Hadronic molecular states of heavy meson-nucleon systems

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in collaboration with

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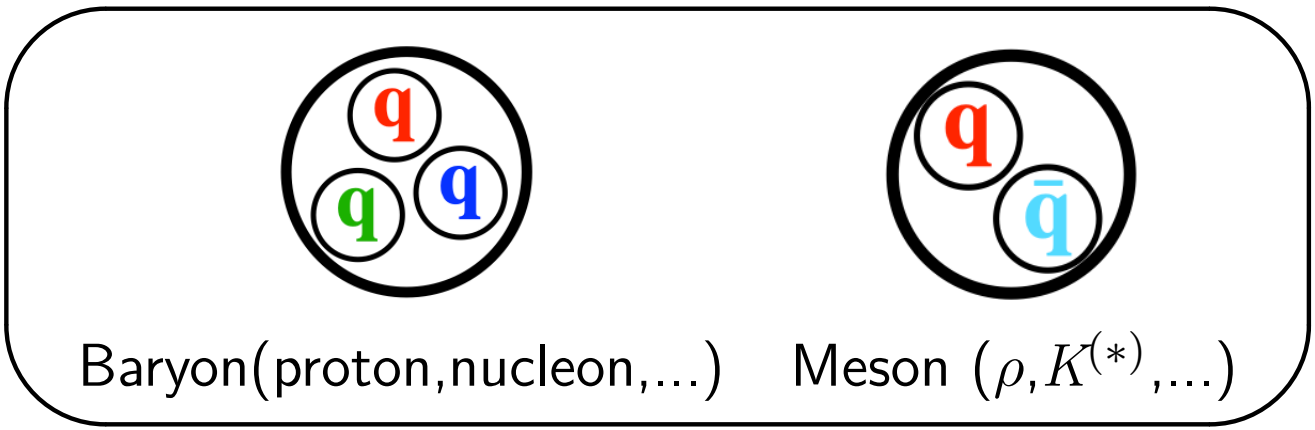
Hadron structure: Constituent quark model

- Hadron = Quark composite system
- Ordinary Hadrons: Baryon (qqq) and Meson ($q\bar{q}$)



