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

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

Shigehiro YASUI

∈ Sasaki Lab. ⊂ SKCM^2 ⊂ Hiroshima University

Heavy-Ion Meeting (HIM 2023-05)@Yonsei University, 26-27 May. 2023

International Institute for Sustainability with Knotted Chiral Meta Matter/SKCM²

World Premier International Research Center Initiative/WPI at Hiroshima University

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knot
by
knot

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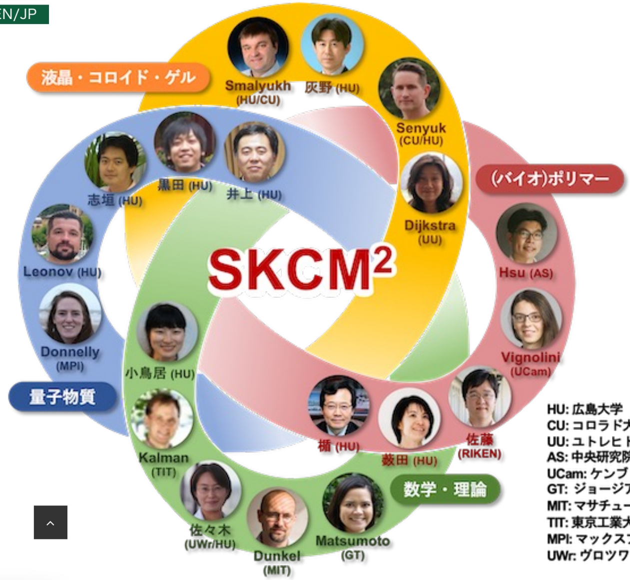

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✔ Cross-pollinates mathematical knot theory and chirality knowledge across disciplines and scales

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

<u>Hadron & nuclear physics group</u>

PI: Kenta SHIGAKI (HU, ALICE member)

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

coPI: Chiho NONAKA (HU)

coPI: Muneto NITTA (HU, Keio Uni.)

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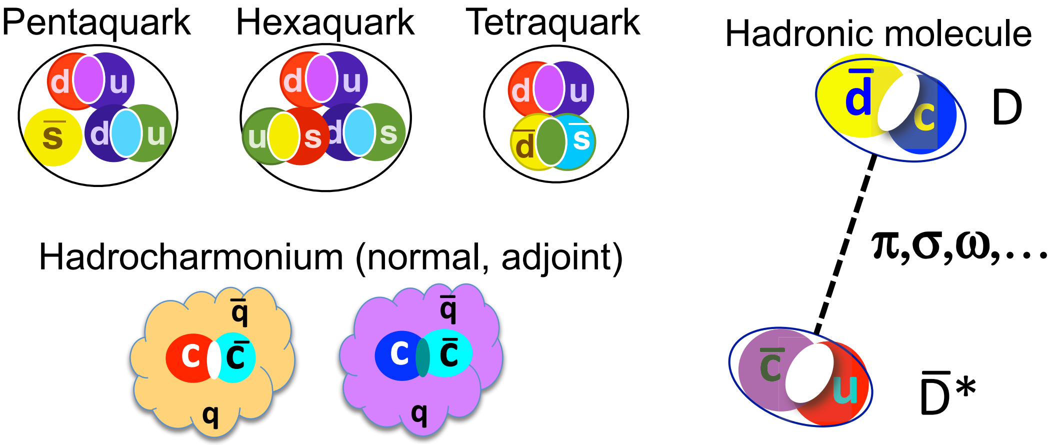
1. **Introduction**
2. Why $\bar{D}$ meson and nucleon?
3. $\bar{D}$ meson and nucleon potential
4. B meson and nucleon potential
5. Discussions –model dependence–
6. Summary

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)

M. Gell-Mann
"Quarks"

Exotic hadrons: Diversity of hadrons



Pentaquark

Hexaquark

Tetraquark

Hadronic molecule

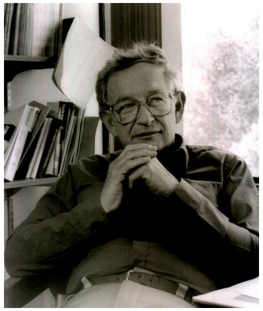
Hadrocharmonium (normal, adjoint)

D

$\pi,\sigma,\omega,\ldots$

$\bar{D}^*$

P. W. Anderson
"More is different"



"More quarks (flavors) are different???"

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

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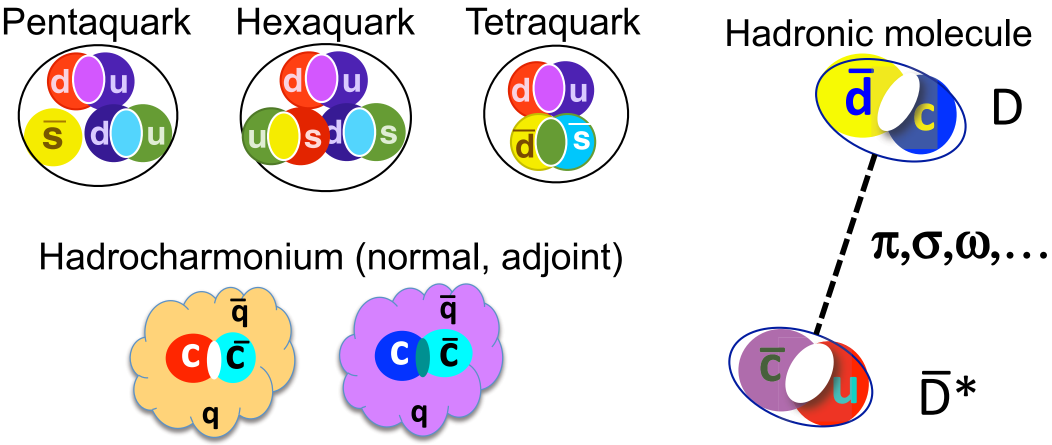

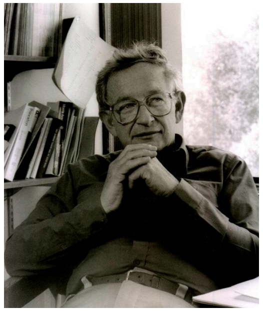

P. W. Anderson
"More is different"

"More quarks (flavors) are different???"

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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 ($m_c, m_b \gg \Lambda_{\mathrm{QCD}}$)
  - ✓ Heavy quark spin symmetry
  - ✓ Many exotics have been found in experiments!

1. Introduction
2. **Why $\bar{D}$ meson and nucleon?**
3. $\bar{D}$ meson and nucleon potential
4. B meson and nucleon potential
5. Discussions –model dependence–
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2. Why $\bar{D}$ meson and nucleon?

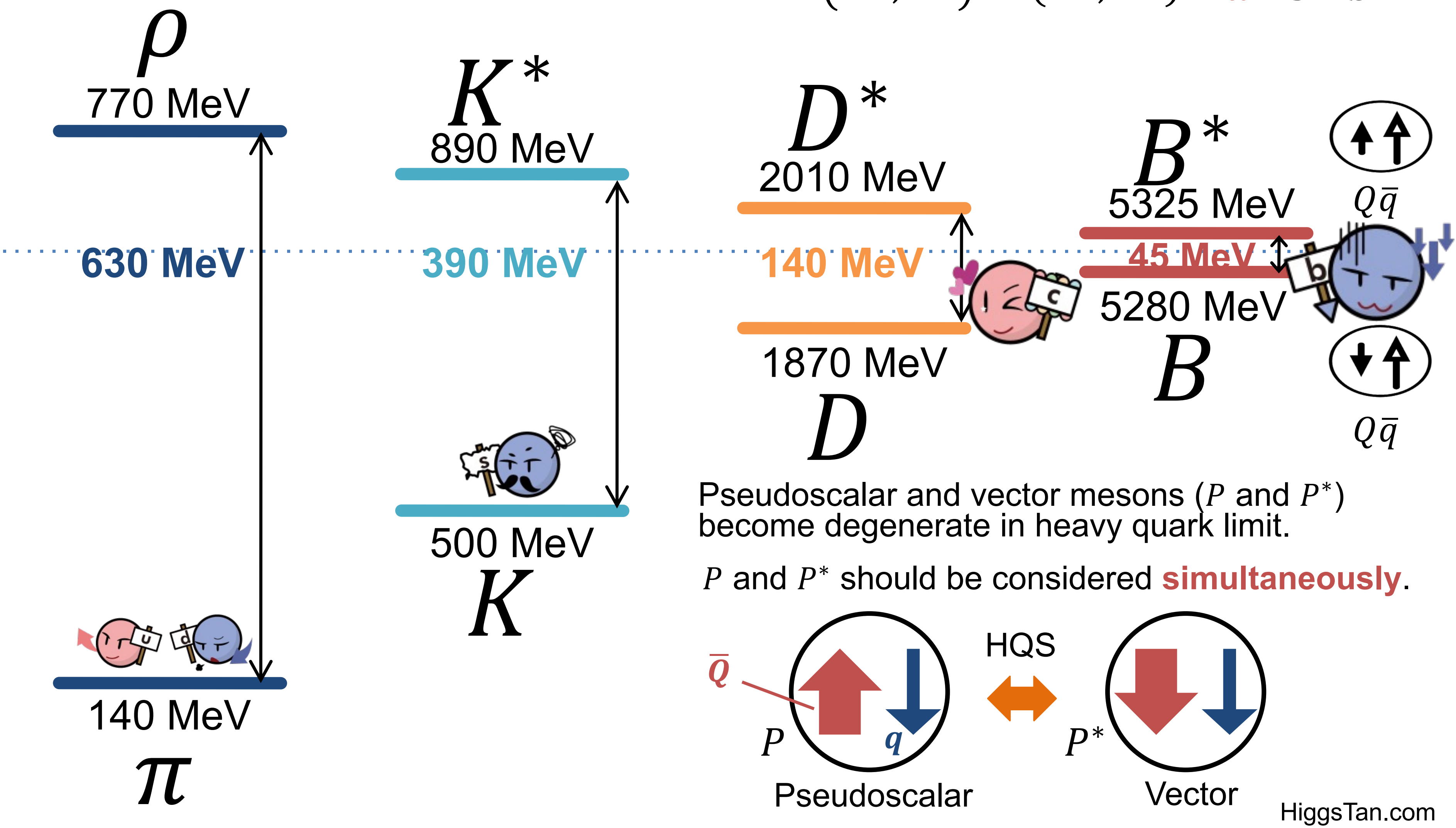
- Structure of $\bar{D}$ meson
  - ✓ Heavy-quark spin (HQS: $Q \to SQ$ with $S \in \mathrm{SU}(2)_{\text{heavy quark spin}}$)
  - ✓ D and D^* mesons as HQS doublet
  - ✓ B and B^* mesons also

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

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

$\boldsymbol{u}$ $\boldsymbol{c}$ $\boldsymbol{t}$

$\boldsymbol{d}$ $\boldsymbol{s}$ $\boldsymbol{b}$



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

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

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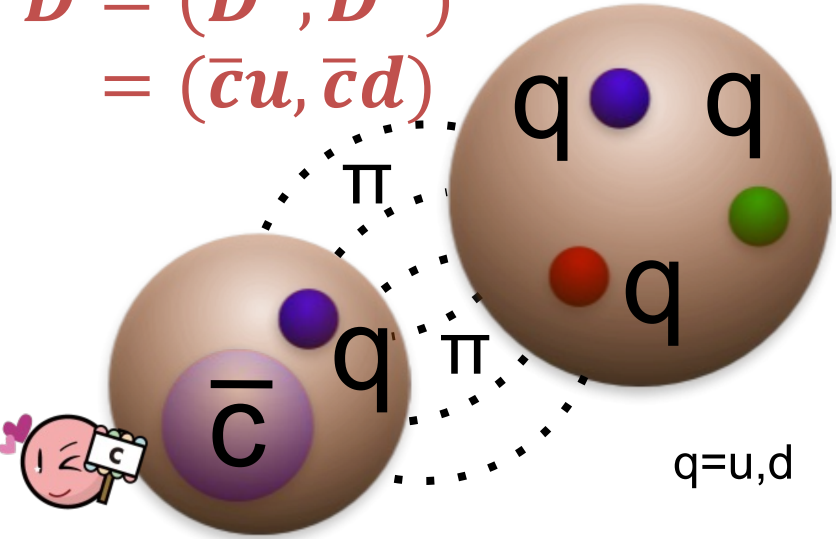
2. Why $\bar{D}$ meson and nucleon?

