Anti-D meson and nucleon interaction from meson exchange model

S. Yamaguchi, S. Yasui, A. Hosaka, arXiv:2206.01921 [hep-ph]
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Shigehiro YASUI (Keio U.)

with Yasuhiro YAMAGUCHI (Nagoya U.) and
Atsushi HOSAKA (RCNP, JAEA)

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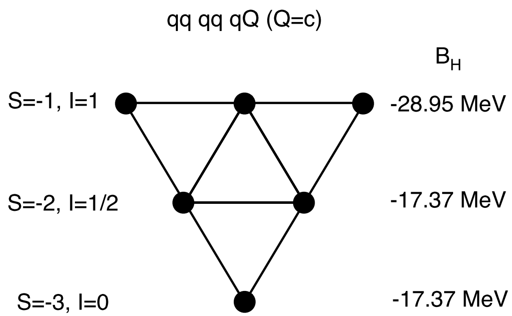
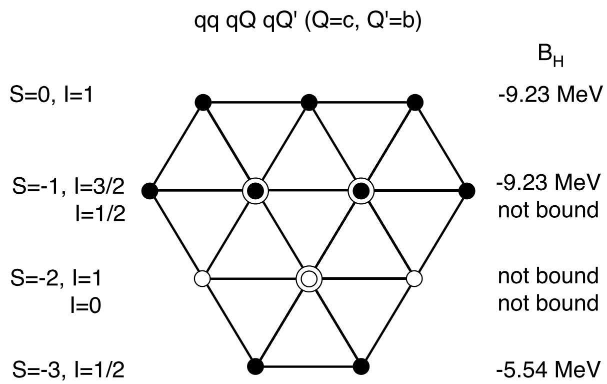
1. Why anti-D meson and nucleon?

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





Flavor multiplets from diquark model
Lee, Yasui, EPJC64, 283 (2009)

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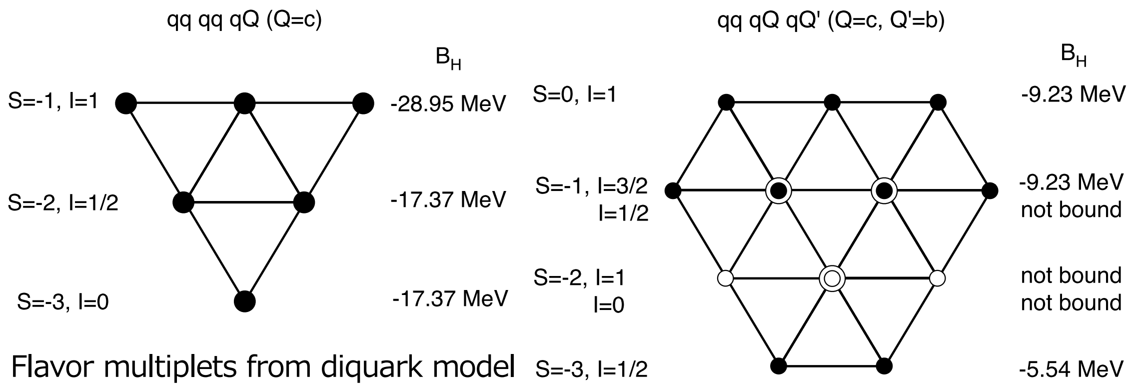
"Quarks"



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P. W. Anderson
"More is different"

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(Question that I ask often to myself)

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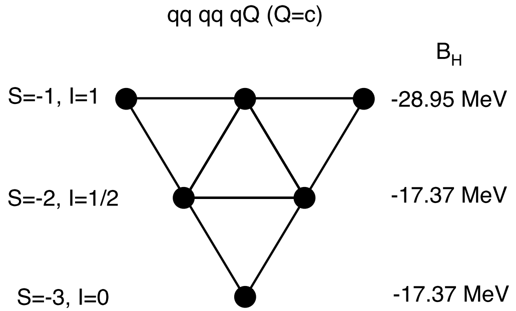

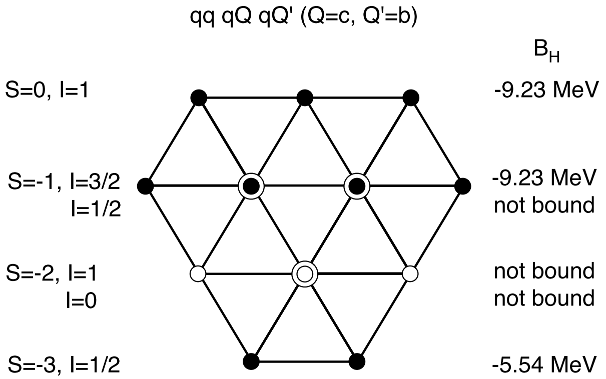

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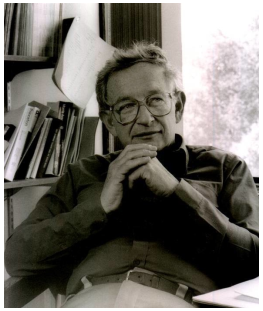

"More quarks are different"
(Question that I ask often to myself)

- What should we do?
  - ✓ What bound/resonant states are produced in QCD?
  - ✓ Find out "periodic tables" (flavor, baryon number, ...) in QCD!