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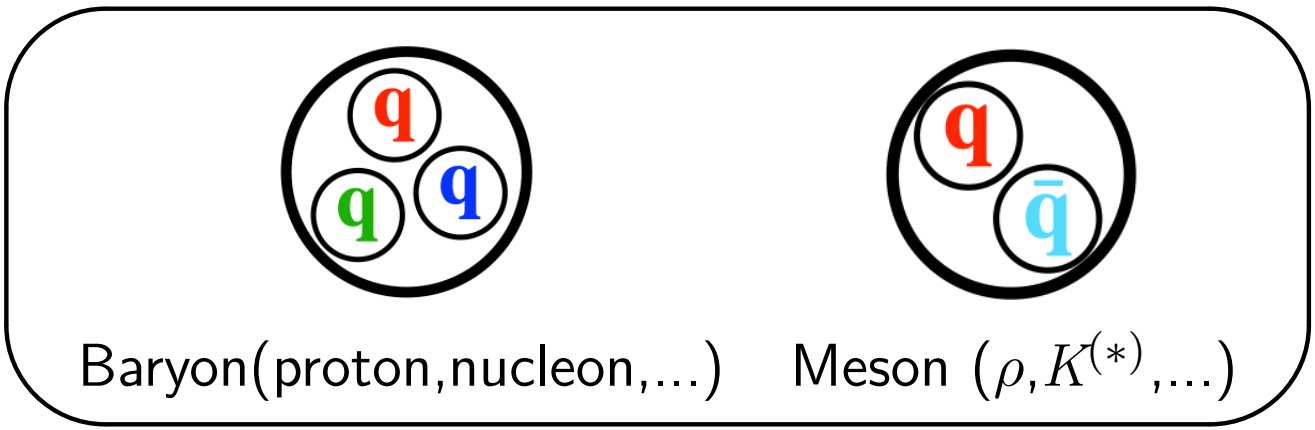
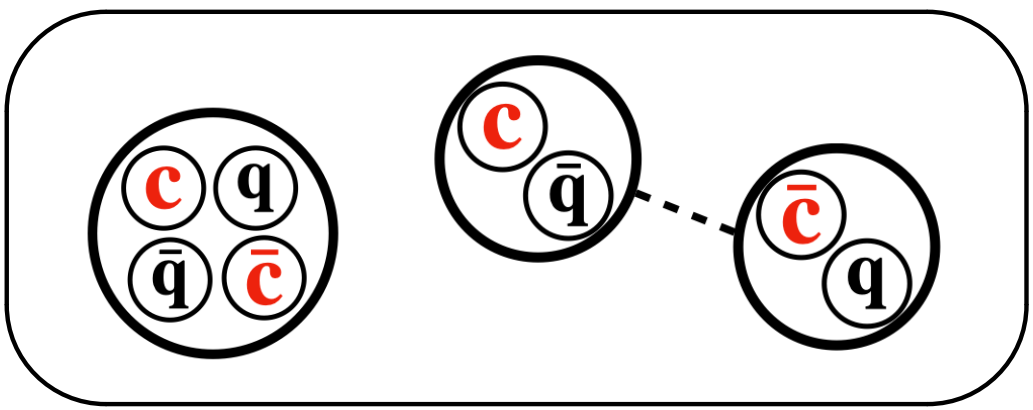
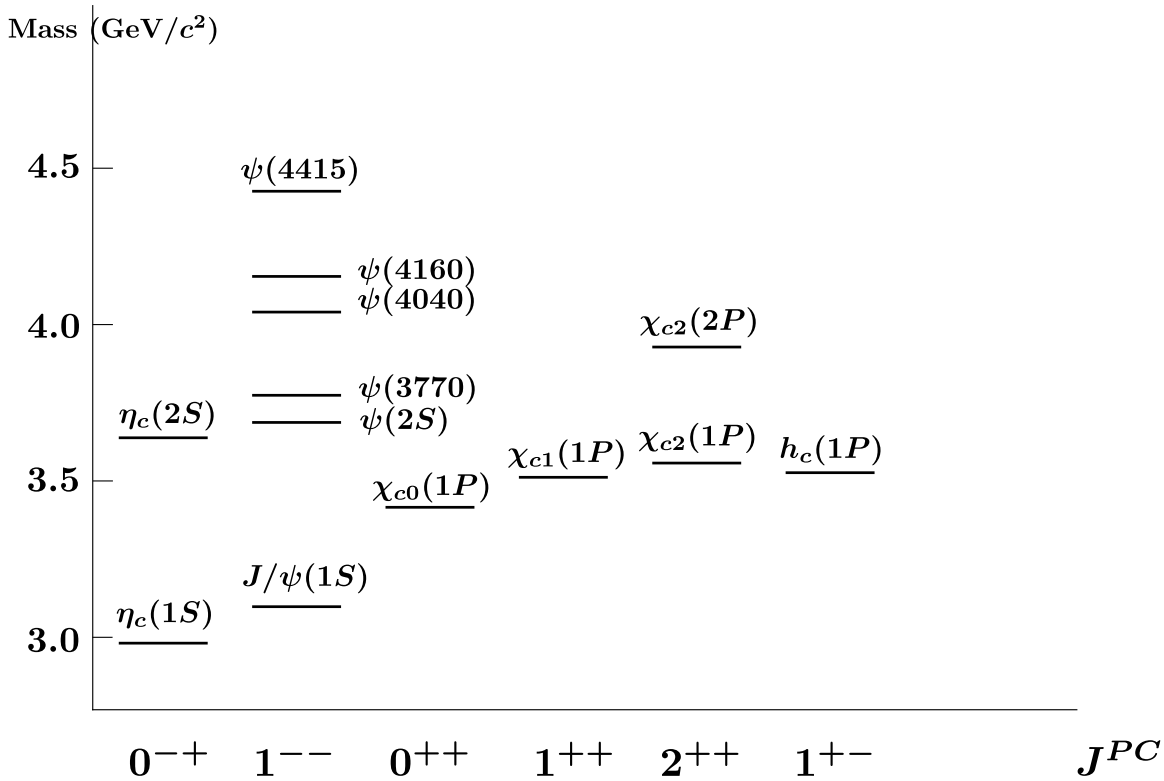