- $\bar{D}$ 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

No annihilation → (relatively) simple

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



$\bar{D}$ meson

(anti D meson)

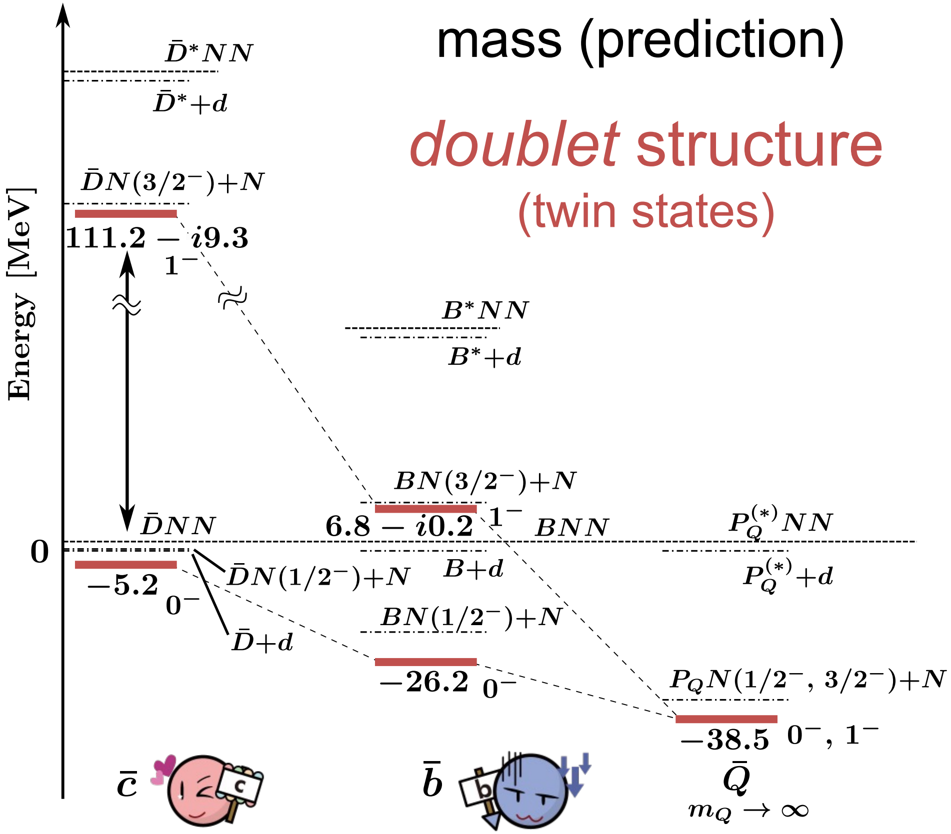
Nucleon

*penta*quark (5 quark)

mass (prediction)

doublet structure

(twin states)



Cohen, Hohler, Lebed, PRD72, 074010 (2005)
Yasui, Sudoh, PRD80, 034008 (2009)
Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84, 014032 (2011), ibid. 85, 054003 (2012)

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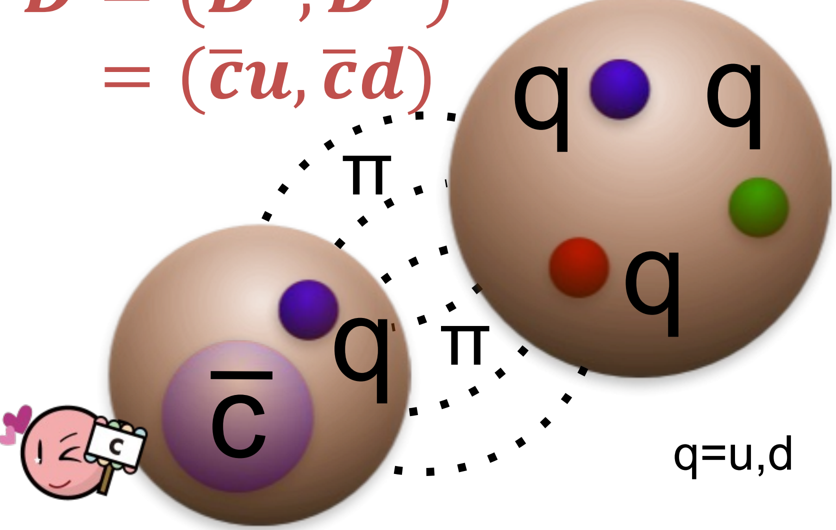

$\bar{D}$ meson **Nucleon**

(anti D meson)

*penta*quark (5 quark)

Cohen, Hohler, Lebed, PRD72, 074010 (2005)
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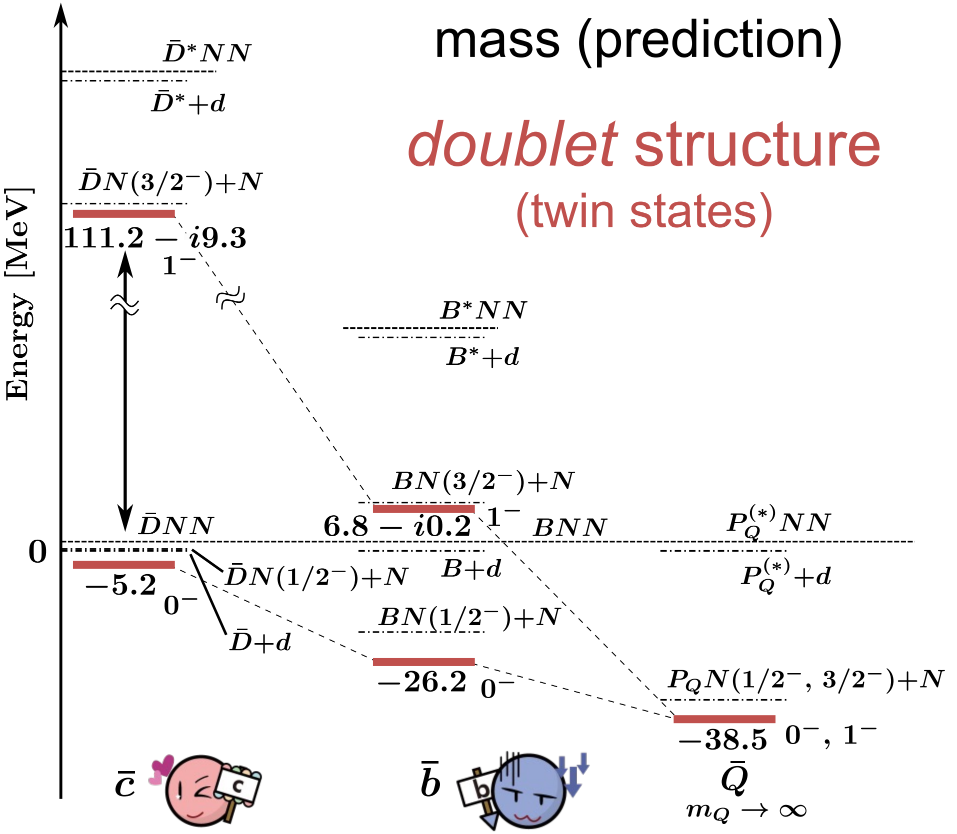

mass (prediction)

doublet structure
(twin states)

Our purpose: *(Anti-)charm* nuclear physics!

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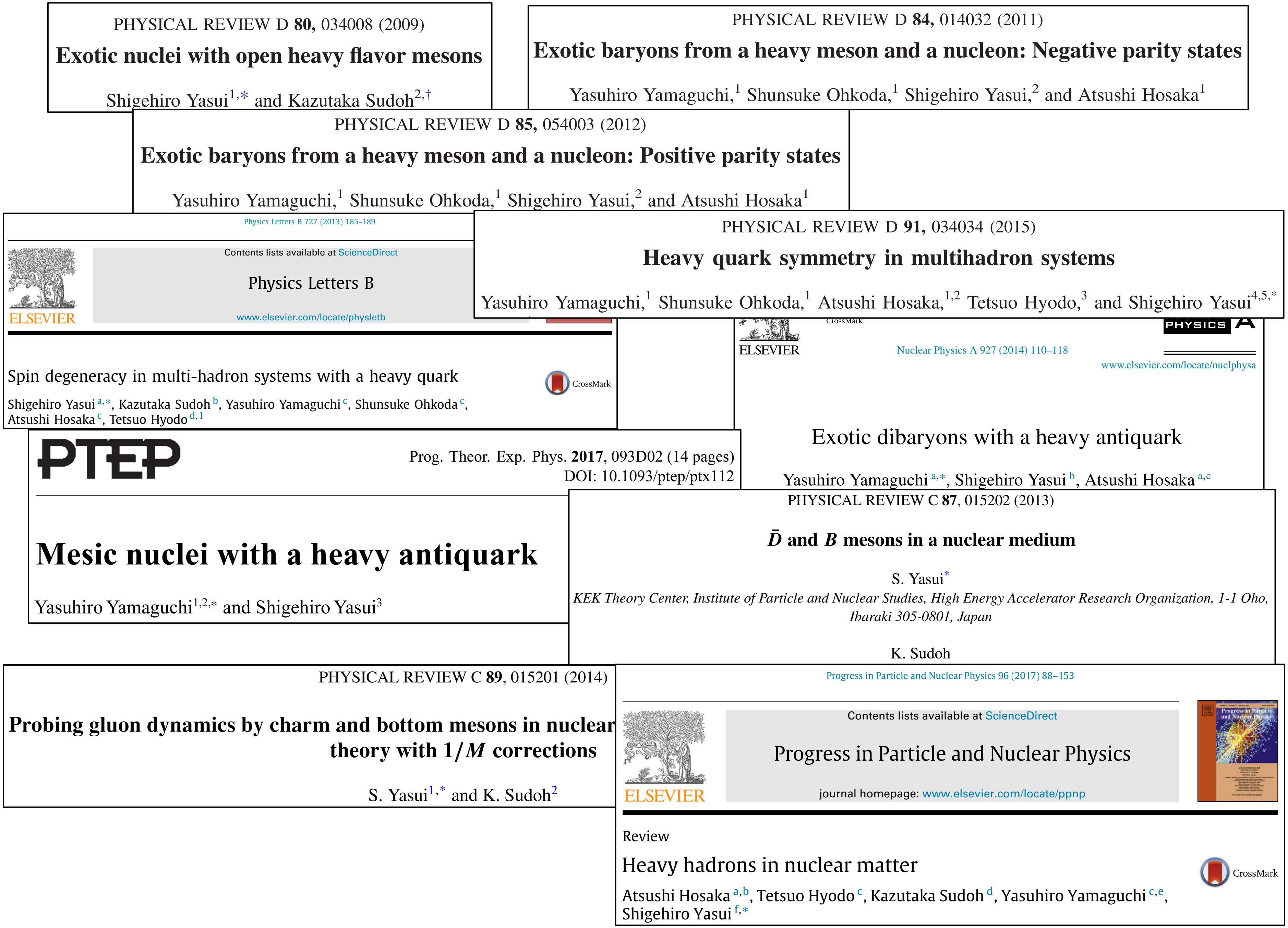
2. Why $\bar{D}$ meson and nucleon?