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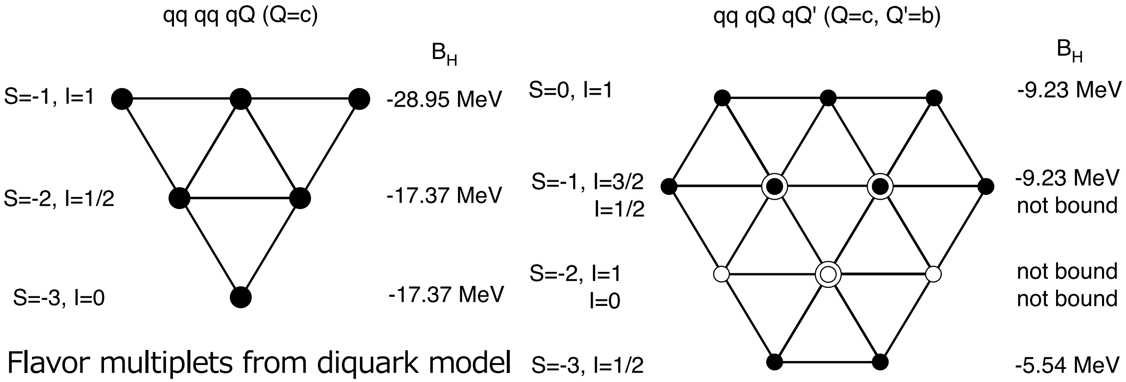

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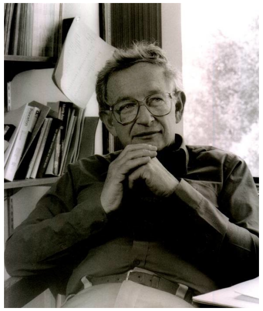

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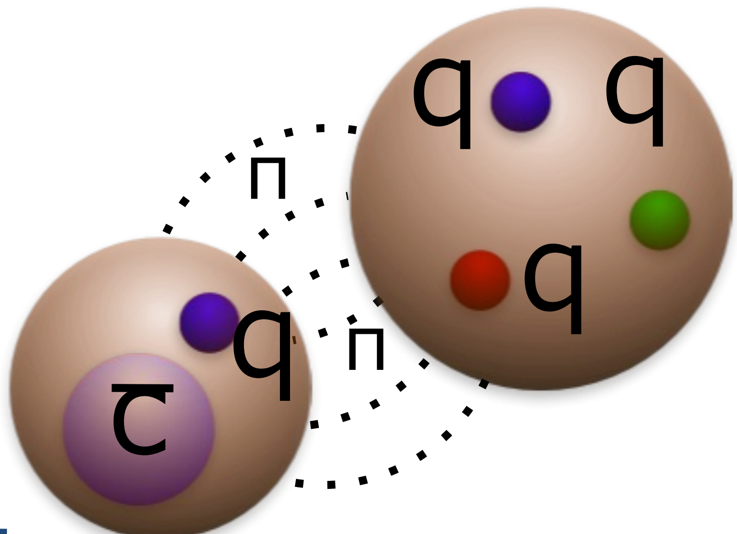
(Question that I ask often to myself)

- What should we do?
  - ✓ What bound/resonant states are produced in QCD?
  - ✓ Find out "periodic tables" (flavor, baryon number, ...) in QCD!

- Let us think exotic hadrons as simple as possible.
  - ✓ Small number of channels (though many quarks...)
  - ✓ Heavy quarks (effective theory of QCD; $\Lambda_{QCD} << M_Q$)
  - ✓ Symmetry (chiral symmetry, spin symmetry, ...)

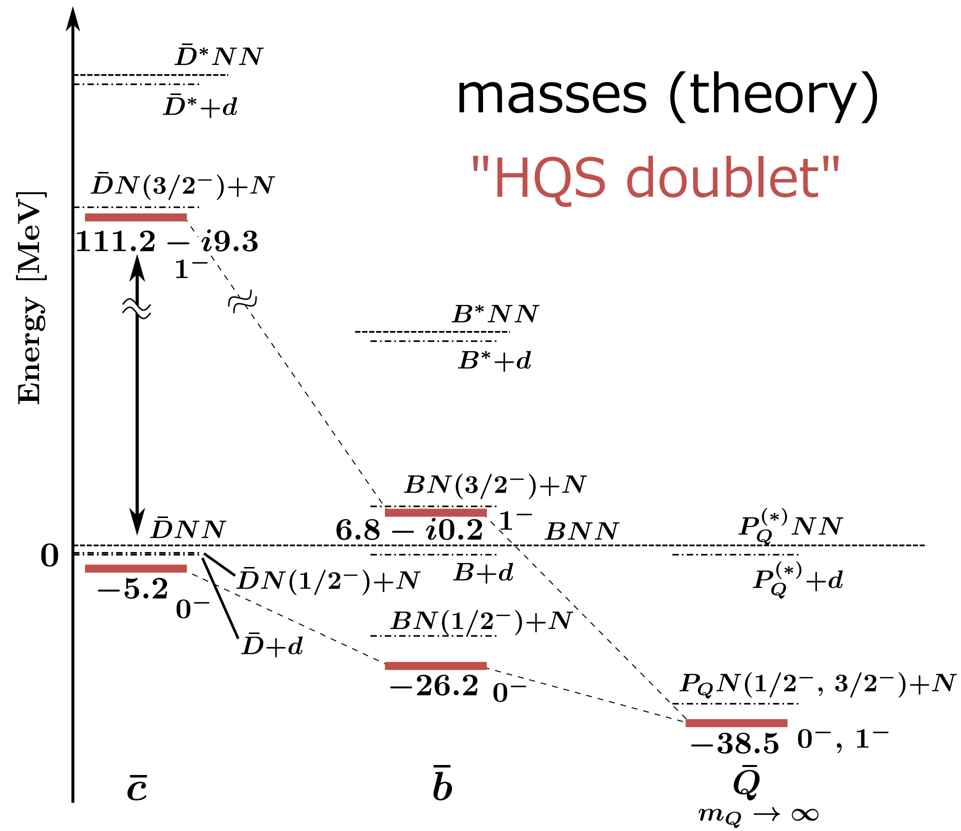
1. Why anti-D meson and nucleon?

