N(^4D_{1/2})$:	0.11

Cf. Deuteron binding energy 2.2 MeV

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

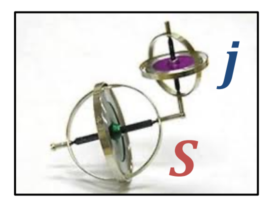
- Results ($\bar{D}$ and N)
  - ✓ bound states ($I = 0, 1$)



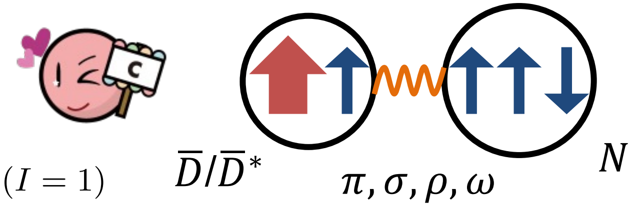
$\bar{D}N$	B.E. [MeV]	Mixing ratio [%]
$I(J^P) = 0(1/2^-)$ **"$j = 1$"**	1.38 **"shallow"**	$\bar{D}N(^2S_{1/2})$ 96.1 $\bar{D}^*N(^2S_{1/2})$ 1.94 $\bar{D}^*N(^4D_{1/2})$ 1.93
$I(J^P) = 1(1/2^-)$ **"$j = 0$"**	5.99 **"deep"**	$\bar{D}N(^2S_{1/2})$: 88.9 $\bar{D}^*N(^2S_{1/2})$: 10.9 $\bar{D}^*N(^4D_{1/2})$: 0.11

Cf. Deuteron binding energy 2.2 MeV

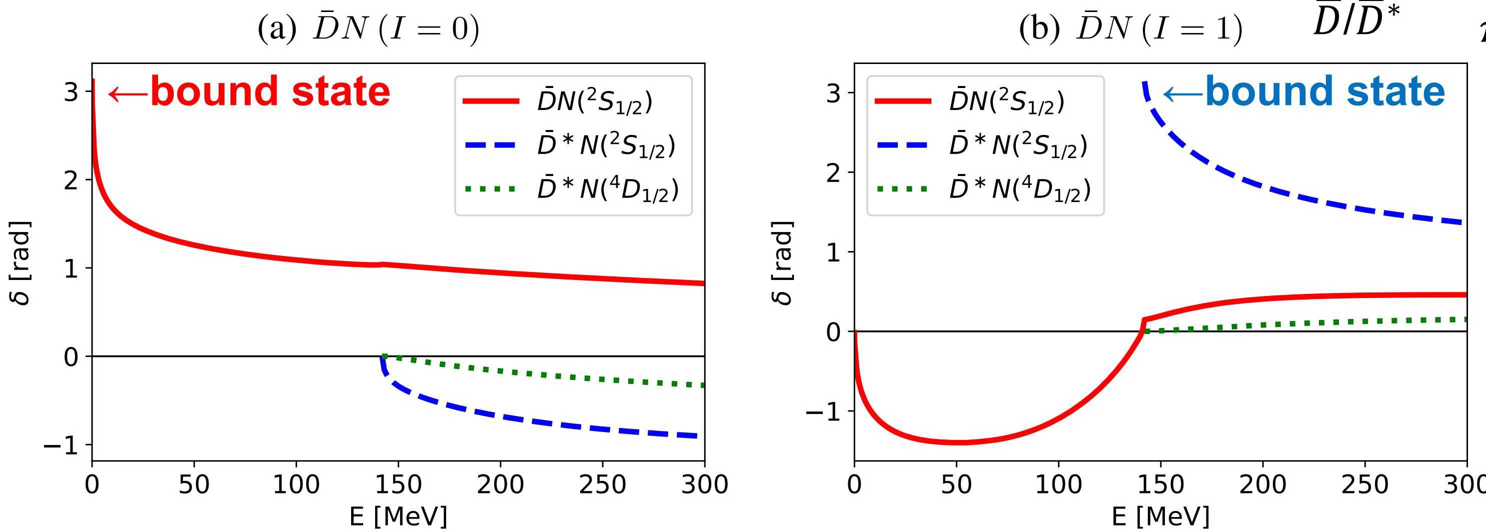
- $I = 0$: shallow bound state (consistent with previous works)
- $I = 1$: deeply bound state (new!)
- Both π and σ are important
- Note: σ pot. in $I = 1$ is very strong
- Internal spin: "$j = 1$" for $I = 0$ and "$j = 0$" for $I = 1$ (approximate)



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



✓ Phase shifts



✓ Scattering lengths

$\bar{D}N$	a [fm]	
$0(1/2^-)$	$\bar{D}N(^2S_{1/2})$	5.21
	$\bar{D}^*N(^2S_{1/2})$	$0.868 - i3.72 \times 10^{-2}$
$1(1/2^-)$	$\bar{D}N(^2S_{1/2})$	2.60
	$\bar{D}^*N(^2S_{1/2})$	$0.944 - i0.722$

1. Introduction: Why $\bar{D}$ meson and nucleon?
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3. B meson and nucleon potential
4. Discussions
5. Summary

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

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

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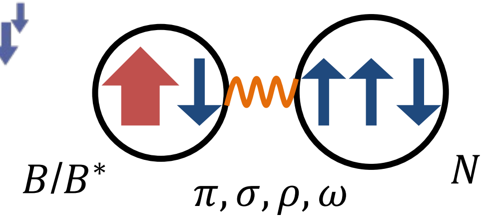
5. Summary

3. B meson and nucleon potential

- Applicable for B meson and nucleon (more ideal in view of HQS)
- Results (B and N)
  - ✓ Bound states (I=0, 1)

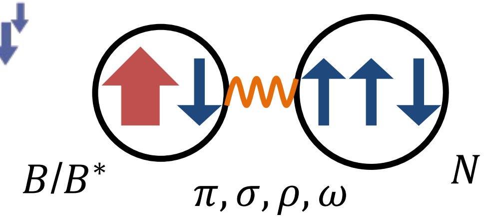


BN	B.E. [MeV]	Mixing ratio [%]	
$I(J^P) = 0(1/2^-)$	29.7	$BN(^2S_{1/2})$	76.4
		$B^*N(^2S_{1/2})$	14.1
	"deep"	$B^*N(^4D_{1/2})$	9.46
$I(J^P) = 1(1/2^-)$	66.0	$BN(^2S_{1/2})$	38.5
		$B^*N(^2S_{1/2})$	61.5
	"very deep"	$B^*N(^4D_{1/2})$	1.82×10^{-2}

Cf. Deuteron binding energy 2.2 MeV

3. B meson and nucleon potential

- Applicable for B meson and nucleon (more ideal in view of HQS)
- Results (B and N)
  - ✓ Bound states (I=0, 1)



BN	B.E. [MeV]	Mixing ratio [%]	
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“$j = 1$”	**“deep”**	$B^*N(^4D_{1/2})$	9.46
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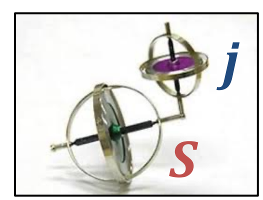
“$j = 0$”	**“very deep”**	$B^*N(^4D_{1/2})$	1.82×10^{-2}

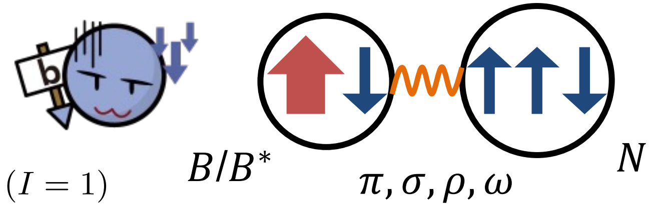
Cf. Deuteron binding energy 2.2 MeV

- $I = 0$: deeply bound state (consistent with previous works)
- $I = 1$: more deeply bound state (new!)
- Both π and σ are important
- Note: σ pot. in $I = 1$ is very strongly attractive
- Internal spin: “$j = 1$” for $I = 0$ and “$j = 0$” for $I = 1$ (approximate)