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

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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,*]

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PHYSICS A

ELSEVIER

Nuclear Physics A 927 (2014) 110–118

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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

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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

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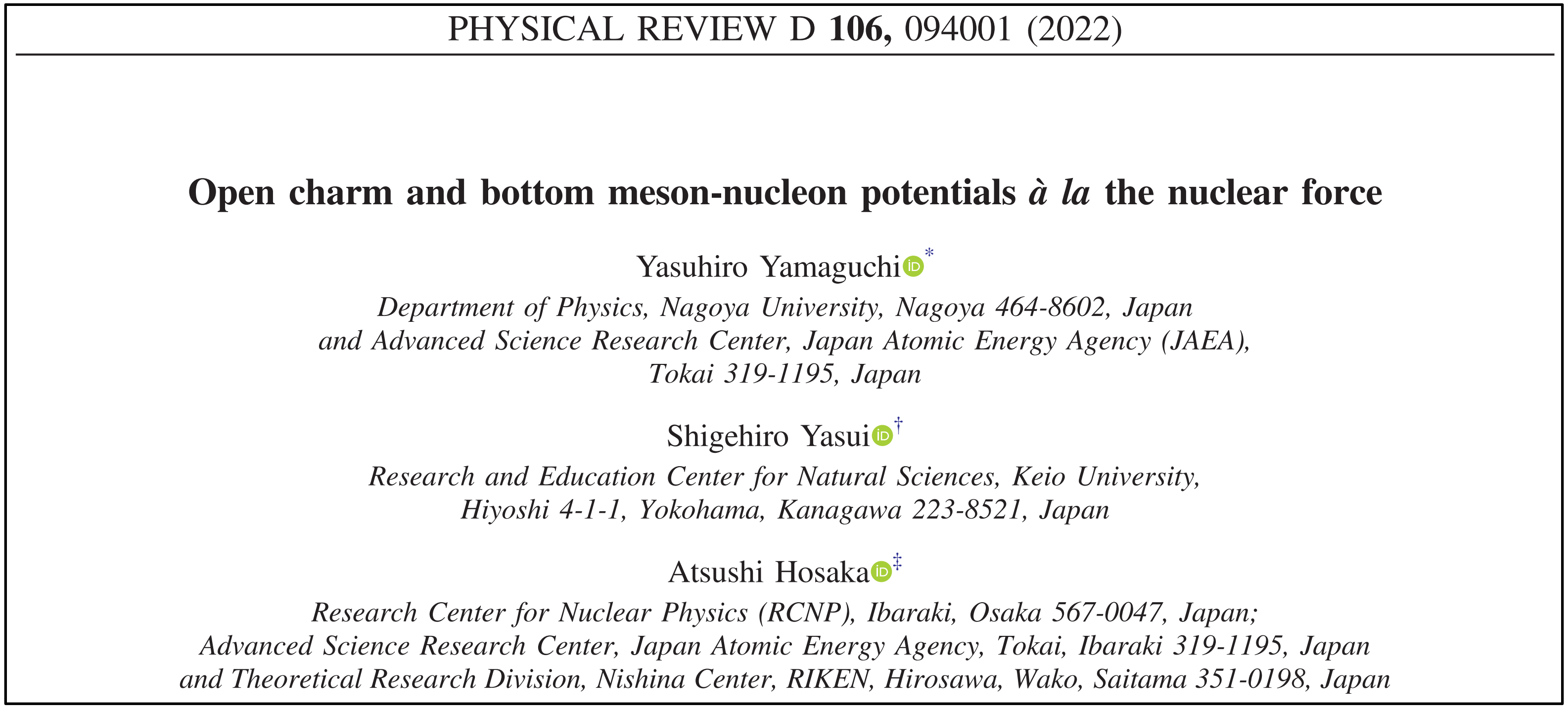
Atsushi Hosaka[a,b], Tetsuo Hyodo[c], Kazutaka Sudoh[d], Yasuhiro Yamaguchi[c,e], Shigehiro Yasui[f,*]

2. 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

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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.

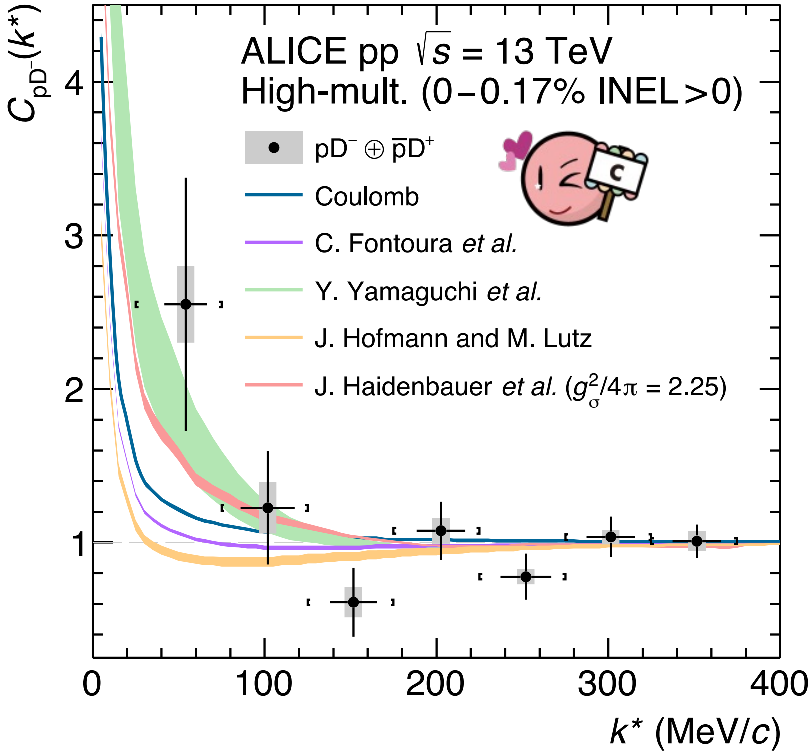
2. Why $\bar{D}$ meson and nucleon?

- 2022: First experiment has appeared!

✓ 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?



	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)

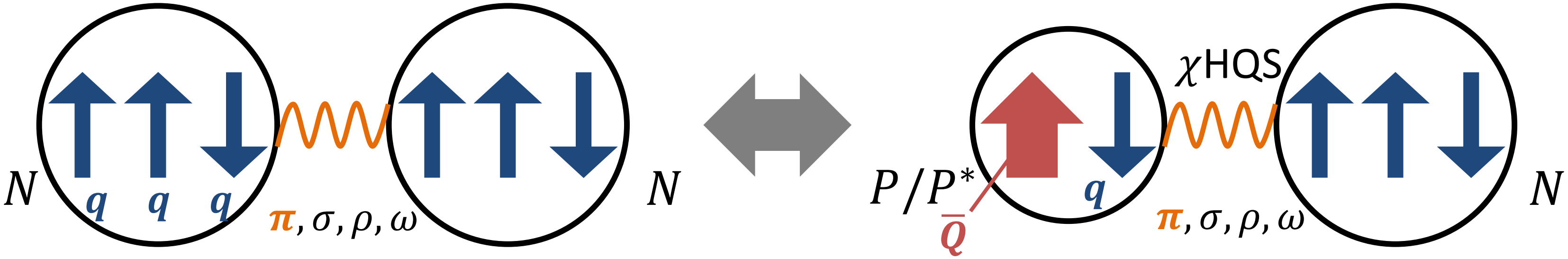
[21] Haidenbauer, Krein, Meißner, Sibirtsev, EPJ. A33, 107 (2007)
[22] Hofmann, Lutz, NPA763, 90 (2005)
[24] Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84, 014032 (2011)
[23] Fontoura, Krein, Vizcarra, PRC87, 025206 (2013)

We should explore $\bar{D}$ meson and nucleon interaction

more seriously!

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

- $\bar{D}$ 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

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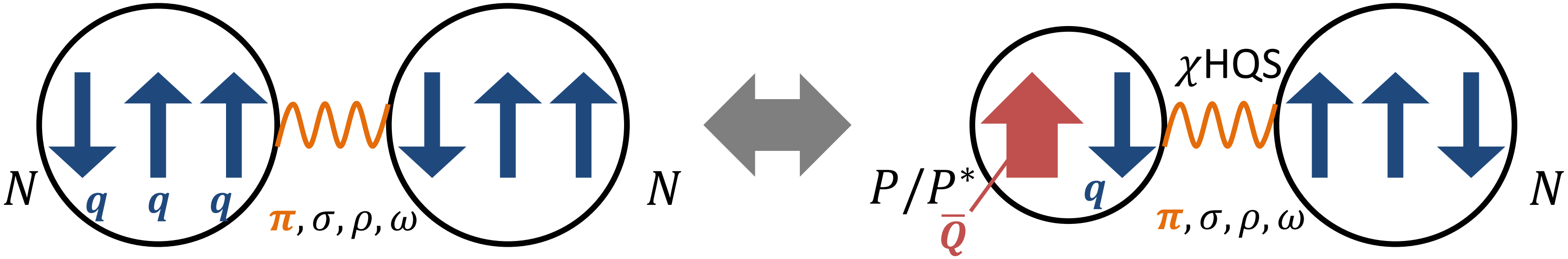

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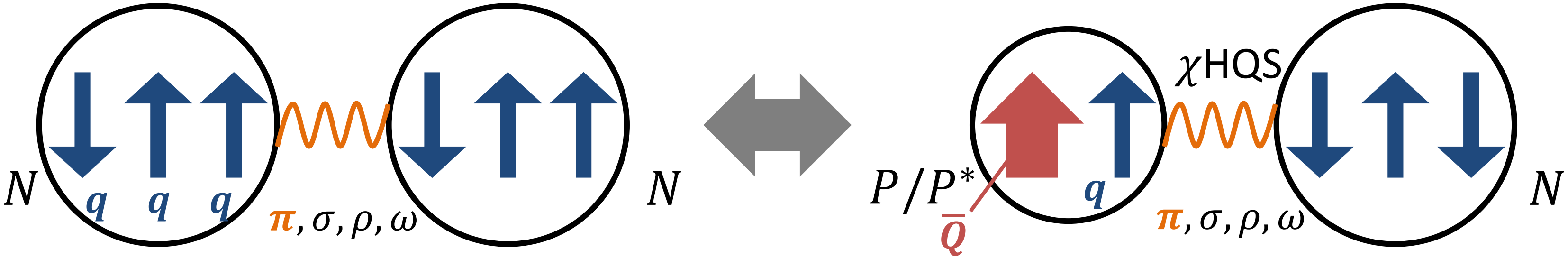

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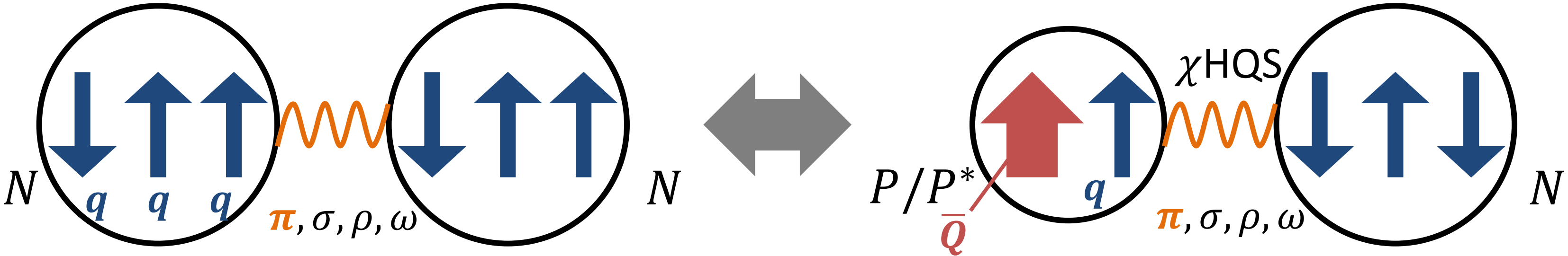

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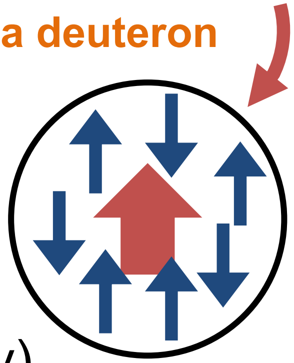
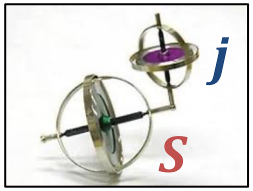


"brown muck"

light spin j

Spin decomposition by light quarks and gluons from heavy quarks

- 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)



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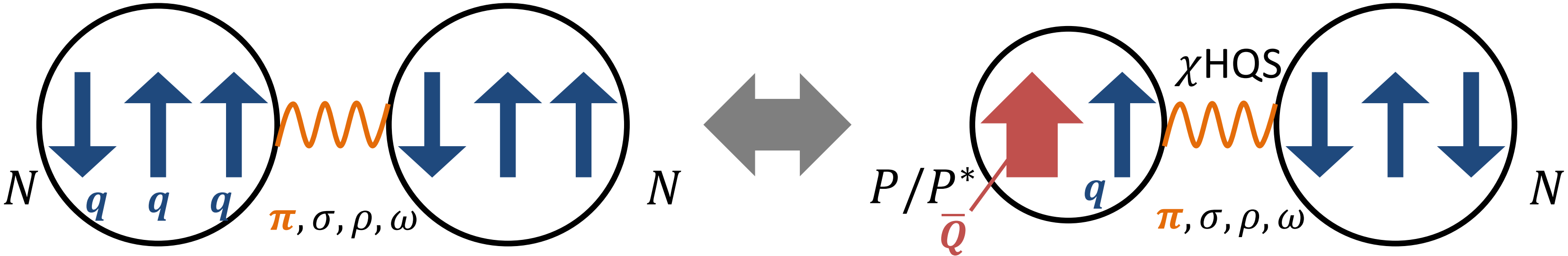

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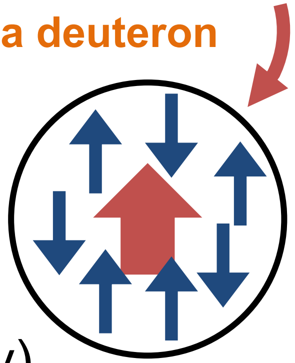

"brown muck"
light spin j
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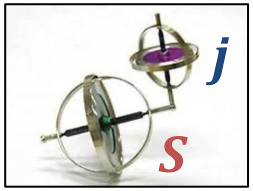

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- We need to solve "QCD" in order to get the answer, but it's difficult.