- Anti-D meson and nucleon (pentaquark channel)
  - ✓ Anti-c+qqqq (q=u,d): no annihilation channel
  - ✓ Anti-charm nuclei? Review paper: Hosaka, Hyodo, Sudoh, Yamaguchi, Yasui, PPNP 96, 88 (2017)
  - ✓ Extension to B meson and nucleon (heavy-quark spin symmetry)



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

as hadronic molecule



masses (theory)

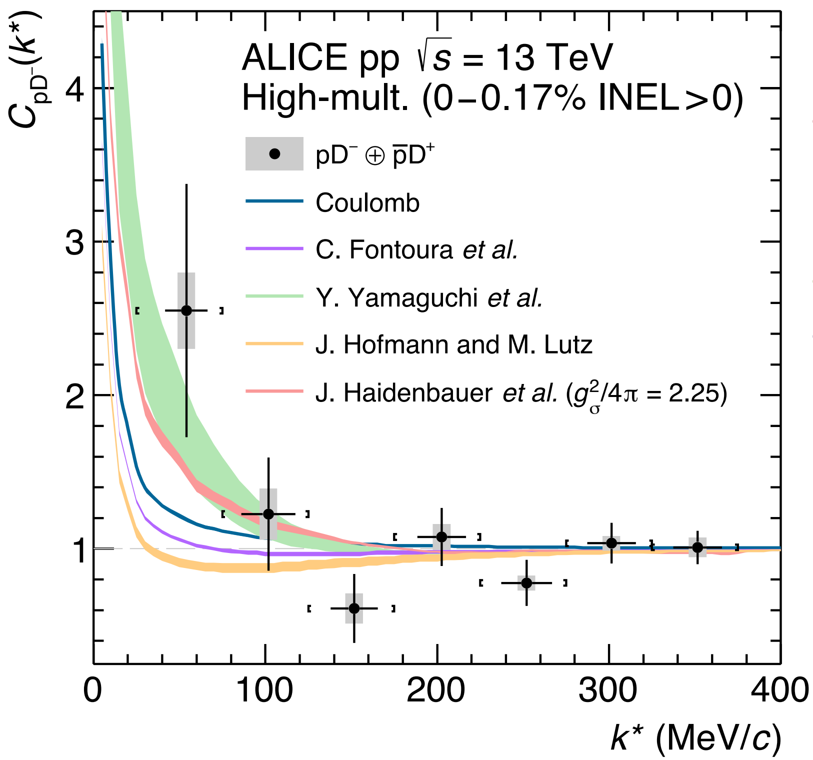
"HQS doublet"

Cohen, Hohler, Lebed, PRD72, 074010 (2005)
Yasui, Sudoh, PRD80, 034008 (2009)
Yamaguchi, Ohkoda, Yasui, Hosaka, PRD84, 014032 (2011), ibid. D85, 054003 (2012)

More than 10 years ago...

1. Why anti-D meson and nucleon?

- 2022: First experiment has appeared!
  - ✓ ALICE Coll.: 2201.05352 (theoretical analysis by Kamiya, Hyodo, Ohnishi)
  - ✓ D^-p correlation function
  - ✓ Attraction suggested?



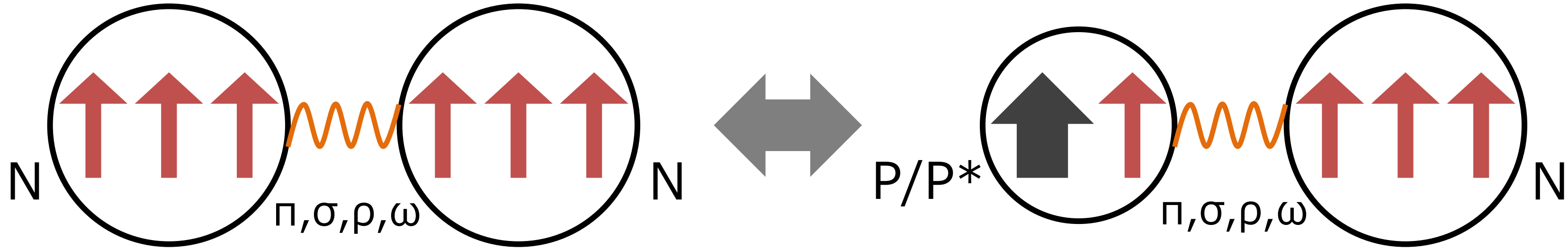
	Model	f_0 (I = 0)	f_0 (I = 1)	n_σ
	Coulomb			(1.1–1.5)
attraction	Haidenbauer et al. [21]			
	$-\ g_\sigma^2/4\pi = 1$	0.14	−0.28	(1.2–1.5)
	$-\ g_\sigma^2/4\pi = 2.25$	0.67	0.04	(0.8–1.3)
repulsion	Hofmann and Lutz [22]	−0.16	−0.26	(1.3–1.6)
attraction (bound)	Yamaguchi et al. [24]	−4.38	−0.07	(0.6–1.1)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

1. Why anti-D meson and nucleon?

- Anti-D meson and nucleon potential (P=anti-D, P*=anti-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 pot. (Note:1/√2 factor for $m_{P^{(*)}P^{(*)}}$)



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

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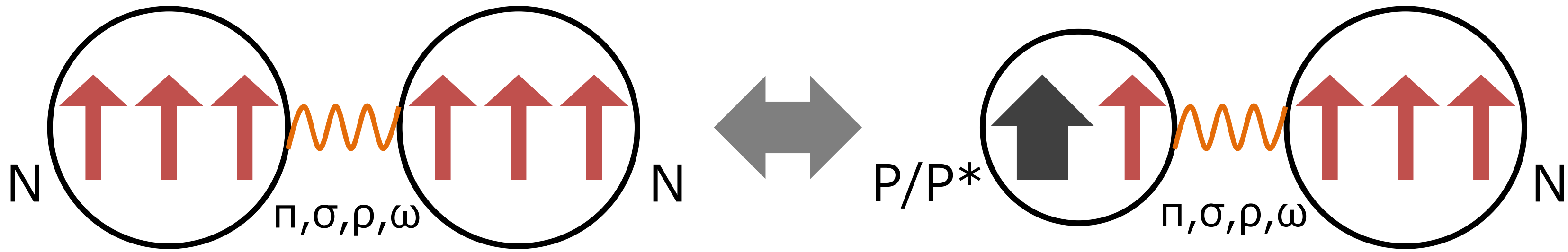
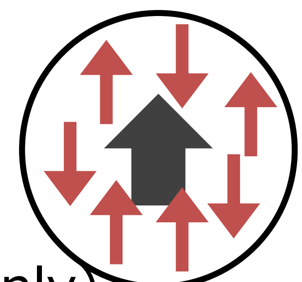