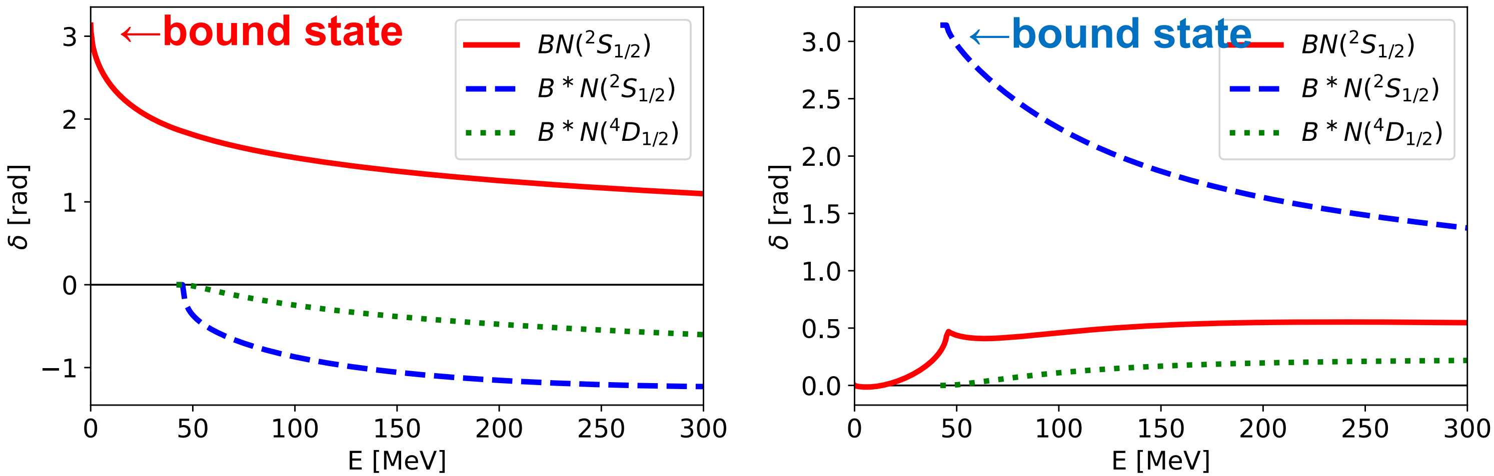
“brown muck”
(light component)
heavy quark

3. B meson and nucleon potential



✔ Phase shifts

(c) $BN\ (I=0)$ (d) $BN\ (I=1)$



✔ Scattering lengths

BN	a [fm]	
$0(1/2^-)$	$BN(^2S_{1/2})$	1.25
	$B^*N(^2S_{1/2})$	$1.03 - i1.07 \times 10^{-2}$
$1(1/2^-)$	$BN(^2S_{1/2})$	3.84×10^{-2}
	$B^*N(^2S_{1/2})$	$0.263 - i0.585$

✔ Why not to research BN correlation function from heavy-ion collisions?

- Very few theoretical works on BN interaction
- Should we explore **B^0p ($I=0$ and 1) channel**?

1. Introduction: Why $\bar{D}$ meson and nucleon?
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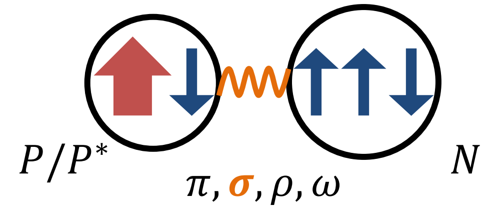
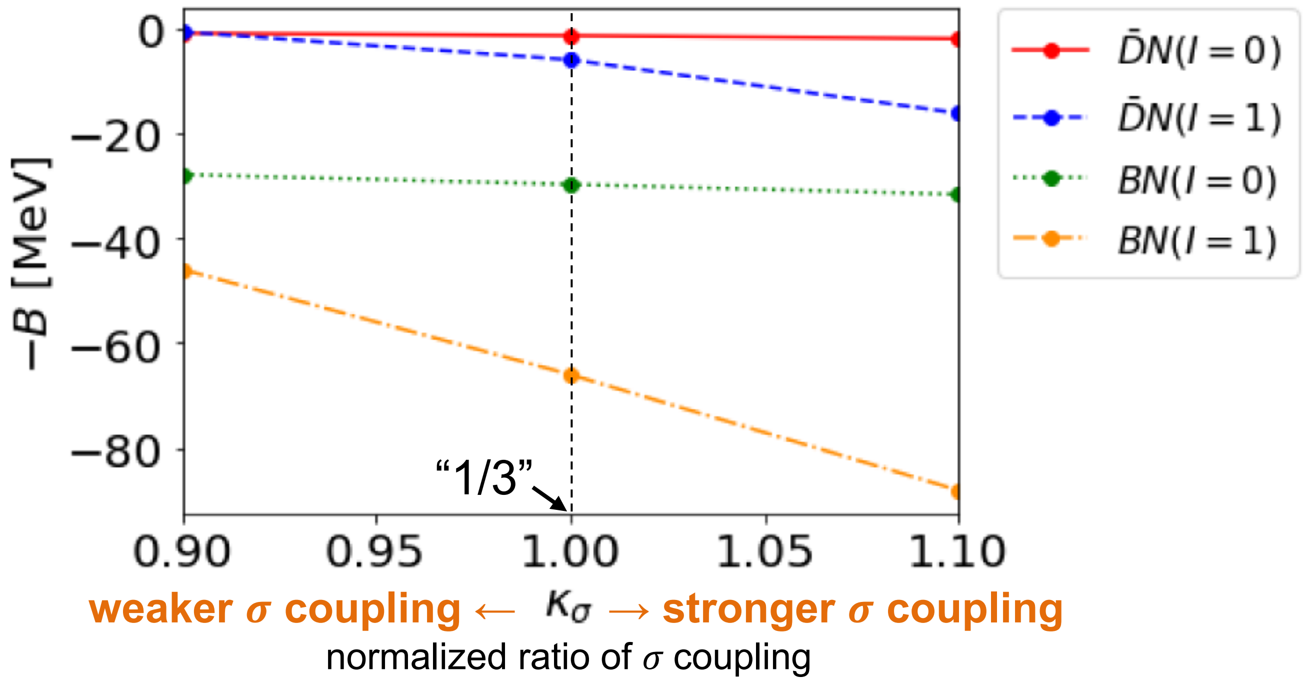
4. Discussions



- Model dependence
  - ✓ Ambiguity in σ potentials
    - We assumed $P^{(*)}P^{(*)}\sigma$ strength coupling is “1/3” of that in $NN\sigma$
  - ✓ Estimate the uncertainty from σ couplings
    - Dependence in binding energies



    - Similar results for scattering lengths for PN and P^*N
  - ✓ $I = 0$ is *less* dependent, but $I = 1$ is *more* dependent
    - σ is ***less*** important in $\boldsymbol{I = 0}$, but ***more*** important in $\boldsymbol{I = 1}$

4. Discussions

Cf. Hosaka, Hyodo, Sudoh, Yamaguchi, Yasui, Prog. Part. Nucl. Phys. 96, 88 (2017)

Flavor nuclei:
Diversity of matter

- Charm (bottom) nuclei?
  - ✓ Can charm (bottom) nuclei exist as stable states?
  - ✓ What about $\bar{D}$ mesons in nuclear medium?
    - Stability: binding energy?

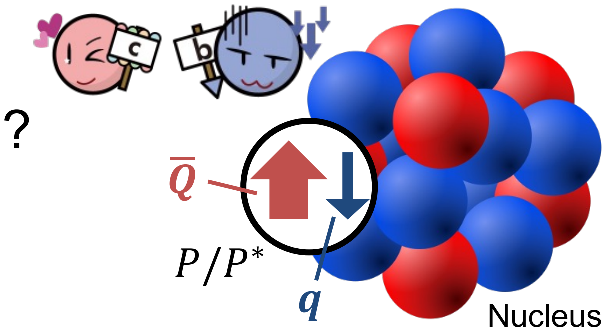


TABLE I. List of the mass shifts of the $\bar{D}$ meson in nuclear medium in previous works: quark meson coupling (QMC) model, QCD sum rule, coupled channel analysis, and chiral effective model.