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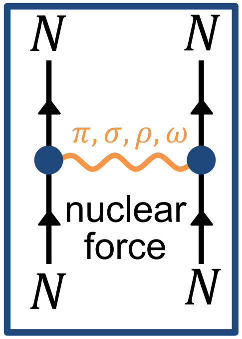
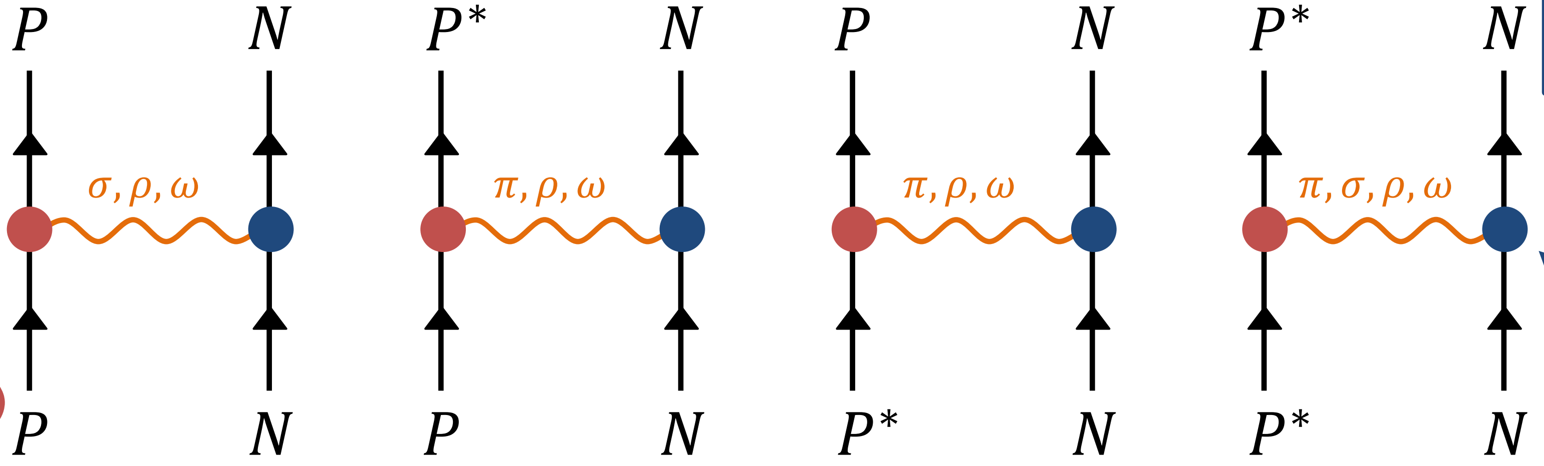
3. $\bar{D}$ meson and nucleon potential

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





HMET (vertex)

CD-Bonn (vertex)

- **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 ($m = \pi, \boldsymbol{\sigma}, \rho, \omega$)

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

$$\mathcal{L}_{\sigma_I HH} = g_{\sigma_I} \mathrm{tr}\left(H \sigma_I \bar{H}\right) \longleftarrow$$ **$\boldsymbol{\sigma}$ is new!** **Cf. σ is important for NN ($I = 0, 1$ channels).**

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

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

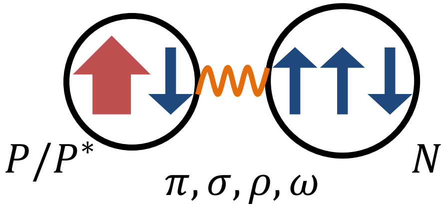
3. $\bar{D}$ meson and nucleon potential

- $P^{(*)}N$ state ($J^P = 1/2^-$, $I = 0$ or 1) Note: applicable to $J^P = 3/2^-$ (HQS partner)
  - ✓ Particle basis: $PN(^2S_{1/2})$, $P^*N(^2S_{1/2})$, $P^*N(^4D_{1/2})$ ← **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)

3. $\bar{D}$ 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: $PN(^2S_{1/2})$, $P^*N(^2S_{1/2})$, $P^*N(^4D_{1/2})$ ← **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)

- $P^{(*)}N(1/2^-)$ 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)



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

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

including **HQS singlet/doublet**

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

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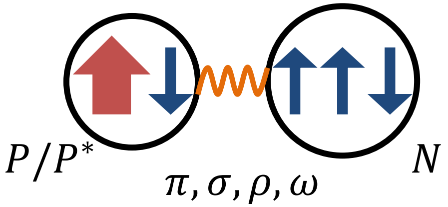

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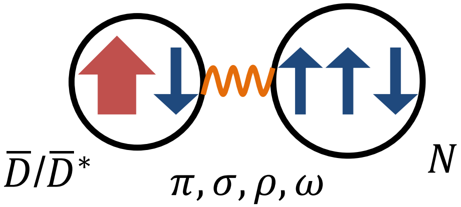
$$V^{v}_{1/2^-} = \begin{pmatrix} C'_v & 2\sqrt{3}C_v & \sqrt{6}T_v \\ 2\sqrt{3}C_v & C'_v - 4C_v & \sqrt{2}T_v \\ \sqrt{6}T_v & \sqrt{2}T_v & C'_v + 2C_v + 2T_v \end{pmatrix}$$

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)

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

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

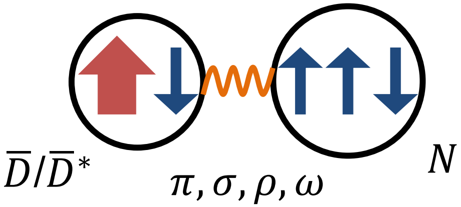


$\bar{D}N$	B.E. [MeV]	Mixing ratio [%]
$I(J^P) = 0(1/2^-)$	1.38 **"shallow"**	$\bar{D}N(^2S_{1/2})$ 96.1 $\bar{D}^*N(^2S_{1/2})$ 1.94 $\bar{D}^*N(^4D_{1/2})$ 1.93
$I(J^P) = 1(1/2^-)$	5.99 **"deep"**	$\bar{D}N(^2S_{1/2})$: 88.9 $\bar{D}^*N(^2S_{1/2})$: 10.9 $\bar{D}^*N(^4D_{1/2})$: 0.11

Cf. Deuteron binding energy 2.2 MeV

3. $\bar{D}$ 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
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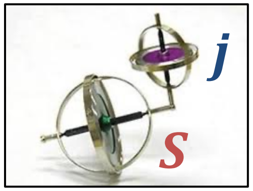
Cf. Deuteron binding energy 2.2 MeV

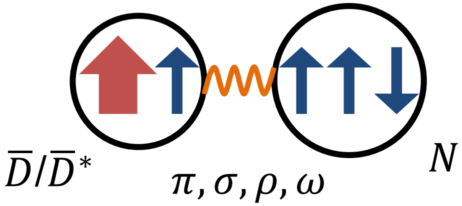
- $I = 0$: shallow bound state (consistent with previous works)
- $I = 1$: deeply bound state (new!)
- Both π and σ are important
- Note: σ pot. in $I = 1$ is very strong
- Internal spin: "$j = 1$" for $I = 0$ and "$j = 0$" for $I = 1$ (approximate)



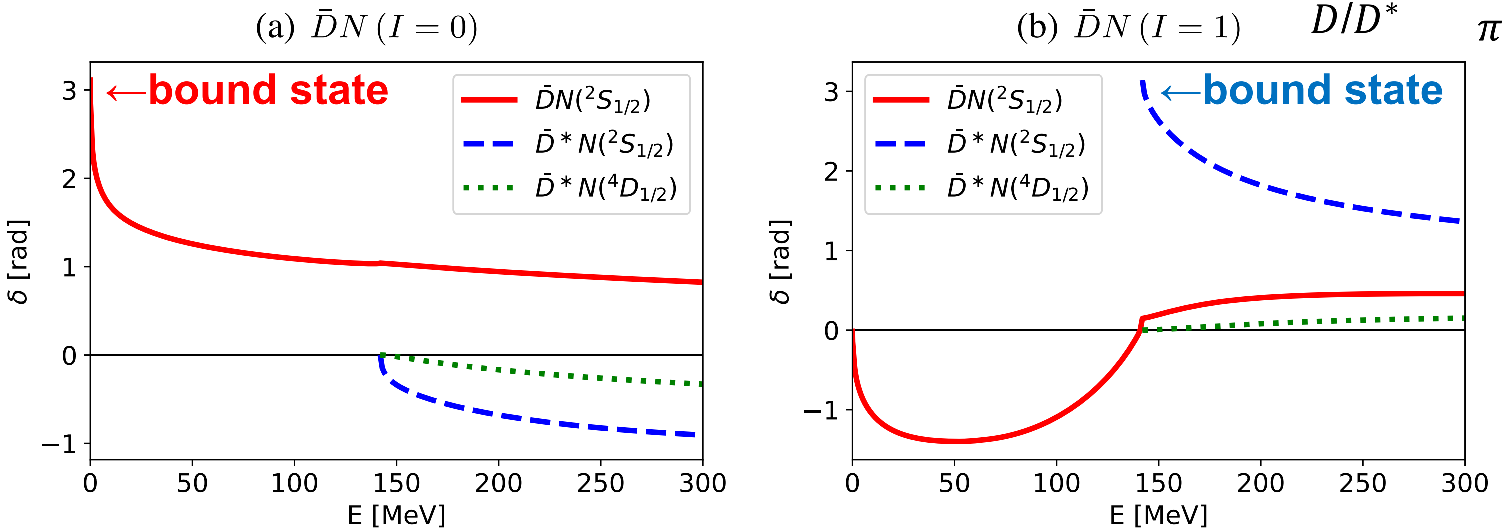
"brown muck"
(light component)

heavy quark

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



✓ Phase shifts



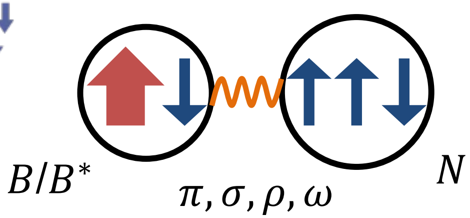
✓ Scattering lengths

$\bar{D}N$	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
2. Why $\bar{D}$ meson and nucleon?
3. $\bar{D}$ meson and nucleon potential
4. **B meson and nucleon potential**
5. Discussions –model dependence–
6. Summary

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

Cf. Deuteron binding energy 2.2 MeV

4. B meson and nucleon potential

- Applicable for B meson and nucleon (more ideal in view of HQS)
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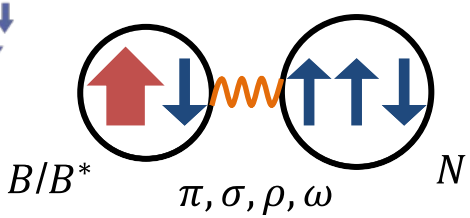

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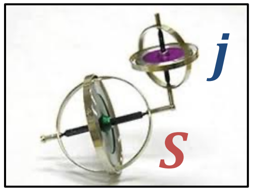
Cf. Deuteron binding energy 2.2 MeV

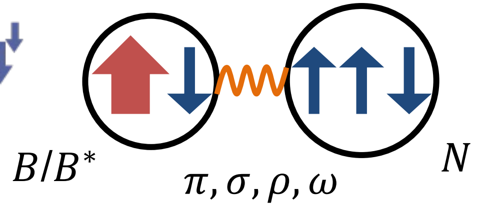
- $I = 0$: deeply bound state (consistent with previous works)
- $I = 1$: more deeply bound state (new!)
- Both π and σ are important
- Note: σ pot. in $I = 1$ is very strongly attractive
- Internal spin: “$j = 1$” for $I = 0$ and “$j = 0$” for $I = 1$ (approximate)



“brown muck”
(light component)