π exchange → spin flipping (P, P* mixing) like in a deuteron

- Spin-structure (q: light quark, N: nucleon)
  - ✓ **(Anti-Q q) N = Anti-Q [q N]**
  - ✓ HQS multiplets
    - **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)



Spin decomposition of heavy-quark from light quarks and gluons

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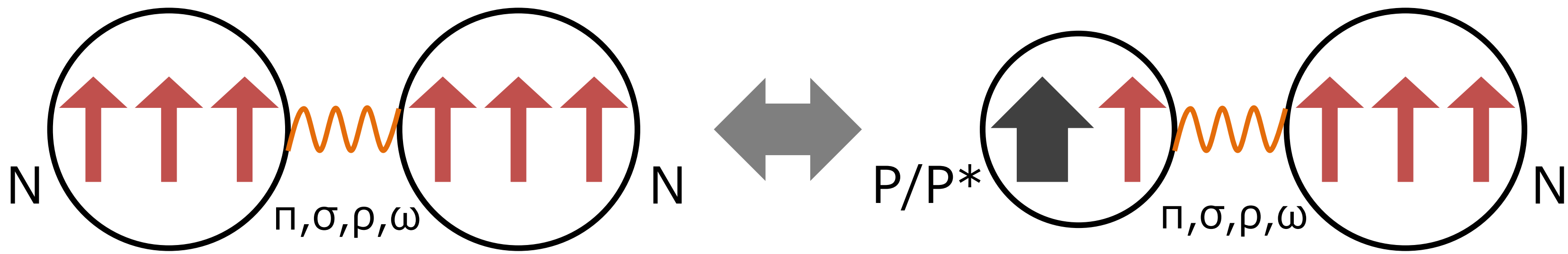

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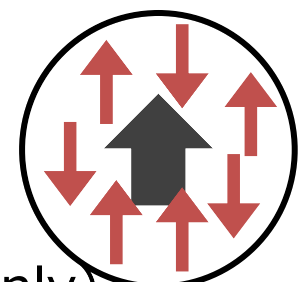
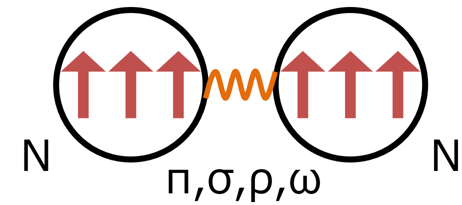


Spin decomposition of heavy-quark from light quarks and gluons

- Is qN analogous to "nucleon-nucleon" (NN) ?
  - ✓ If qN is deuteron-like, then qN spin j=1 indicates HQS doublet.
  - ✓ We need to solve QCD for getting the answer.

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

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



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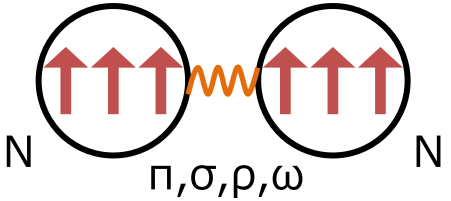

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- CD-Bonn is a realistic NN potential
  - ✓ Reproducing the fundamental properties of NN force
  - ✓ Simple model: 1-meson exchange (π, σ, ρ, ω, ...)
  - ✓ ...However still complicated (heavier mesons included)

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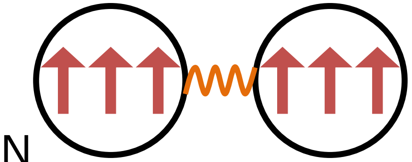

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- We consider the simpler version of CD-Bonn ("modified CD-Bonn")
  - ✓ We consider only mesons with lower masses
  - ✓ Coupling constants as the same as in CD-Bonn
  - ✓ Price to be paid: rescaling of the momentum cutoffs