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

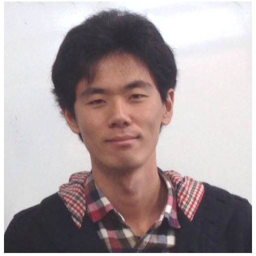
*D. Suenaga, S. Yasui., M. Harada, Phys. Rev. C96, 015204 (2017) [See this paper for the reference numbers.]

Possible open question: can we study *(anti-)charm* nuclei through $\bar{D}N$ interaction?

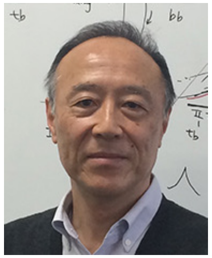
5. Summary

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

- $\bar{D}$ (B) meson and nucleon potential is important for exotic hadrons and nuclei.
- We considered $\pi, \sigma, \rho, \omega$ exchanges based on chiral and HQS symmetries
- Bound states of $\bar{D}$ meson and nucleon with $I(J^P) = 0(1/2^-)$, $1(1/2^-)$
- Deeply bound states of B meson and nucleon with same $I(J^P)$
- Future studies: theories and experiments (LHC, Belle, J-PARC, etc.)
  - ✓ Heavy ion collisions (LHC) ExHIC: PRL106 212001 (2011); PRC84, 064910 (2011), PPNP95, 279 (2017)
  - ✓ Fixed target experiments (J-PARC) Yamagata-Sekihara, Garcia-Recio, Nieves, Salcedo, Tolos, PLB754, 26 (2016)
  - ✓ More states in the other $I(J^P)$?
  - ✓ More states in bottom?
  - ✓ Lattice QCD?
  - ✓ $D_s^- N$? $\bar{D}\Lambda$? (from u, d to u, d, s)
  - ✓ Multi-baryons : $P^{(*)}NN$, $P^{(*)}\alpha$?? Yamaguchi, Yasui, Hosaka, NPA927, 110 (2014)
  - ✓ (Anti-)charm, bottom nuclei???



Y. Yamaguchi
Nagoya U.



A. Hosaka
RCNP, Osaka U.

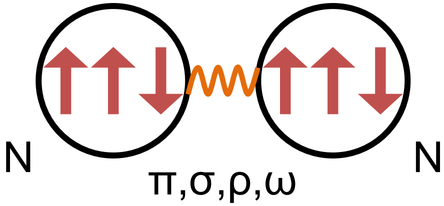
Can (anti-)charm nuclei exist in our nature?

Thanks!

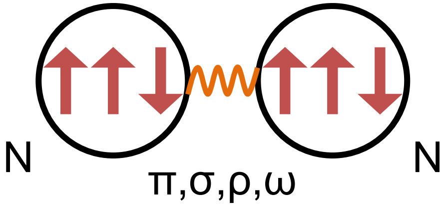
Appendix

A. Nucleon-nucleon pot. (modified CD-Bonn)

- Reference system: nucleon-nucleon (NN)
  - ✓ Similarity between NN and qN
  - ✓ π, σ, ρ, ω exchange
  - ✓ σ is important to consider both I=0 and I=1 in NN



A. Nucleon-nucleon pot. (modified CD-Bonn)



- Reference system: nucleon-nucleon (NN)
  - ✓ Similarity between NN and qN
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  - ✓ σ is important to consider both I=0 and I=1 in NN

- **CD-Bonn** is a realistic NN potential
  - ✓ Reproducing the fundamental properties of NN force
  - ✓ Simple model: one-meson exchange (π, σ, ρ, ω, ...)
  - ✓ However still complicated (because heavier mesons included)

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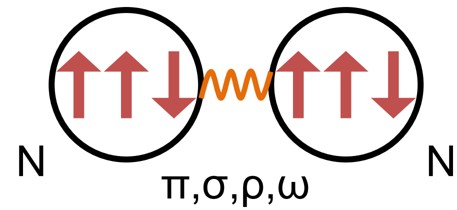

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  - ✓ Reproducing the fundamental properties of NN force
  - ✓ Simple model: one-meson exchange (π, σ, ρ, ω, ...)
  - ✓ However still complicated (because heavier mesons included)

- We consider the simpler version of CD-Bonn (**"modified CD-Bonn"**)
  - ✓ We consider only mesons with lower masses
  - ✓ Coupling constants as the same as in CD-Bonn
  - ✓ Price to be paid: rescaling of the momentum cutoffs

Masses and coupling constants of exchanged mesons (same as CD-Bonn)

Mesons	Masses [MeV]	$g^2/4\pi$	f/g
π	138.04	13.6	—
ρ	769.68	0.84	6.1
ω	781.94	20	0.0
σ_0	350	0.51673	—
σ_1	452	3.96451	—

Scattering lengths, effective ranges, binding energy of a deuteron in modified CD-Bonn

channel	κ_I ($I=0$ and $I=1$)	a [fm]	r_e [fm]	B_d [MeV]
$^3S_1$ ($I=0$)	0.8044226	5.296	1.562	2.225*
$^1S_0$ ($I=1$)	0.7729982	23.740*	2.337	—

Reduction scale factor in momentum cutoffs

Consistent with experiment values
$a(^3S_1)=5.419\pm0.007$ fm, $r_e(^3S_1)=1.753\pm0.008$ fm, $B_d=2.225$ MeV
$a(^1S_0)=23.740\pm0.020$ fm, $r_e(^1S_0)=2.77\pm0.05$ fm

A. Nucleon-nucleon pot. (modified CD-Bonn)

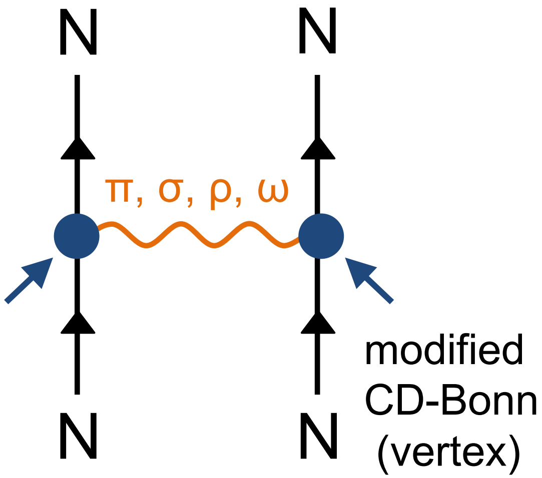
- Interaction Lagrangian

$$\mathcal{L}_{\pi NN} = -g_\pi \bar{\psi} i\gamma_5 \boldsymbol{\tau} \cdot \boldsymbol{\pi} \psi,$$

$$\mathcal{L}_{\sigma_I NN} = -g_{\sigma_I} \bar{\psi} \sigma_I \psi,$$

$$\mathcal{L}_{\rho NN} = -g_\rho \bar{\psi} \gamma_\mu \boldsymbol{\tau} \cdot \boldsymbol{\rho}^\mu \psi - \frac{f_\rho}{4m_N} \bar{\psi} \sigma_{\mu\nu} \boldsymbol{\tau} \cdot (\partial^\mu \boldsymbol{\rho}^\nu - \partial^\nu \boldsymbol{\rho}^\mu) \psi,$$

$$\mathcal{L}_{\omega NN} = -g_\omega \bar{\psi} \gamma_\mu \omega^\mu \psi,$$



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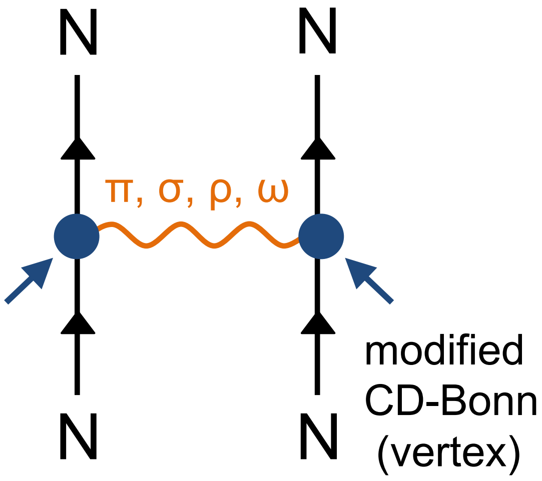
$$\mathcal{L}_{\omega NN} = -g_\omega\bar{\psi}\gamma_\mu\omega^\mu\psi,$$