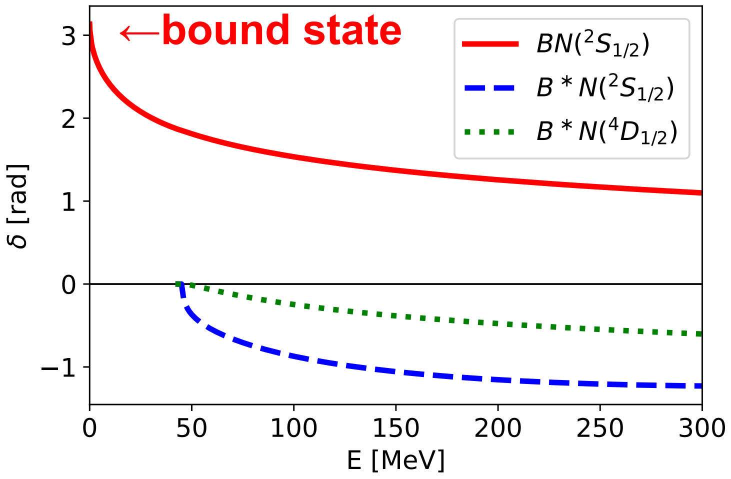
heavy quark

4. B meson and nucleon potential

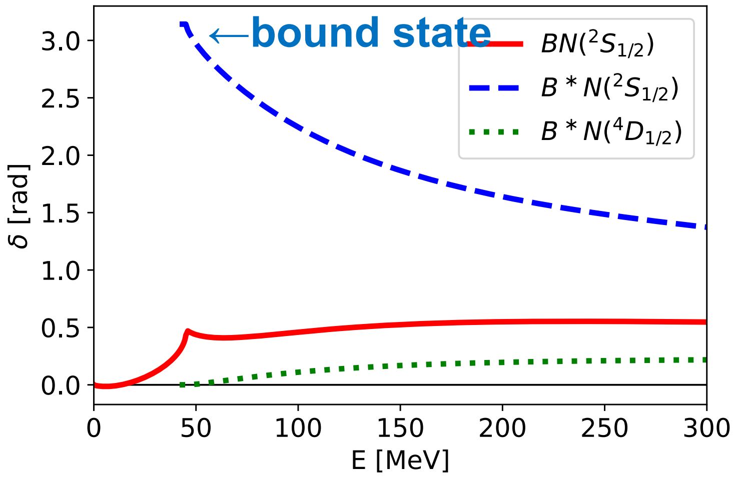


✓ Phase shifts

(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
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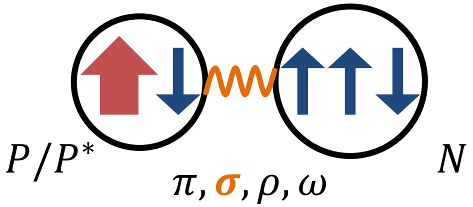
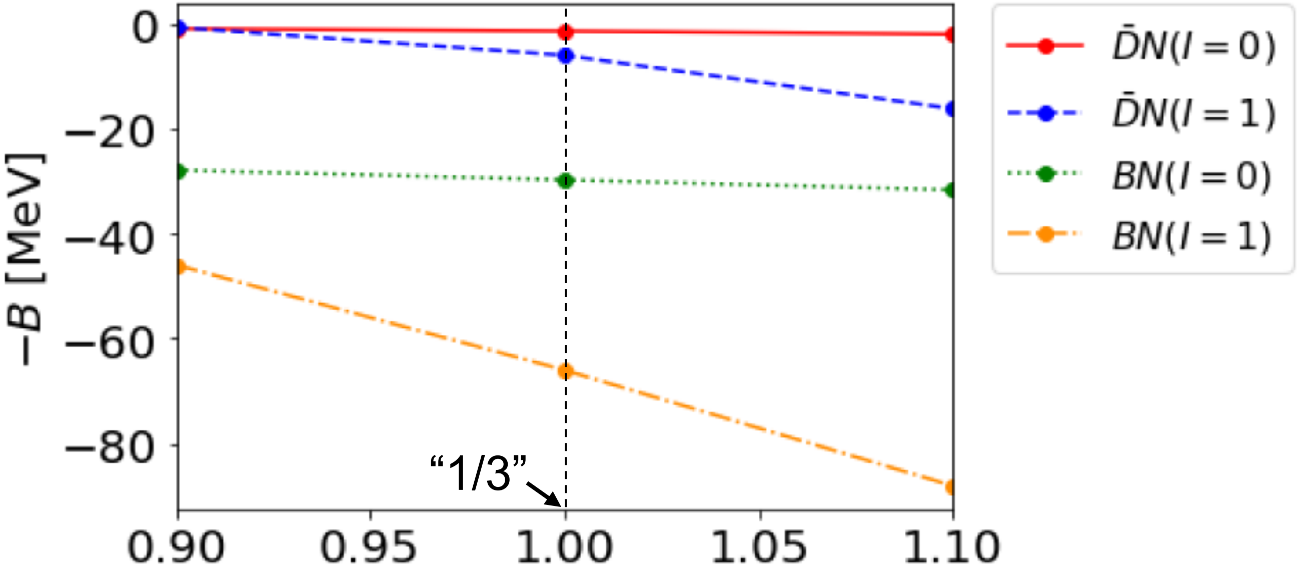
4. B meson and nucleon potential
5. **Discussions –model dependence–**
6. Summary

5. Discussions



- Model dependence
  - ✓ Uncertainty in σ pot. couplings
    - We assumed $P^{(*)}P^{(*)}\sigma$ strength coupling is “1/3” of that in $NN\sigma$
  - ✓ The uncertainty from σ pot. couplings
    - Dependence on binding energies



weaker σ coupling ← κ_σ → **stronger σ coupling**

normalized ratio of σ coupling

- 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 $\boldsymbol{I = 1}$

5. 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?
    - Binding energies?

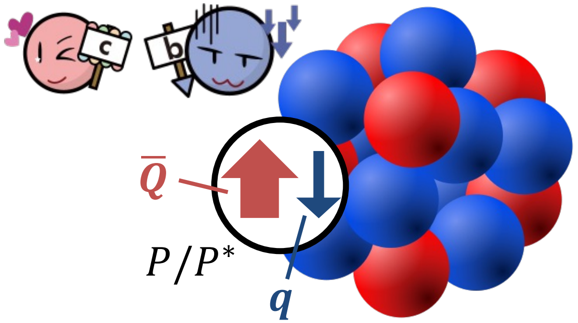


TABLE I. List of the mass shifts of the $\bar{D}$ meson in nuclear medium in previous works: quark meson coupling (QMC) model, QCD sum rule, coupled channel analysis, and chiral effective model.

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?

6. Summary

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

- $\bar{D}$ (B) meson and nucleon potential (chiral and HQS symmetries)

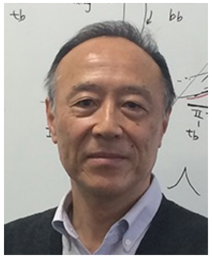
- We considered $\pi, \sigma, \rho, \omega$ exchanges by reference to CD-Bonn pot.

- 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: experiments (LHC, Belle, J-PARC, etc.) and theories
  - ✓ 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.

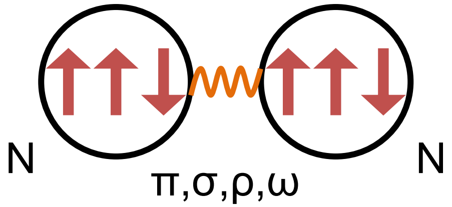
"More quarks (flavors) are different???"

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



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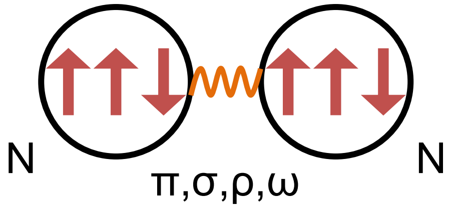

- Reference system: nucleon-nucleon (NN)
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- **CD-Bonn** is a realistic NN potential
  - ✓ Reproducing the fundamental properties of NN force
  - ✓ Simple model: one-meson exchange (π, σ, ρ, ω, ...)
  - ✓ However still complicated (because heavier mesons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

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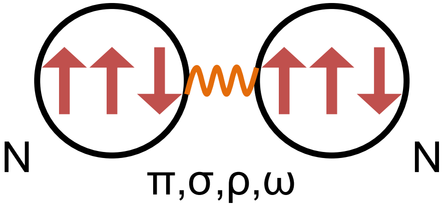

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- We consider the simpler version of CD-Bonn (**"modified CD-Bonn"**)
  - ✓ We consider only mesons with lower masses
  - ✓ Coupling constants as the same as in CD-Bonn
  - ✓ Price to be paid: rescaling of the momentum cutoffs

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±0.007 fm, r_e(${}^3S_1$)=1.753±0.008 fm, B_d=2.225 MeV
a(${}^1S_0$)=23.740±0.020 fm, r_e(${}^1S_0$)=2.77±0.05 fm

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

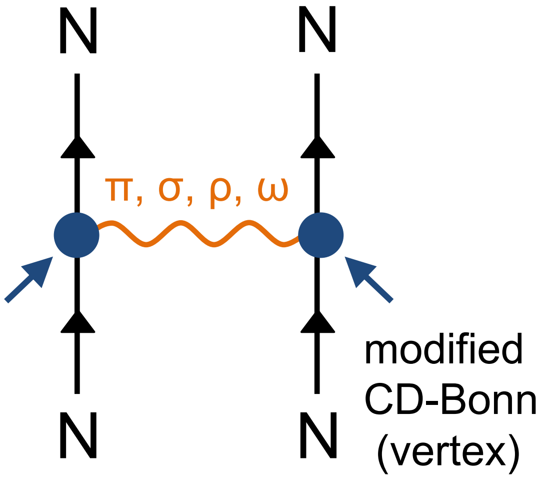
- Interaction Lagrangian

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

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

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

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



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

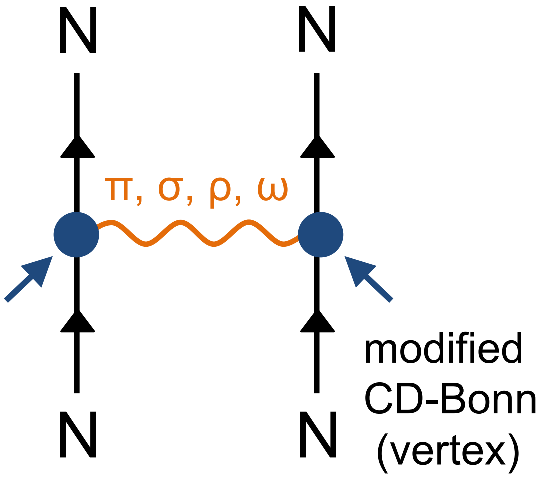
- Interaction Lagrangian

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

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

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

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



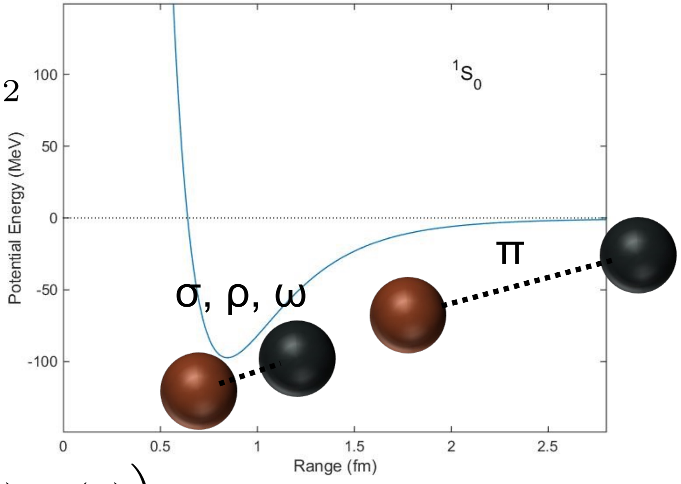
- NN potential

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

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

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

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



B. Open problems in T_{cc}


nature physics

LETTERS

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

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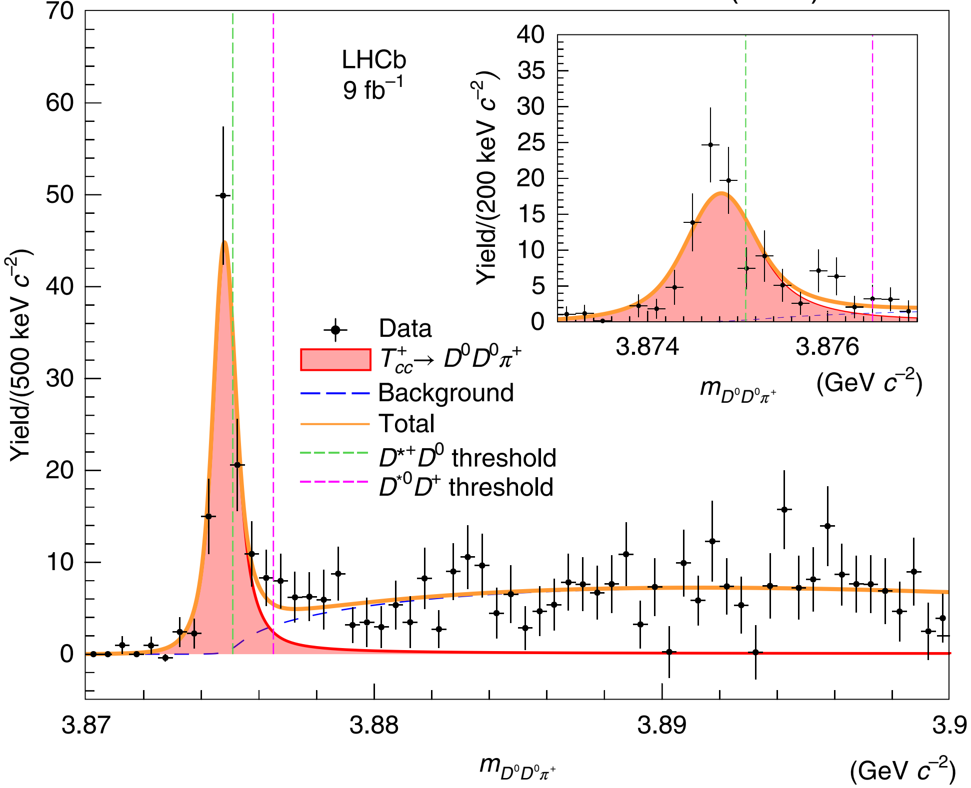
OPEN

Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

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

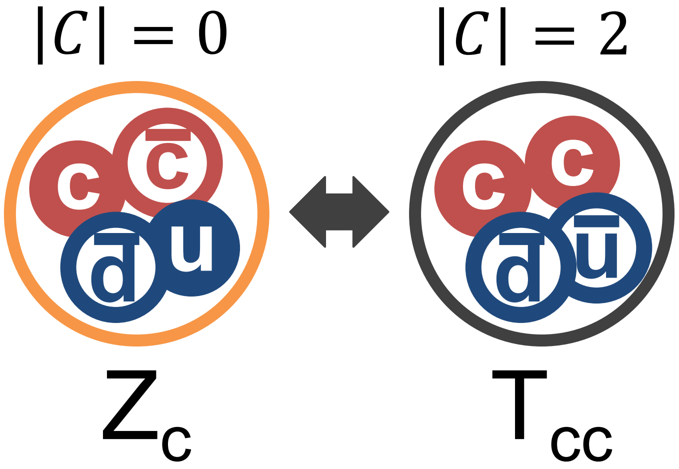


Bound state below $D^{*+}D^0$ threshold

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

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

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) ?

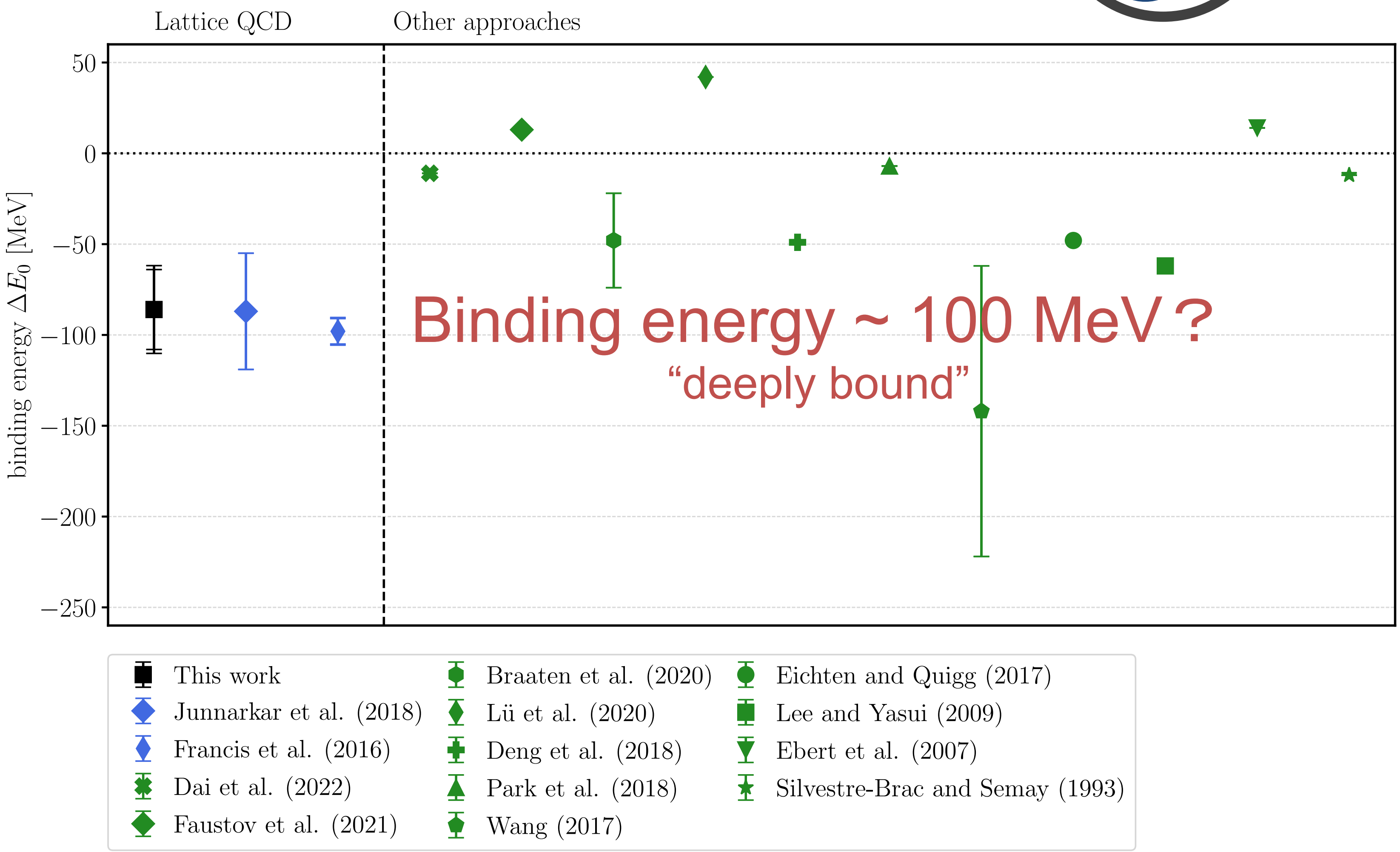
etc.

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*



Binding energy ~ 100 MeV？

“deeply bound”

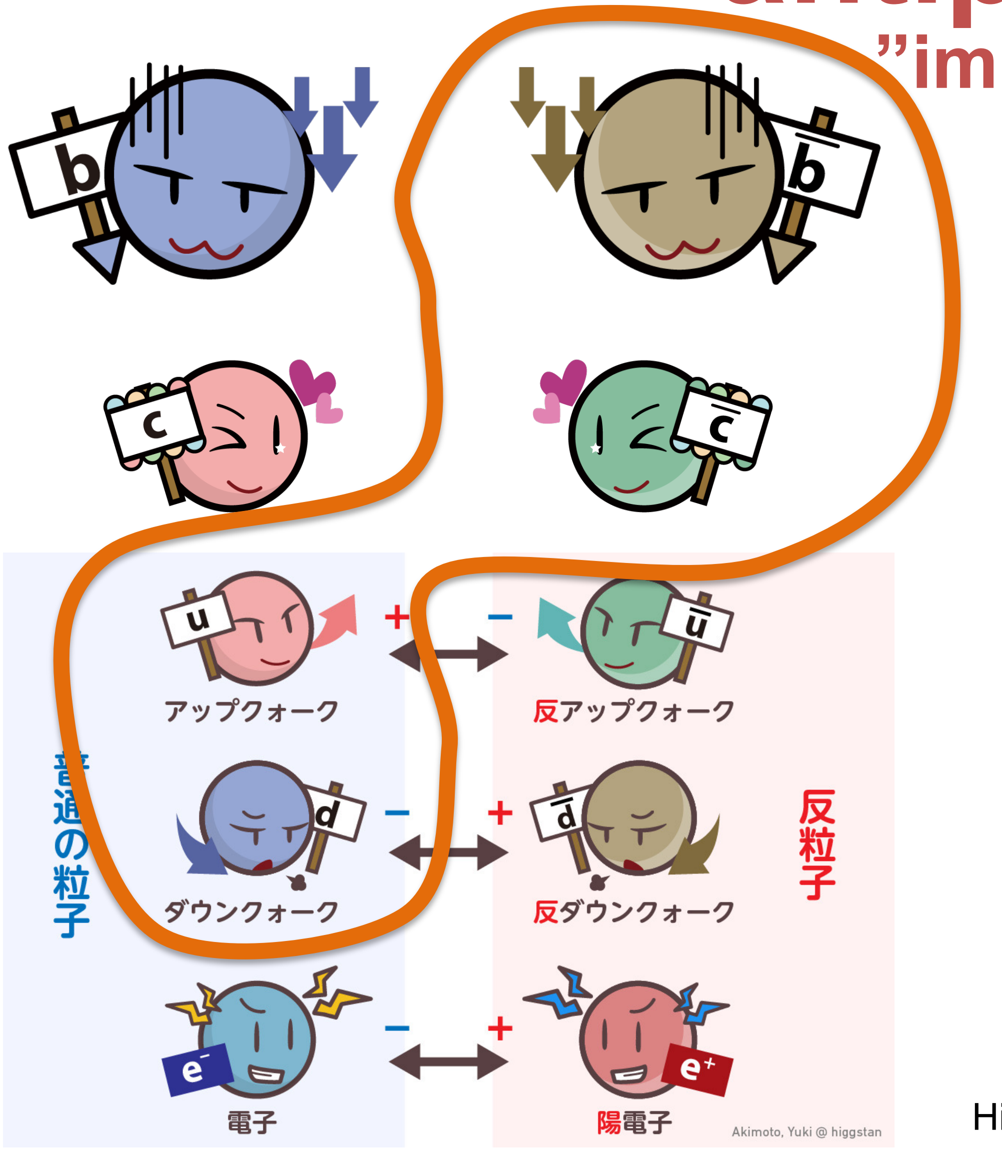
Why don’t we study T_{bb} in future experiments？

C. New state of matter

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

heavy antiparticle

"impurity"

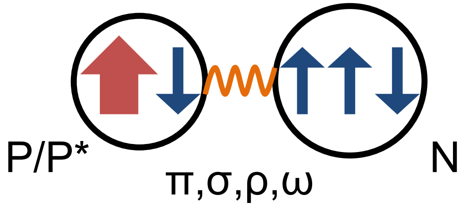


light particle

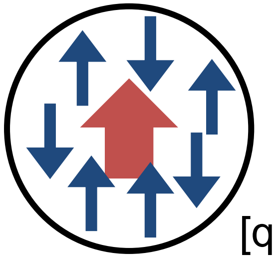
"nucleus"

HiggsTan.com

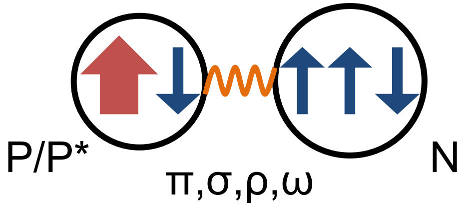
D. Light spin structure



- 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?