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

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

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

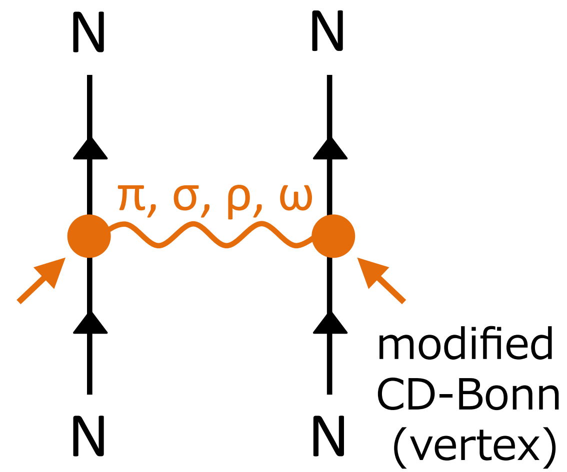
- Interaction Lagrangian

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

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

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

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



- NN potential

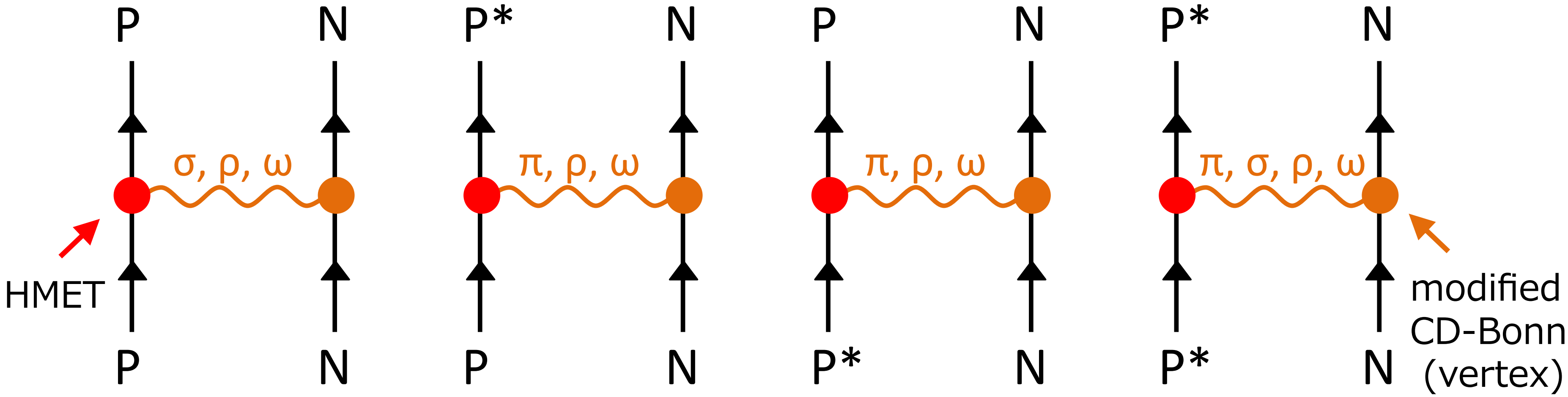
$$V_\pi(r) = \left(\frac{g_{\pi NN}}{2m_N}\right)^2\frac{1}{3}\Big(\boldsymbol{\sigma}_1\cdot\boldsymbol{\sigma}_2 C_\pi(r) + S_{12}(\hat{\boldsymbol{r}})T_\pi(r)\Big)\boldsymbol{\tau}_1\cdot\boldsymbol{\tau}_2$$

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

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

3. Anti-D meson and nucleon potential

- $P^{(*)}N$ potential (P=anti-D, B meson; P*=anti-D*, B* meson)
  - PN-P*N channel couplings (different channels, different mesons)



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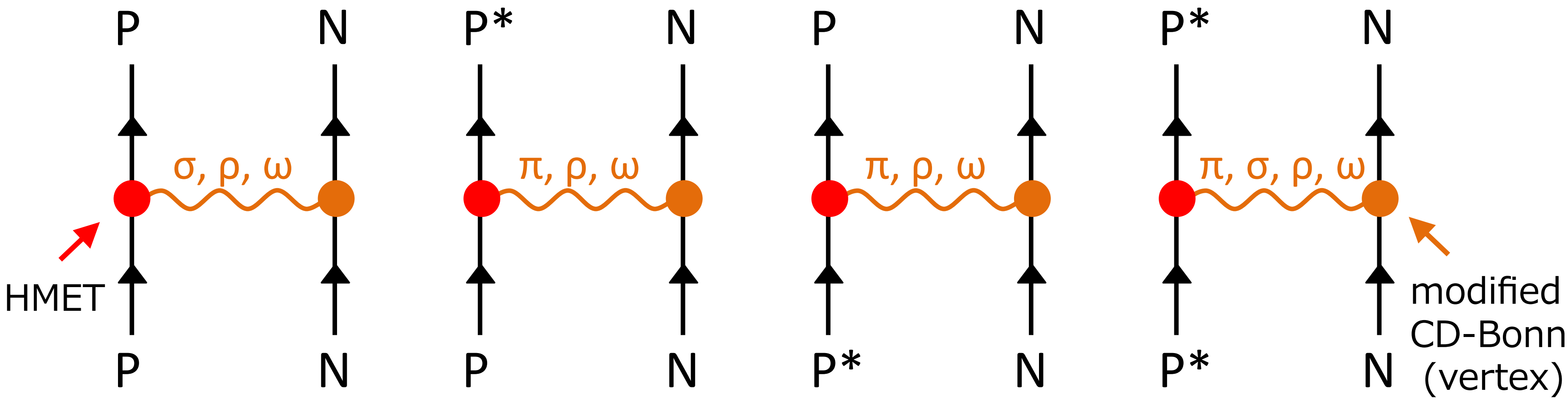

- Heavy Meson Effective Theory (HMET)
  - ✓ Hadronic effective theory based on χ + HQS symmetries
  - ✓ Effective field: $H_\alpha = \left(P^{*\mu}_\alpha \gamma_\mu + P_\alpha \gamma_5\right) \frac{1-\not{v}}{2}$ $\quad H_\alpha \underset{\text{HQS + χ sym.}}{\rightarrow} S H_\beta U^\dagger_{\beta\alpha}$
  - ✓ $P^{(*)}P^{(*)}m$ vertices are uniquely determined (m=π, σ, ρ, ω)

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

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

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

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

3. Anti-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: **$PN(^2S_{1/2})$, $P^*N(^2S_{1/2})$, $P^*N(^4D_{1/2})$**
  - ✓ HQS basis: $[\text{Anti-}Q_{j=1/2}[qN]_{j=1}]_{JP=1/2-}$ Cf. Yasui, Sudoh, Yamaguchi, Ohkoda, Hosaka, Hyodo, PLB727, 185 (2013); PRD91, 034034 (2015)

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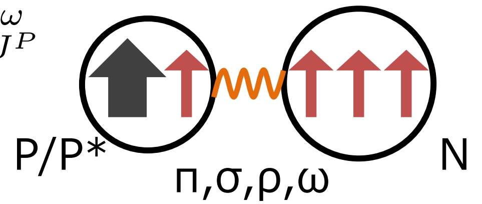
- $P^{(*)}N(1/2^-)$ Hamiltonian $H_{J^P} = K_{J^P} + V^{\pi}_{J^P} + V^{\sigma_I}_{J^P} + V^{\rho}_{J^P} + V^{\omega}_{J^P}$