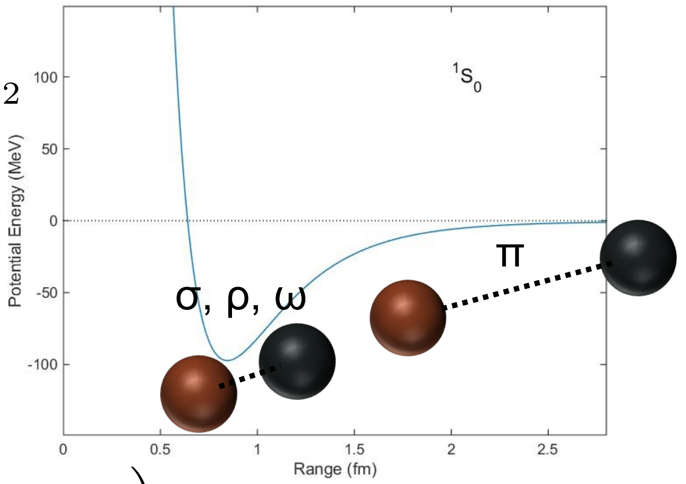
- NN potential

$$V_\pi(r) = \left(\frac{g_{\pi NN}}{2m_N}\right)^2\frac{1}{3}\Big(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 C_\pi(r) + S_{12}(\hat{\boldsymbol{r}})T_\pi(r)\Big)\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$

$$V_{\sigma_I}(r) = -\left(\frac{g_{\sigma_I}}{2m_N}\right)^2\left(\left(\frac{2m_N}{m_{\sigma_I}}\right)^2 - 1\right)C_{\sigma_I}(r)$$

$$V_v(r) = g_{vNN}^2\left(\frac{1}{m_v^2} + \frac{1+f_v/g_{vNN}}{2m_N^2}\right)C_v(r)$$

$$+ g_{vNN}^2\left(\frac{1+f_v/g_{vNN}}{2m_N}\right)^2\frac{1}{3}\Big(2\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 C_v(r) - S_{12}(\hat{\boldsymbol{r}})T_v(r)\Big)$$



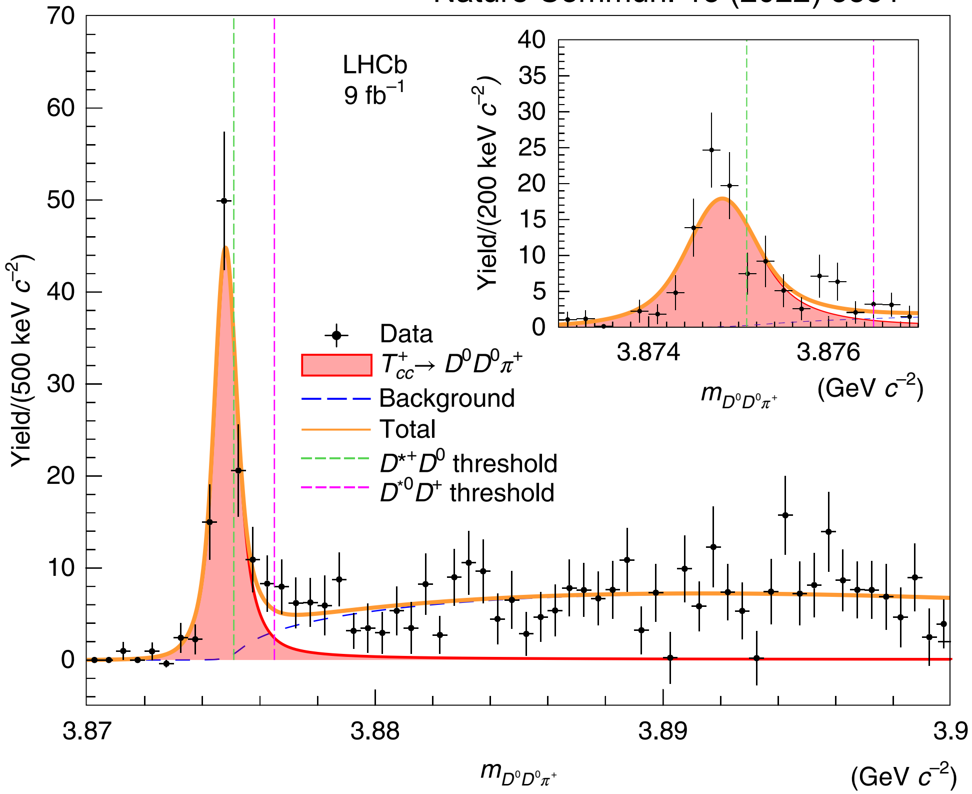
B. Open problems in T_{cc}

nature physics
LETTERS
https://doi.org/10.1038/s41567-022-01614-y
Check for updates
OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

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

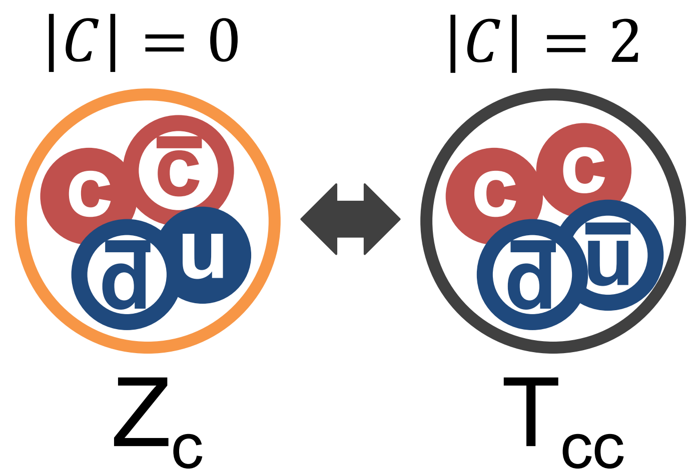


Bound state below $D^{*+}D^0$ threshold

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

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

T_{cc}: doubly charmed tetraquark



T_{cc} is genuinely exotic hadron (four quark at least)!

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) ?