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

D. Light spin structure



- Heavy-quark spin structures (**I=0**)
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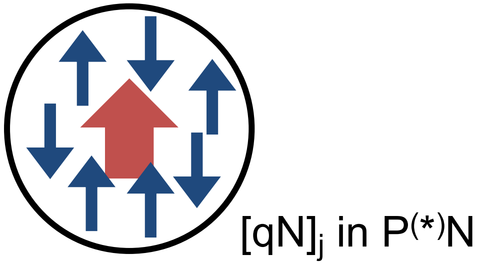


- Heavy-quark spin structures (**I=1**)
  - ✓ Calculated mxing ratios
    - Anti-DN($^2S_{1/2}$):anti-D*N($^2S_{1/2}$) = 90:11 (→ **j=1**)
    - BN($^2S_{1/2}$):B*N($^2S_{1/2}$) = 39:62 (→ **j=0**)
  - ✓ The spin-complex $[qN]_j$ **j=0** is favored in I=1 in HQ limit?
    - This question should be related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

E. Exotic hadrons

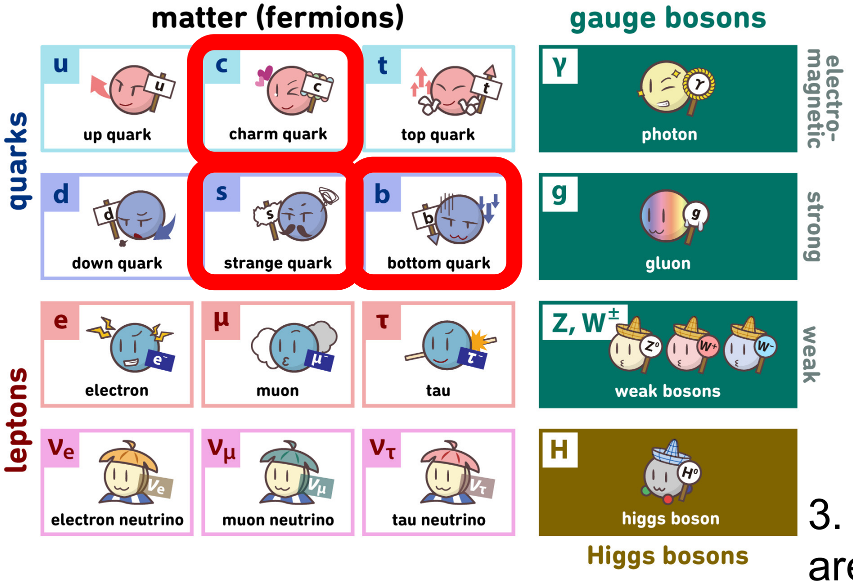
- Motivation to study exotic hadrons (multiquarks)
  ✓ Color confinement (Yang-Mills mass gap)
  ✓ Flavor multiplets (unconventional)
  ✓ Multi-baryons (ex. strange/charm nuclei)

M. Gell-Mann
"Quarks"

Hadron physics in a nutshell

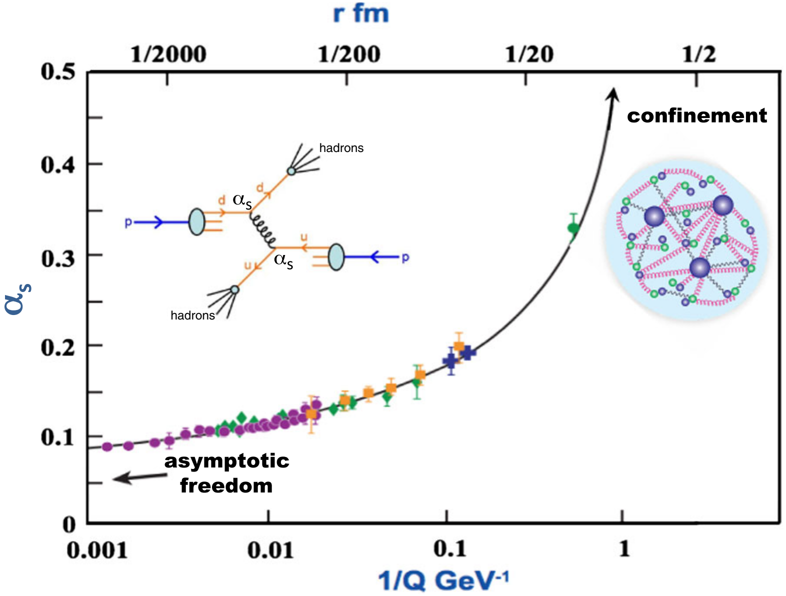
1. QCD (Quantum Chromodynamics)

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

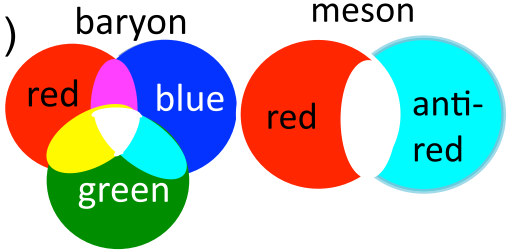


HiggsTan.com

2. Strong coupling at low energy

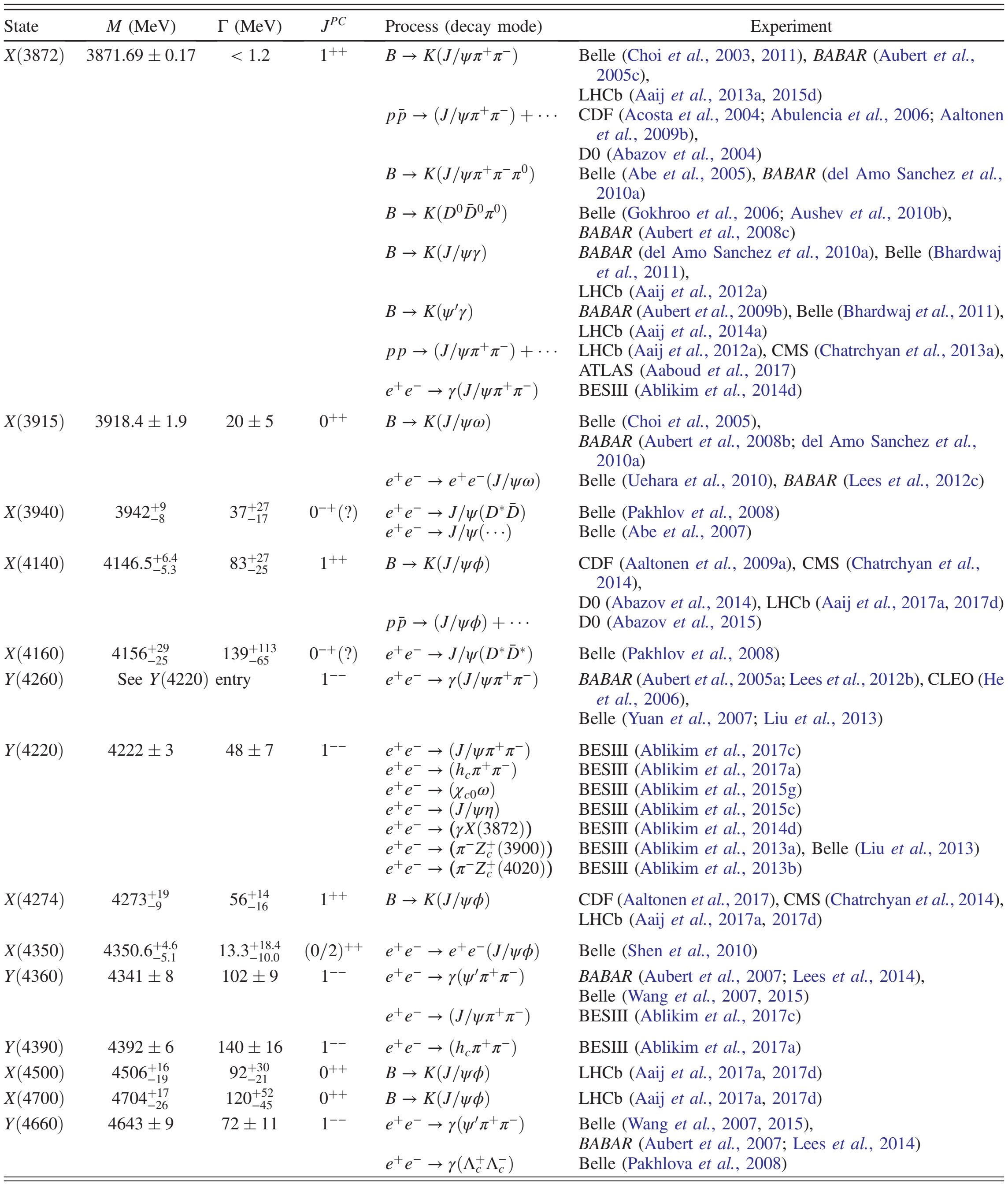


3. Quarks (**red**, **blue**, **green**) are confined in hadrons, baryons (3 quark) and mesons (2 quark).



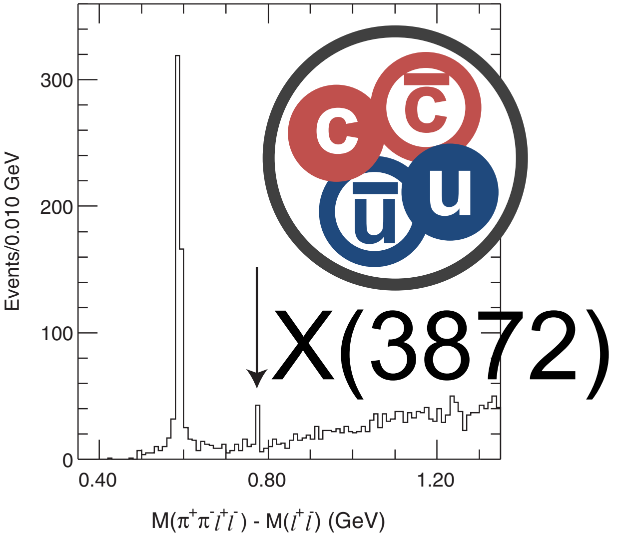
E. Exotic hadrons

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



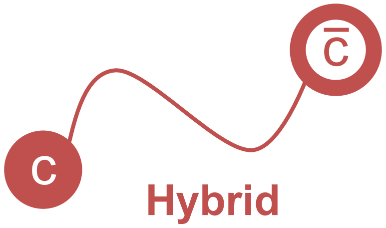
State	M (MeV)	Γ (MeV)	J^{PC}	Process (decay mode)	Experiment
$X(3872)$	3871.69 ± 0.17	< 1.2	1^{++}	$B \to K(J/\psi\pi^+\pi^-)$	Belle (Choi *et al.*, 2003, 2011), *BABAR* (Aubert *et al.*, 2005c), LHCb (Aaij *et al.*, 2013a, 2015d)
				$p\bar{p} \to (J/\psi\pi^+\pi^-) + \cdots$	CDF (Acosta *et al.*, 2004; 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^{+-}	$e^+e^- \to \pi^{-,0}(J/\psi\pi^{+,0})$ $e^+e^- \to \pi^{-,0}(D\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2013a, 2015f), Belle (Liu *et al.*, 2013) BESIII (Ablikim *et al.*, 2014b, 2015e)
$Z_c^{+,0}(4020)$	4024.1 ± 1.9	13 ± 5	$1^{+-}(?)$	$e^+e- \to \pi^{-,0}(h_c\pi^{+,0})$ $e^+e^- \to \pi^{-,0}(D^*\bar{D}^*)^{+,0}$	BESIII (Ablikim *et al.*, 2013b, 2014c) 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^+	$B \to K(J/\psi\pi^+)$ $B \to K(\psi'\pi^+)$	Belle (Chilikin *et al.*, 2014) 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^+	$B \to K(\psi'\pi^+)$ $B \to K(J\psi\pi^+)$	Belle (Choi *et al.*, 2008; Mizuk *et al.*, 2009), Belle (Chilikin *et al.*, 2013), LHCb (Aaij *et al.*, 2014b, 2015b) 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^{+-}	$Y_b(10860) \to \pi^{-,0}(\Upsilon(nS)\pi^{+,0})$ $Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$ $Y_b(10860) \to \pi^-(B\bar{B}^*)^+$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015), Belle (Krokovny *et al.*, 2013) Belle (Bondar *et al.*, 2012) Belle (Garmash *et al.*, 2016)
$Z_b^+(10650)$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$Y_b(10860) \to \pi^-(\Upsilon(nS)\pi^+)$ $Y_b(10860) \to \pi^-(h_b(nP)\pi^+)$ $Y_b(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle (Bondar *et al.*, 2012; Garmash *et al.*, 2015) Belle (Bondar *et al.*, 2012) Belle (Garmash *et al.*, 2016)

← **Genuine tetraquark**

Z_c

Electrically charged state (+)

← **Pentaquark**

P_c

Is that all ?