  - ✓ Kinetic term $K_{1/2^-} = \mathrm{diag}\left(K_0, K_0^*, K_2^*\right)$ (S,S,D)
  - ✓ π, σ, v(=ρ, ω) pot. term (1/√2 factor included)

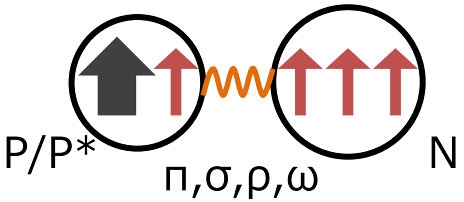
$$V^{\pi}_{1/2^-} = \begin{pmatrix} 0 & \sqrt{3}\,C_\pi & -\sqrt{6}\,T_\pi \\ \sqrt{3}\,C_\pi & -2\,C_\pi & -\sqrt{2}\,T_\pi \\ -\sqrt{6}\,T_\pi & -\sqrt{2}\,T_\pi & C_\pi - 2\,T_\pi \end{pmatrix} \qquad V^{\sigma_I}_{1/2^-} = \begin{pmatrix} C_{\sigma_I} & 0 & 0 \\ 0 & C_{\sigma_I} & 0 \\ 0 & 0 & C_{\sigma_I}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

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

  - ✓ Tensor force in off-diagonal components (strong mixing effect)
  - ✓ Model parameters
    - π pot. coupling ($D^* \to D\pi$)
    - v pot. couplings (universal couplings)
    - σ pot. coupling ~ 1/3 in NN (# of light quarks in $P^{(*)}$ meson)
    - Momentum cutoffs (size ratios of anti-D (B) and N (quark model))

3. Anti-D meson and nucleon potential

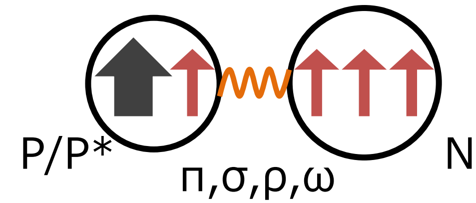
- Results (anti-D and N)
  - ✓ bound states (I=0, 1)



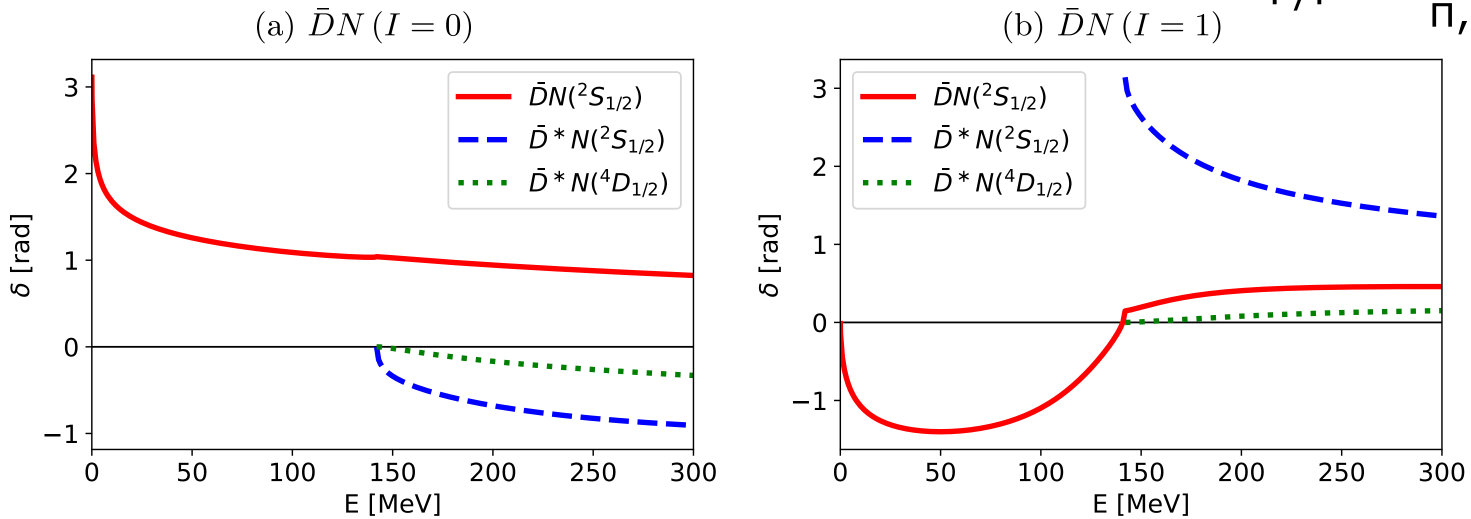
$\bar{D}N$	B.E. [MeV]	Mixing ratio [%]	
$0(1/2^-)$	1.38 **shallow**	$\bar{D}N(^2S_{1/2})$	96.1
		$\bar{D}^*N(^2S_{1/2})$	1.94
		$\bar{D}^*N(^4D_{1/2})$	1.93
$1(1/2^-)$	5.99 **deep**	$\bar{D}N(^2S_{1/2})$:	88.9
		$\bar{D}^*N(^2S_{1/2})$:	10.9
		$\bar{D}^*N(^4D_{1/2})$:	0.11

- I=0: shallow bound state (consistent with previous works)
- I=1: deeply bound state (new!)
- Both π and σ are important
- σ pot. in I=1 is very strong

3. Anti-D meson and nucleon potential



✓ Phase shifts

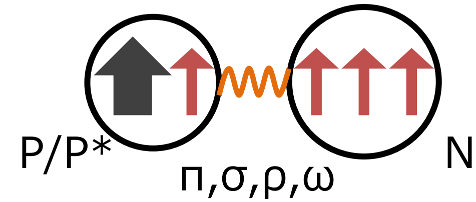


✓ Scattering lengths

$\bar{D}N$	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
	$\bar{D}^*N(^2S_{1/2})$	$0.944 - i0.722$