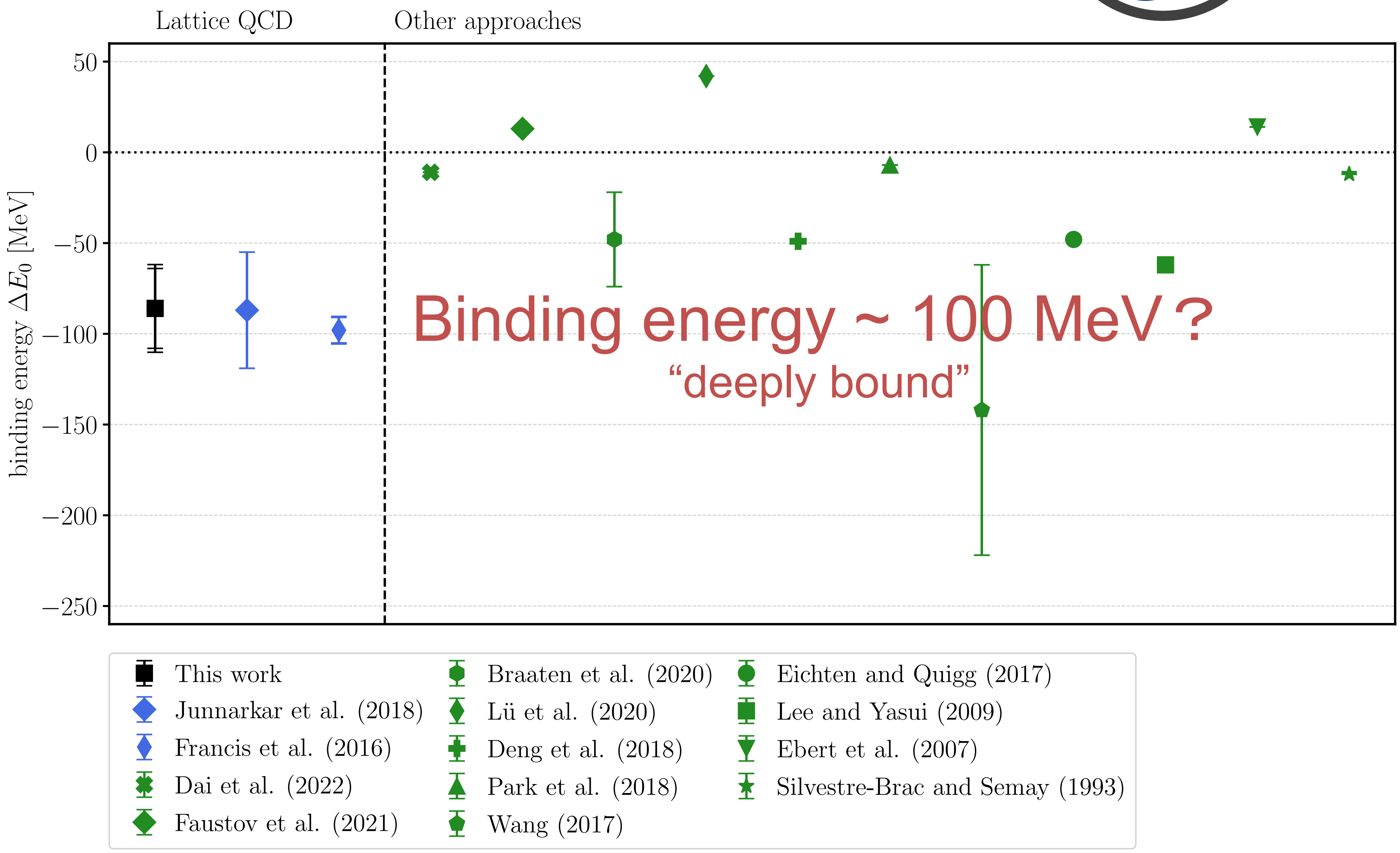
etc.

B. Open problems in T_{cc}

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

T_{bb}

Doubly ***bottom*** *tetraquark*

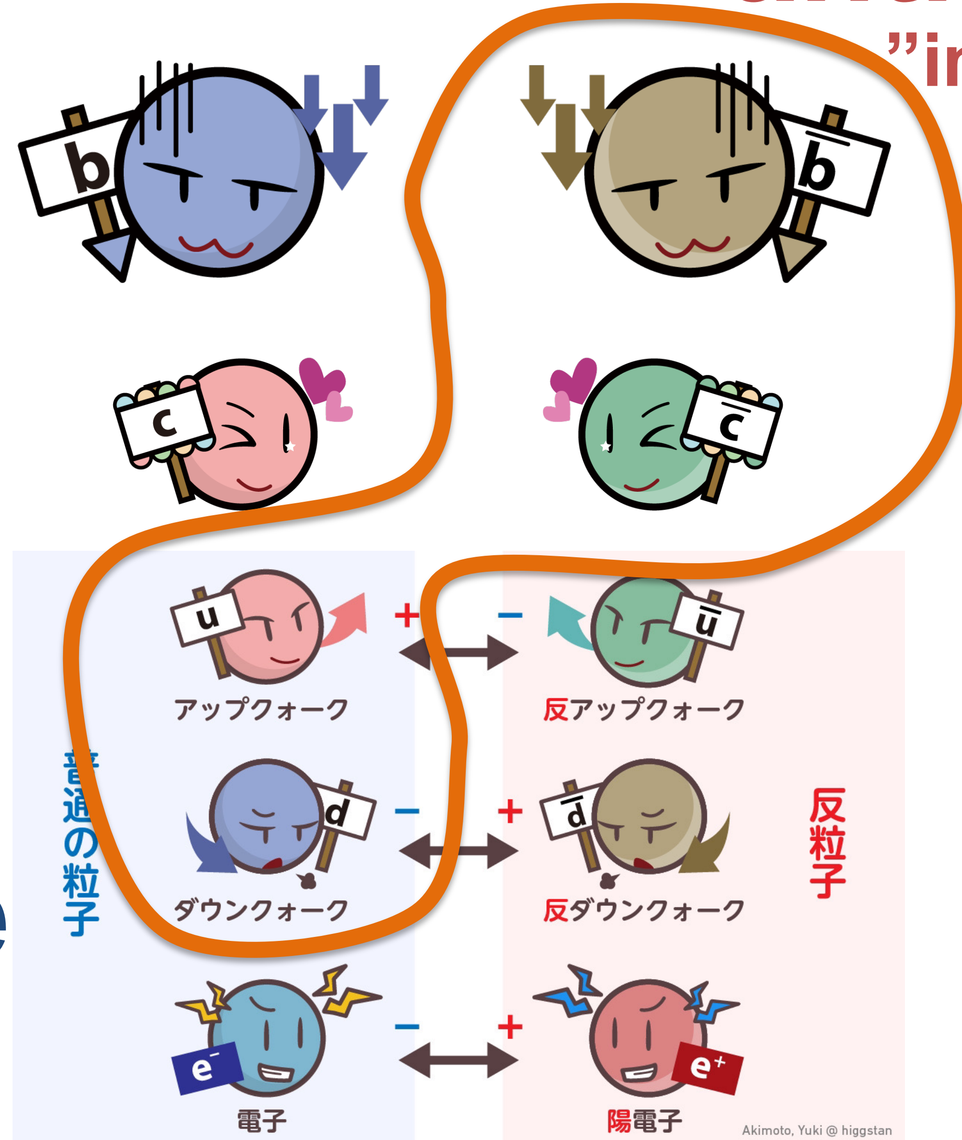


Why don't we study T_{bb} in future experiments？

C. New state of matter

- Charm (bottom) nuclei ?
  - ✓ *Particle-antiparticle hybrid* matter ? ?

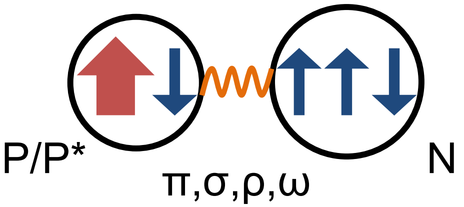
heavy antiparticle
"impurity"



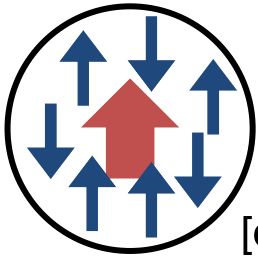
light particle
"nucleus"

HiggsTan.com

D. Light spin structure

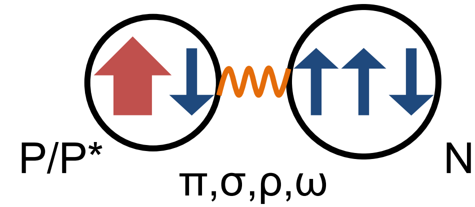


- Heavy-quark spin structures (**I=0**)
  - ✓ Light spin-complex $[qN]_j$ (HQ limit)
    - **j=0: $PN(^2S_{1/2})$:$P^*N(^2S_{1/2})$ = 1:3**
    - **j=1: $PN(^2S_{1/2})$:$P^*N(^2S_{1/2})$ = 3:1** (←relatively similar to this)

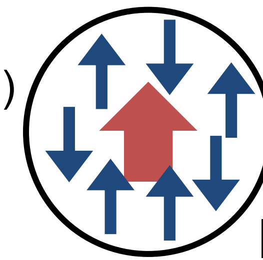


  - ✓ Calculated mxing ratios
    - Anti-$DN(^2S_{1/2})$:anti-$D^*N(^2S_{1/2})$ = 96:2
    - $BN(^2S_{1/2})$:$B^*N(^2S_{1/2})$ = 76:14
  - ✓ Calculated $P^{(*)}N$ includes mostly the spin-complex $[qN]_j$ with **j=1**
  - ✓ $[qN]_{j=1}$ is analogue of a deuteron
    - ***Duality*** between $P^{(*)}N$ and NN?