E. Exotic hadrons

nature physics

LETTERS

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

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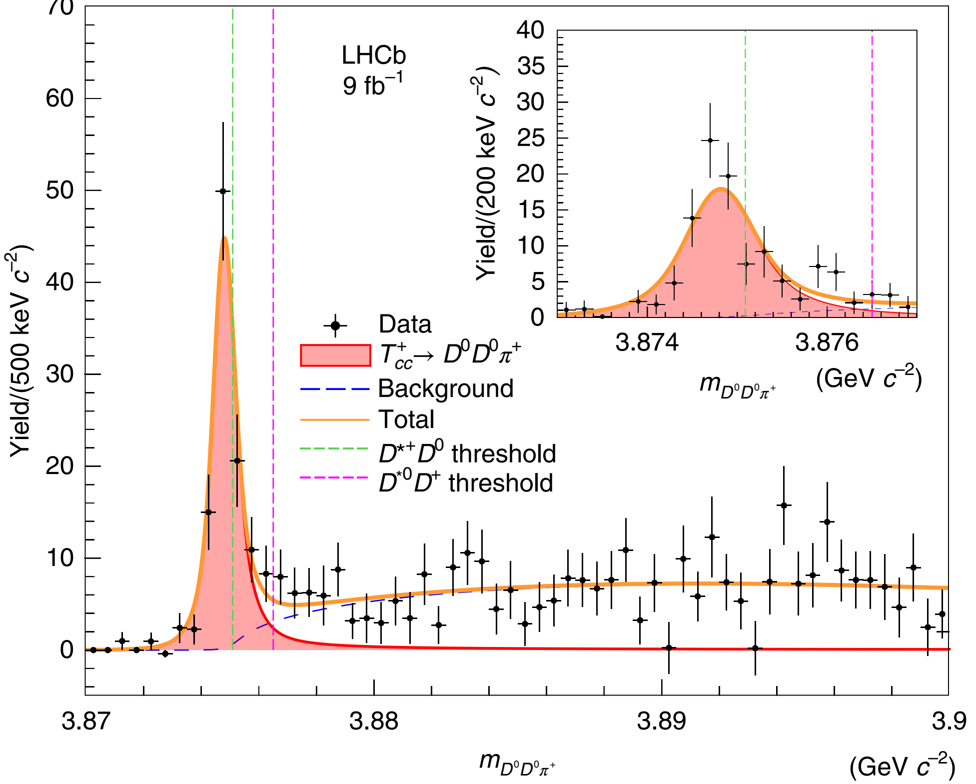
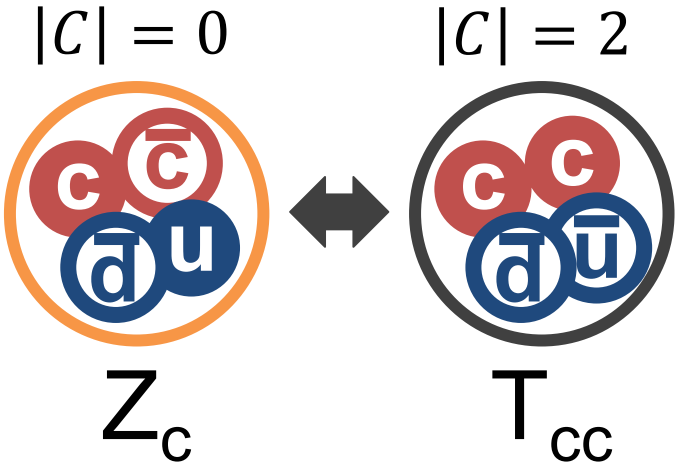
Observation of an exotic narrow doubly charmed tetraquark

LHCb Collaboration*

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



T_{cc}: doubly charmed tetraquark



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

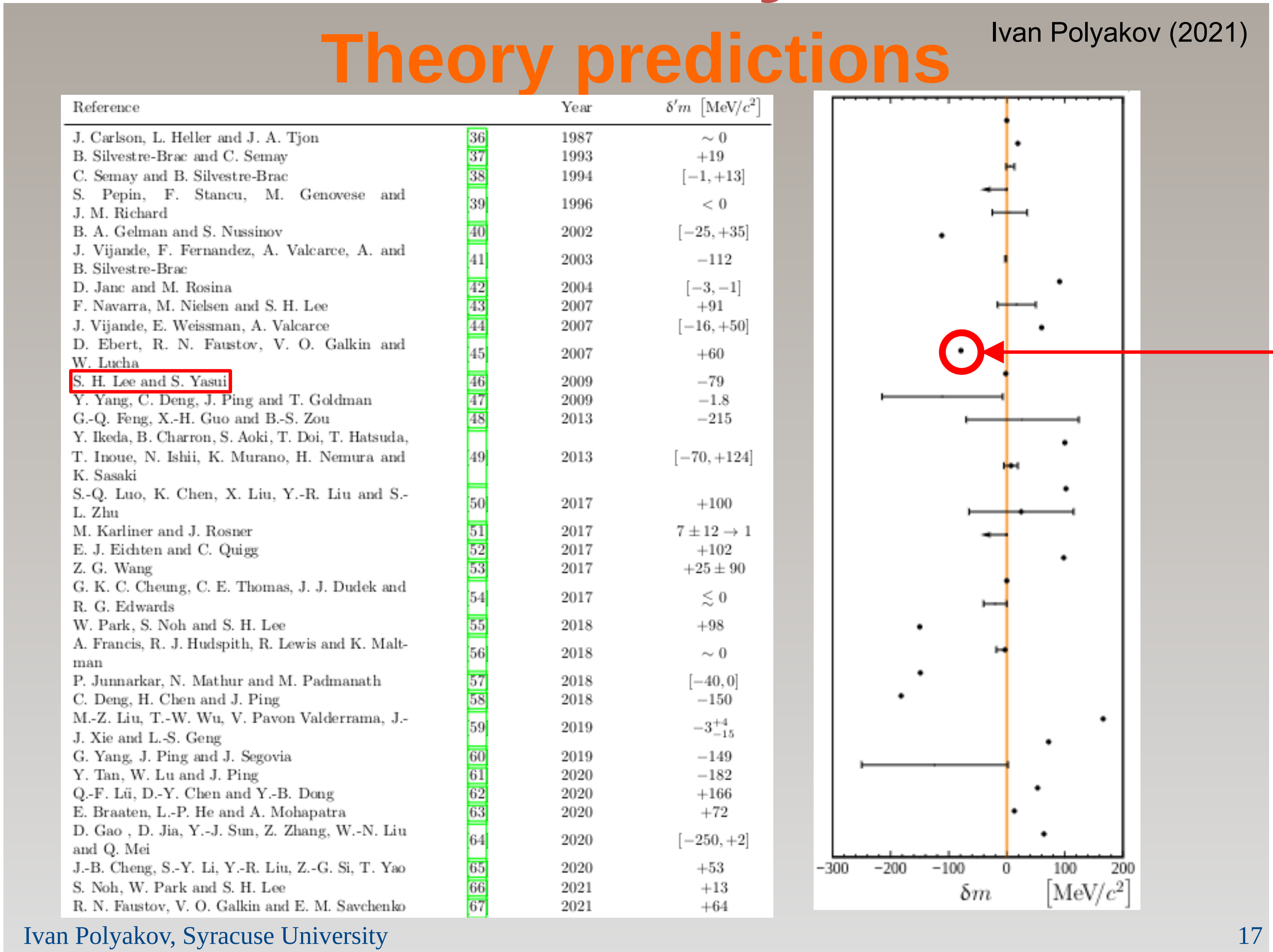
Bound state below $D^{*+}D^0$ threshold

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

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

E. Exotic hadrons

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



Theory predictions

Ivan Polyakov (2021)

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	$+64$

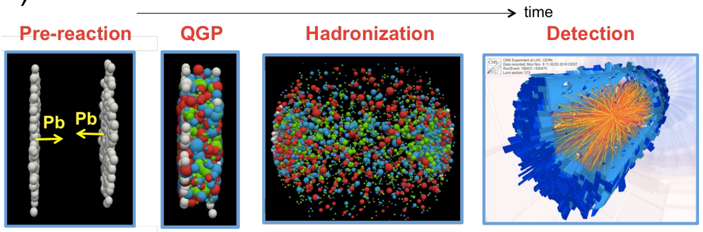
me!

Ivan Polyakov, Syracuse University 17

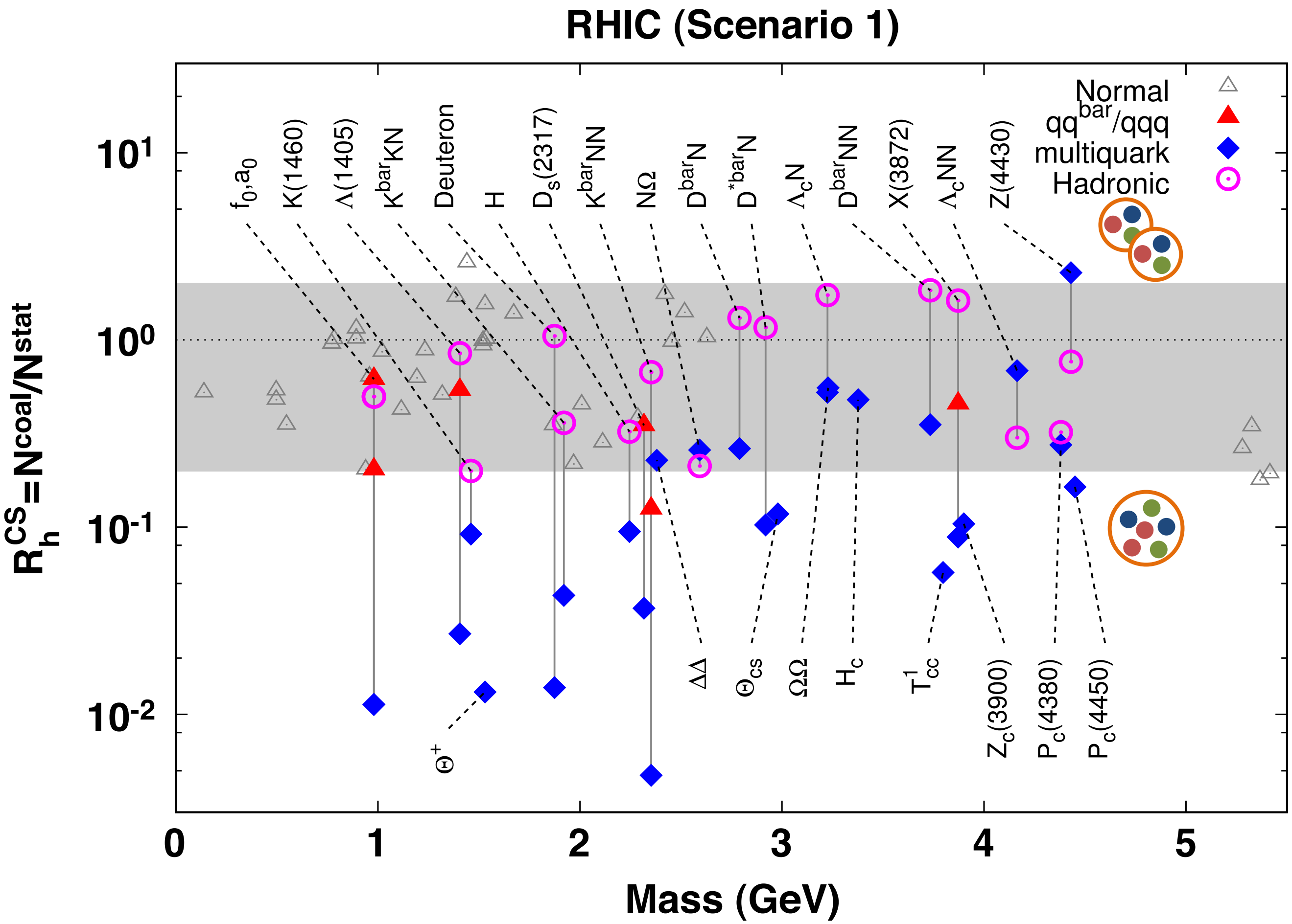
https://indico.desy.de/event/28202/contributions/105627/attachments/67806/84639/EPS-HEP_2021_Polyakov_v5.pdf

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 ?



RHIC (Scenario 1)

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Particle	Scenario 1		Scenario 2		Mol.	Stat.
	$q\bar{q}/qqq$	Multiquark	$q\bar{q}/qqq$	Multiquark		
RHIC						
T^1_{cc}	–	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^0_{cb}	–	9.3×10^{-8}	–	9.9×10^{-8}	–	1.6×10^{-6}
LHC (2.76 TeV)						
T^1_{cc}	–	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}
$\bar{D}^*N$	–	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^0_{cb}	–	1.1×10^{-6}	–	1.3×10^{-6}	–	2.7×10^{-5}
LHC (5.02 TeV)						
T^1_{cc}	–	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^0_{cb}	–	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)