4. B meson and nucleon potential

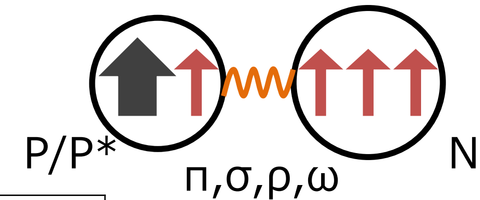
- Same discussion for B meson and nucleon (more ideal for HQS)
- Results (B and N)
  - ✓ Bound states (I=0)



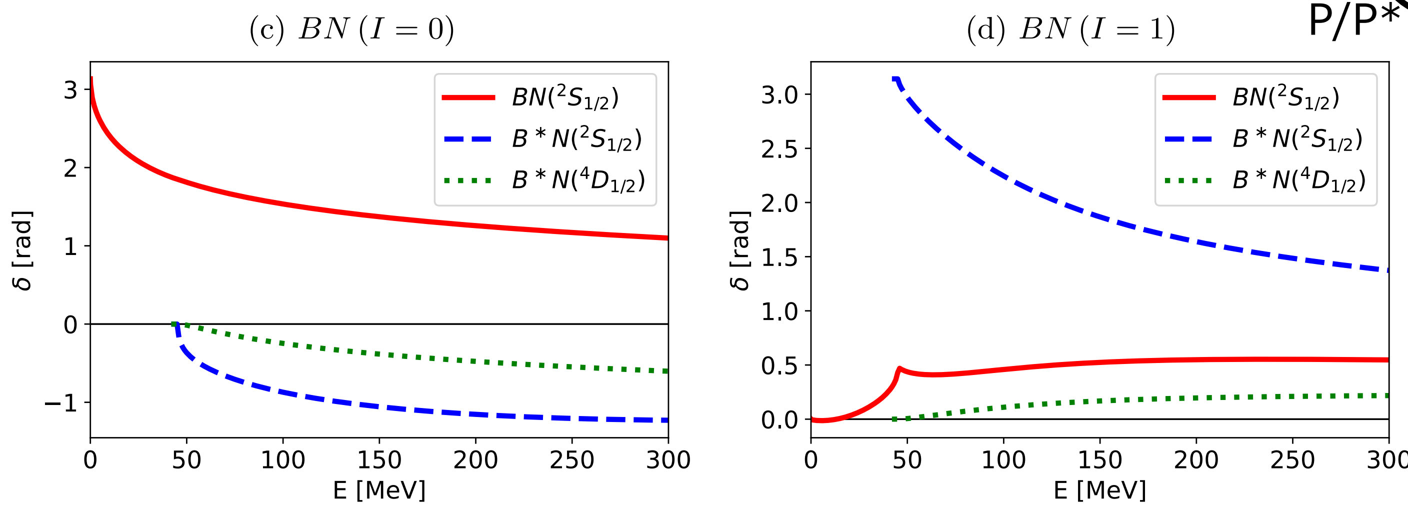
BN	B.E. [MeV]	Mixing ratio [%]	
$0(1/2^-)$	29.7	$BN(^2S_{1/2})$	76.4
		$B^*N(^2S_{1/2})$	14.1
	deep	$B^*N(^4D_{1/2})$	9.46
$1(1/2^-)$	66.0	$BN(^2S_{1/2})$	38.5
		$B^*N(^2S_{1/2})$	61.5
	very deep	$B^*N(^4D_{1/2})$	1.82×10^{-2}

- I=0: deeply bound state (consistent with previous works)
- I=1: more deeply bound state (new!)
- Both π and σ are important
- σ pot. in I=1 is very strongly attractive

4. B meson and nucleon potential



✓ Phase shifts



✓ Scattering lengths

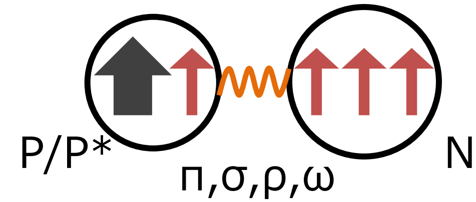
BN		a [fm]
$0(1/2^-)$	$BN(^2S_{1/2})$	1.25
	$B^*N(^2S_{1/2})$	$1.03 - i1.07 \times 10^{-2}$
$1(1/2^-)$	$BN(^2S_{1/2})$	3.84×10^{-2}
	$B^*N(^2S_{1/2})$	$0.263 - i0.585$

✓ Why not to predict BN correlation function for HIC?

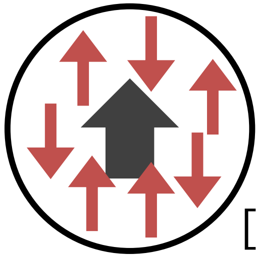
- Very few theory papers on BN interaction yet
- B^0p (I=0, 1)?

5. Discussions

- I=0 spin structures



✓ 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



✓ 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 $P^{(*)}N$ includes mostly the spin-complex $[qN]_j$ with j=1

✓ $[qN]_{j=1}$ is analogue of a deuteron
  - Duality between $P^{(*)}N$ and NN?

5. Discussions

- I=0 spin structures
  - ✓ Calculated mxing ratios
    - Anti-DN($^2S_{1/2}$):anti-D*N($^2S_{1/2}$) = 96:2
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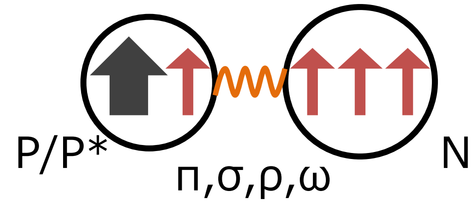
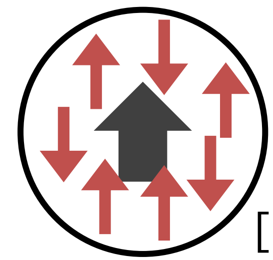
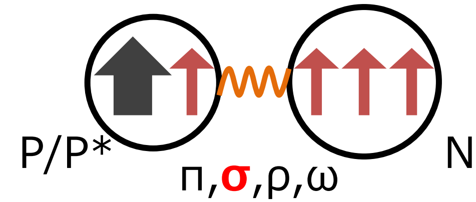
    - Duality between $P^{(*)}N$ and NN?