D. Light spin structure



- Heavy-quark spin structures (**I=0**)
  - ✓ Light spin-complex $[qN]_j$ (HQ limit)
    - **j=0: $PN(^2S_{1/2})$:$P^*N(^2S_{1/2})$ = 1:3**
    - **j=1: $PN(^2S_{1/2})$:$P^*N(^2S_{1/2})$ = 3:1** (←relatively similar to this)



$[qN]_j$ in $P^{(*)}N$

  - ✓ Calculated mxing ratios
    - Anti-$DN(^2S_{1/2})$:anti-$D^*N(^2S_{1/2})$ = 96:2
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  - ✓ Calculated $P^{(*)}N$ includes mostly the spin-complex $[qN]_j$ with **j=1**
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- Heavy-quark spin structures (**I=1**)
  - ✓ Calculated mxing ratios
    - Anti-$DN(^2S_{1/2})$:anti-$D^*N(^2S_{1/2})$ = 90:11 (→ **j=1**)
    - $BN(^2S_{1/2})$:$B^*N(^2S_{1/2})$ = 39:62 (→ **j=0**)
  - ✓ The spin-complex $[qN]_j$ **j=0** is favored in I=1 in HQ limit?
    - This question should be related to ***the origin of σ potential***

E. Exotic hadrons

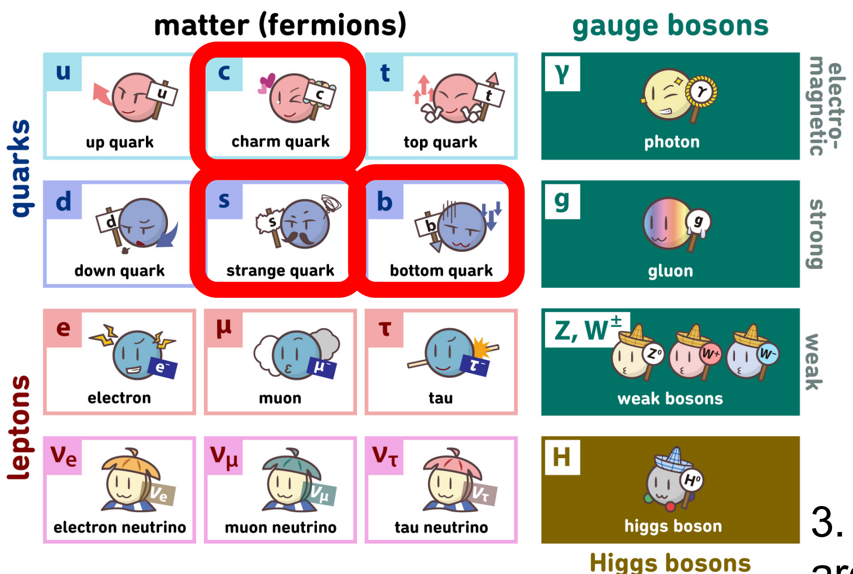
- Motivation to study exotic hadrons (multiquarks)
  - ✓ Color confinement (Yang-Mills mass gap)
  - ✓ Flavor multiplets (unconventional)
  - ✓ Multi-baryons (ex. strange/charm nuclei)

M. Gell-Mann
"Quarks"

Hadron physics in a nutshell

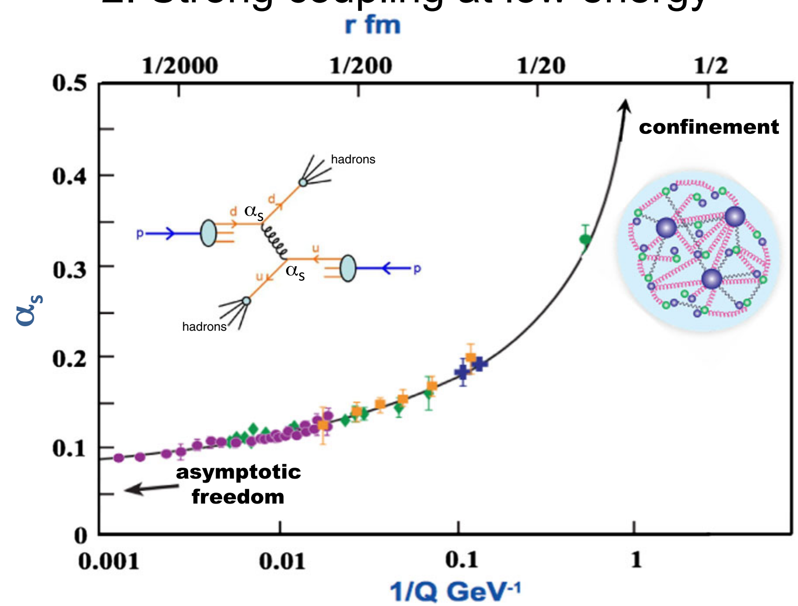
1. QCD (Quantum Chromodynamics)

$$\mathcal{L}_{\rm QCD}[\bar{\psi}, \psi, A] = \sum_f \bar{\psi}_f (i\partial\!\!\!/ - g_s A_\mu - m_f)\psi_f - \frac{1}{4} F_{a\mu\nu} F^{a\mu\nu}$$

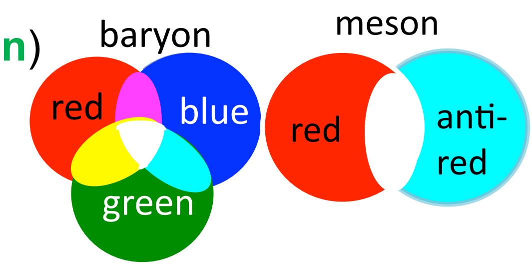


HiggsTan.com

2. Strong coupling at low energy



3. Quarks (**red**, **blue**, **green**) are confined in hadrons, baryons (3 quark) and mesons (2 quark).

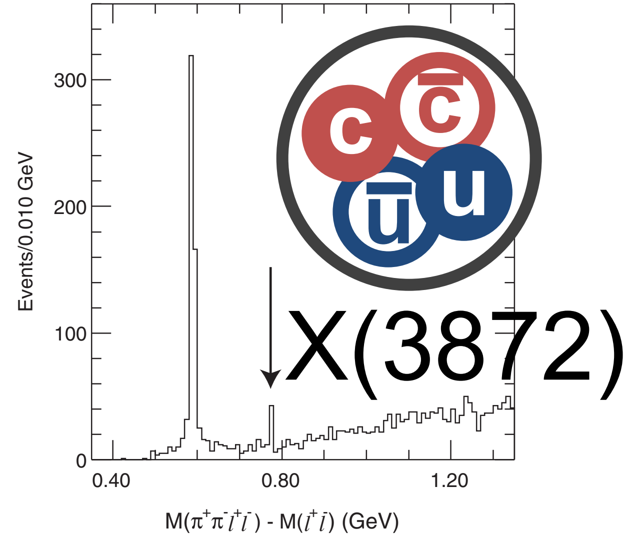


E. Exotic hadrons

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

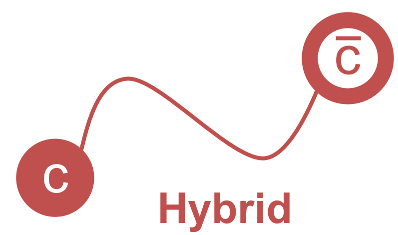
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$	Belle (Choi *et al.*, 2003, 2011), *BABAR* (Aubert *et al.*, 2005c), LHCb (Aaij *et al.*, 2013a, 2015d)
				$p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots$	CDF (Acosta *et al.*, 2004; 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)**



Y(4260)