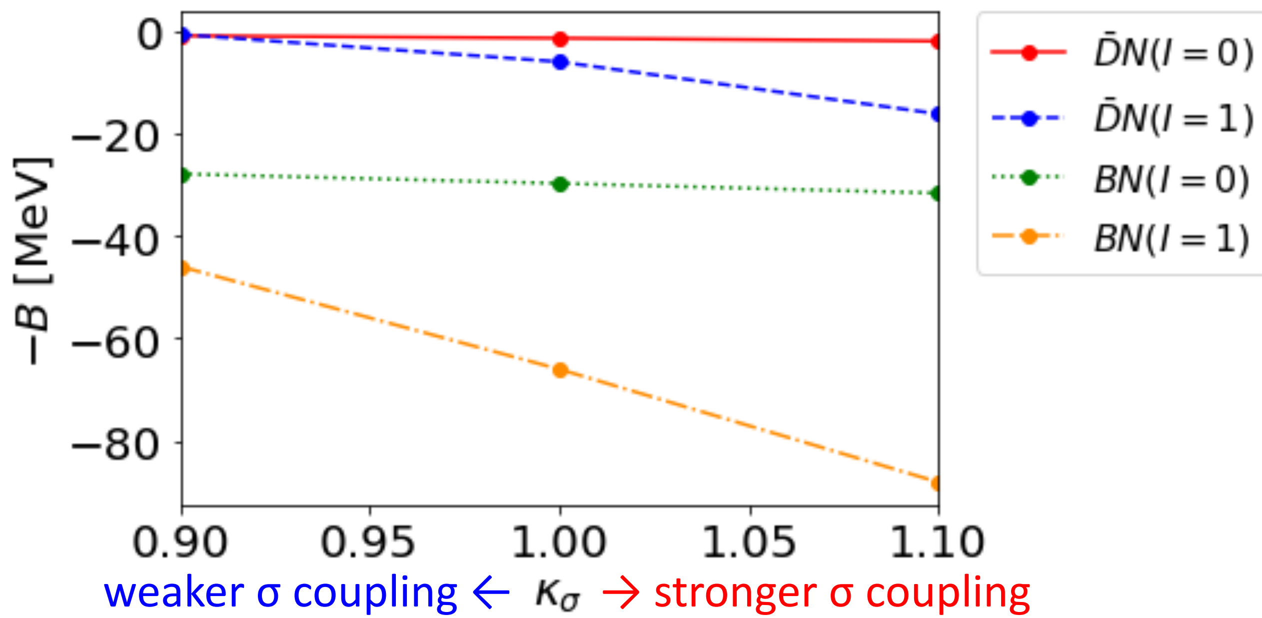


- I=1 spin structures
  - ✓ Calculated mxing ratios
    - Anti-DN($^2S_{1/2}$):anti-D*N($^2S_{1/2}$) = 90:11 (→ j=1)
    - BN($^2S_{1/2}$):B*N($^2S_{1/2}$) = 39:62 (→ j=0)
  - ✓ The spin-complex $[qN]_j$ j=0 is favored in I=1 in HQ limit?

5. Discussions



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



  - Similar results for scattering lengths for PN and P*N
  - ✓ I=0 is less dependent, and I=1 is more dependent.
    - σ is less important in I=0, and more important in I=1

6. Summary

- Anti-D (B) meson and nucleon potential (χ and HQS symmetries)

- We considered π, σ, ρ, ω exchanges by reference to CD-Bonn pot.

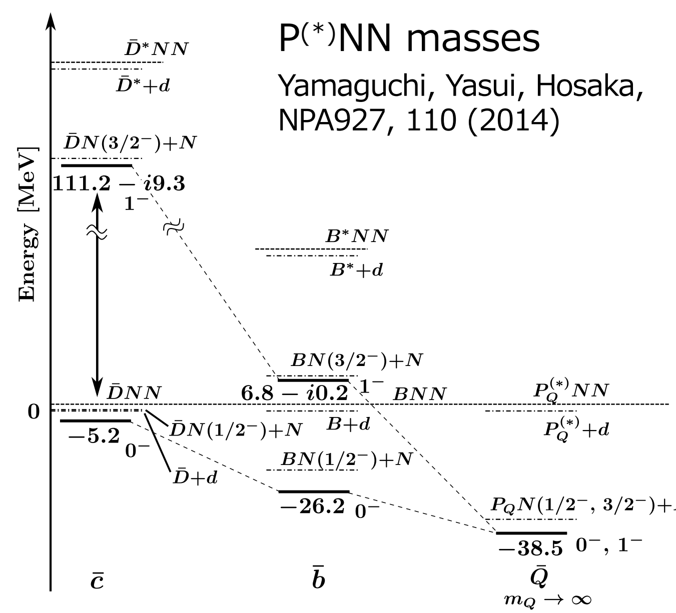
- Bound states in anti-D meson and nucleon with $I(J^P)=0(1/2^-)$, $1(1/2^-)$

- More deeply bound states in 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 $I(J^P)$?
  - ✓ D_s^-N ? Anti-DΛ ? (from u,d to u,d,s)
  - ✓ lattice QCD?
  - ✓ More states in bottom?
  - ✓ Multi-baryons : $P^{(*)}NN$, $P^{(*)}α$??
  - ✓ Anti-charm, bottom nuclei???

P$^{(*)}$NN masses

Yamaguchi, Yasui, Hosaka, NPA927, 110 (2014)



Thanks!