E. 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 ?

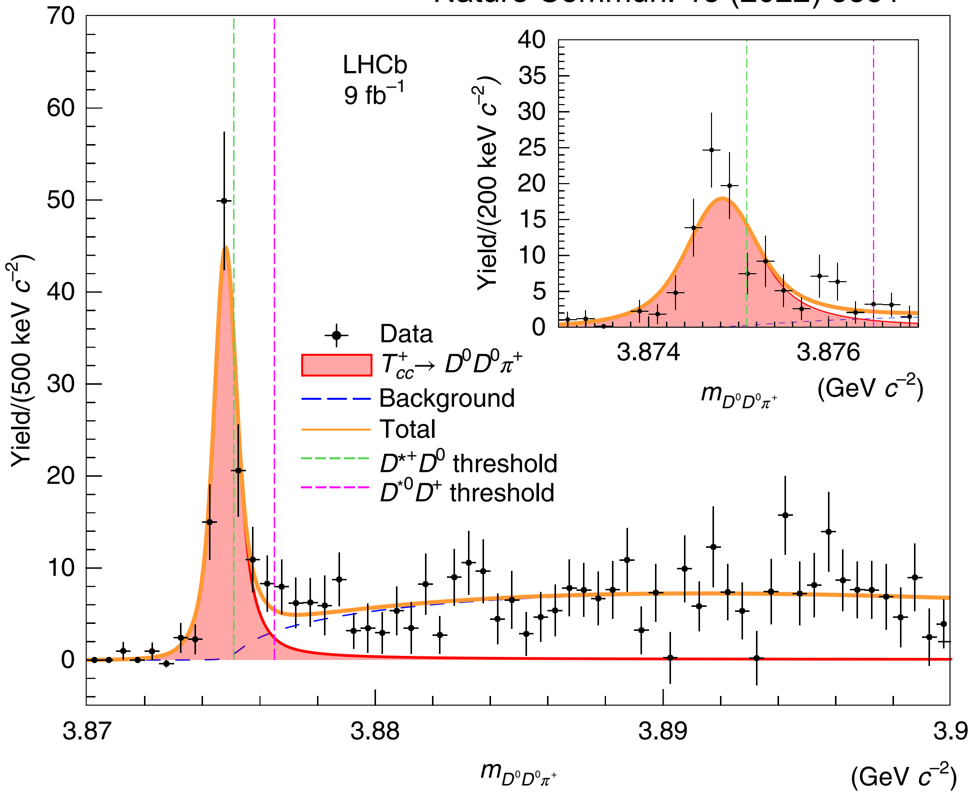
E. Exotic hadrons

nature physics
LETTERS
https://doi.org/10.1038/s41567-022-01614-y
Check for updates
OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

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



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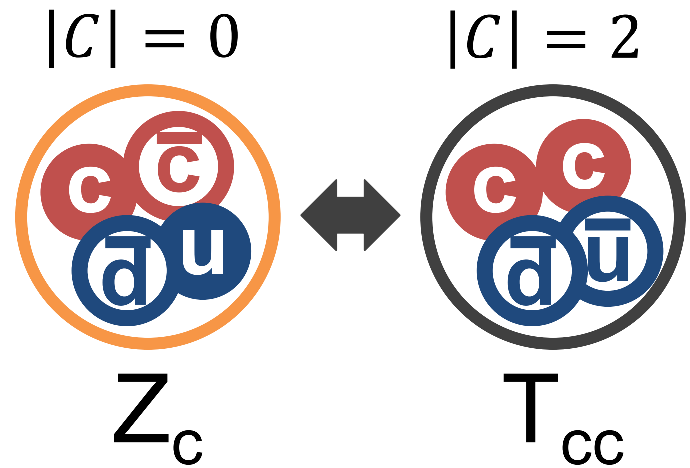
$$\Gamma_{\rm BW} = \underline{410} \pm 165 \pm 43\,^{+18}_{-38}\ \text{keV},$$

T_{cc}: doubly charmed tetraquark



T_{cc} is genuinely exotic hadron (four quark at least)!

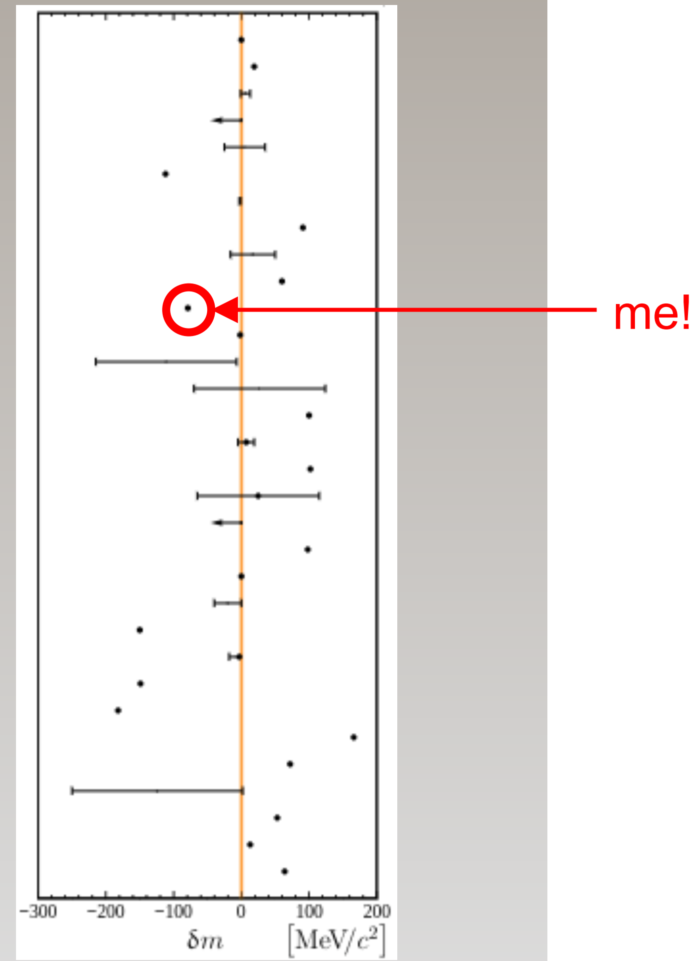
E. Exotic hadrons

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	$+64$

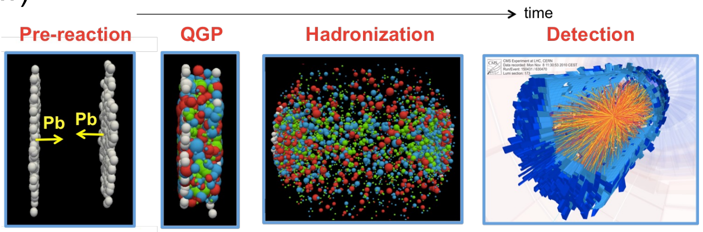


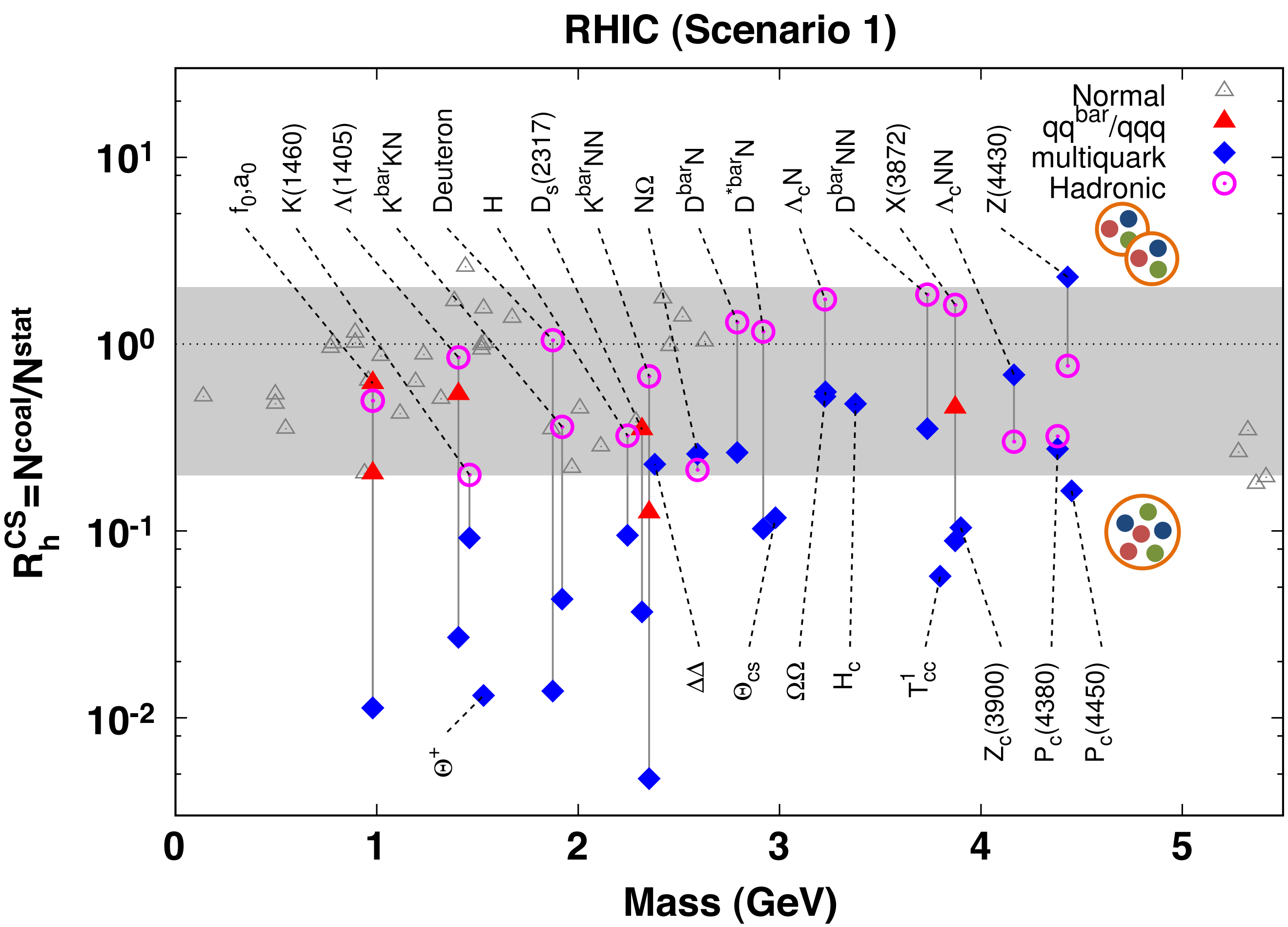
https://indico.desy.de/event/28202/contributions/105627/attachments/67806/84639/EPS-HEP_2021_Polyakov_v5.pdf

E. Exotic hadrons

ExHIC collaboration: Phys. Rev. Lett. 106, 212001 (2011), Phys. Rev. C84 (2011) 064910; Prog. Part. Nucl. Phys. 95 (2017) 279 (review)

- Production in relativistic heavy-ion collisions ?
  - ✓ Quarks are abundant
    - Possibility to find ***rare*** events
  - ✓ X(3872) was already observed in HIC CMS@LHC, Phys. Rev. Lett. 128, 032001 (2020)
    - Possibility to find other exotic hadrons ?





E. Exotic hadrons

ExHIC collaboration: Phys. Rev. Lett. 106, 212001 (2011), Phys. Rev. C84 (2011) 064910; Prog. Part. Nucl. Phys. 95 (2017) 279 (review)

Particle	Scenario 1		Scenario 2		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark	$q\bar{q}/qqq$	Multiquark		
RHIC						
T_{cc}^1	–	5.0×10^{-5}	–	5.3×10^{-5}	–	8.9×10^{-4}
$\bar{D}N$	–	2.6×10^{-3}	–	2.6×10^{-3}	1.3×10^{-2}	1.0×10^{-2}
$\bar{D}^*N$	–	9.8×10^{-4}	–	9.3×10^{-4}	1.1×10^{-2}	9.6×10^{-3}
Θ_{cs}	–	7.4×10^{-4}	–	7.4×10^{-4}	–	6.4×10^{-3}
H_c	–	2.7×10^{-4}	–	2.8×10^{-4}	–	5.7×10^{-4}
$\bar{D}NN$	–	1.8×10^{-5}	–	1.8×10^{-5}	9.4×10^{-5}	5.1×10^{-5}
$\Lambda_c N$	–	1.5×10^{-3}	–	1.5×10^{-3}	5.0×10^{-3}	2.9×10^{-3}
$\Lambda_c NN$	–	6.7×10^{-6}	–	6.7×10^{-6}	2.9×10^{-6}	9.8×10^{-6}
T_{cb}^0	–	9.3×10^{-8}	–	9.9×10^{-8}	–	1.6×10^{-6}
LHC (2.76 TeV)						
T_{cc}^1	–	1.1×10^{-4}	–	1.3×10^{-4}	–	2.7×10^{-3}
$\bar{D}N$	–	4.3×10^{-3}	–	4.2×10^{-3}	2.3×10^{-2}	1.9×10^{-2}
D^*N	–	1.6×10^{-3}	–	1.3×10^{-3}	2.0×10^{-2}	1.8×10^{-2}
Θ_{cs}	–	1.2×10^{-3}	–	1.2×10^{-3}	–	1.2×10^{-2}
H_c	–	3.8×10^{-4}	–	4.0×10^{-4}	–	8.6×10^{-4}
$\bar{D}NN$	–	2.0×10^{-5}	–	2.0×10^{-5}	1.1×10^{-4}	6.7×10^{-5}
$\Lambda_c N$	–	2.2×10^{-3}	–	2.2×10^{-3}	7.0×10^{-3}	4.3×10^{-3}
$\Lambda_c NN$	–	6.7×10^{-6}	–	6.5×10^{-6}	2.7×10^{-6}	9.9×10^{-6}
T_{cb}^0	–	1.1×10^{-6}	–	1.3×10^{-6}	–	2.7×10^{-5}
LHC (5.02 TeV)						
T_{cc}^1	–	1.8×10^{-4}	–	2.1×10^{-4}	–	4.4×10^{-3}
$\bar{D}N$	–	5.3×10^{-3}	–	5.3×10^{-3}	3.0×10^{-2}	2.4×10^{-2}
$\bar{D}^*N$	–	2.0×10^{-3}	–	1.7×10^{-3}	2.6×10^{-2}	2.3×10^{-2}
Θ_{cs}	–	1.5×10^{-3}	–	1.4×10^{-3}	–	1.6×10^{-2}
H_c	–	4.7×10^{-4}	–	4.9×10^{-4}	–	1.1×10^{-3}
$\bar{D}NN$	–	2.5×10^{-5}	–	2.5×10^{-5}	1.5×10^{-4}	8.6×10^{-5}
$\Lambda_c N$	–	2.7×10^{-3}	–	2.7×10^{-3}	9.1×10^{-3}	5.5×10^{-3}
$\Lambda_c NN$	–	8.2×10^{-6}	–	8.0×10^{-6}	3.5×10^{-6}	1.3×10^{-5}
T_{cb}^0	–	2.3×10^{-6}	–	2.7×10^{-6}	–	5.6×10^{-5}

per nucleus-nucleus collision

Cf. D meson ~1

F. Glossary

N … Nucleon (uud, udd)

$\pi, \sigma, \rho, \omega$ … Light mesons (carrying forces between two hadrons)

q … Light quark (u quark, d quark)

Q … Heavy quark (c quark, b quark)

$\bar{Q}$… Heavy *anti*quark ($\bar{c}$ *anti*quark, $\bar{b}$ *anti*quark)

$\bar{D}$ meson … Heavy-light meson with $\bar{c}q$ ($q = u, d$)

B meson … Heavy-light meson with $\bar{b}q$ ($q = u, d$)

P … Pseudoscalar (spin 0) $\bar{Q}q$ meson, such as $\bar{D}$ (charm) or B (bottom)

P^* … Vector (spin 1) $\bar{Q}q$ meson, such as $\bar{D}^*$ (charm) or B^* (bottom)