- Exotic Hadrons ($\neq qqq,\ q\bar{q}$): **Multiquark? Multihadron?**



Observations of exotic hadrons containing $c\bar{c}$

- e.g. $c\bar{c}$ mesons (Charmonium) sector



one-g exchange

$+$

Confinement

$\Downarrow$

$$V(r) = -\frac{\alpha_s}{r} + cr + \ldots$$

N. Brambilla,*et al.* Eur.Phys.J.C **71**(2011)1534, S. Godfrey and N. Isgur, PRD**32**(1985)189

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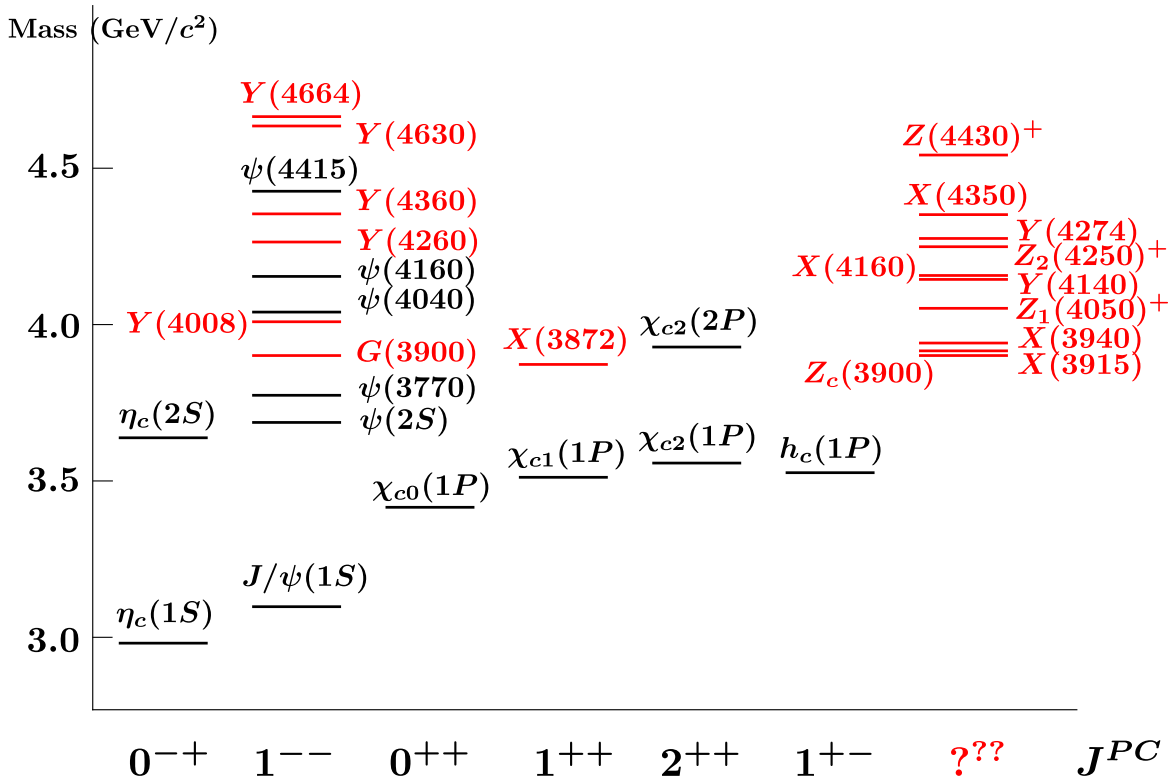

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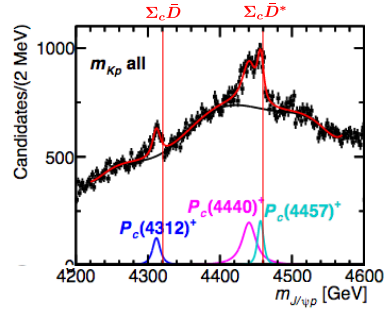
- Many Exotics $\neq c\bar{c}$ have been observed in the Experiments (BaBar, Belle, BESIII, LHCb,...) since the discovery of **$X(3872)$ in 2003!**

Recent reports of exotic hadrons

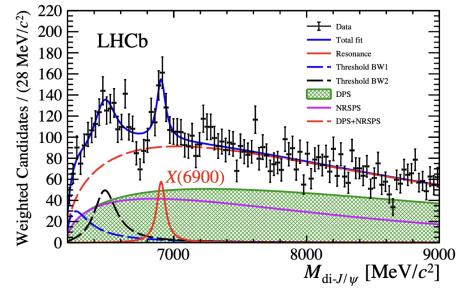
- **2019:** $P_c(4312)$, $P_c(4440)$, $P_c(4457)$
  LHCb, PRL**122**(2019)222001
- **2020:** $X(6900)$, $X_{0,1}(2900)$
  LHCb, Science Bulletin 65 (2020) 1983, PRL125, 242001 (2020), PRD102, 112003 (2020)
- **2021:** Z_{cs}, P_{cs}
  BESIII PRL126, 102001 (2021), LHCb Sci.Bull.**66**(2021)1278
- **2022:** $P_c(4337)$, T_{cc}^+, $P_{cs}(4338)$, $T_{cs}(2900)$
  LHCb, PRL**128**(2022)062001, Nature Phys. **18** (2022) 751-754, Nature Commun. **13** (2022) 3351
- **2023:** $T^{\theta}_{\psi s1}(4000)^0$, **2024:** $h_c(4300)$
  LHCb, arXiv:2301.04899[hep-ex], LHCb arXiv:2406.03156

- New exotic hadrons have been reported Every Year, especially at **Large Hadron Collider (LHC)**
- One of the important topics in the hadron spectroscopy!

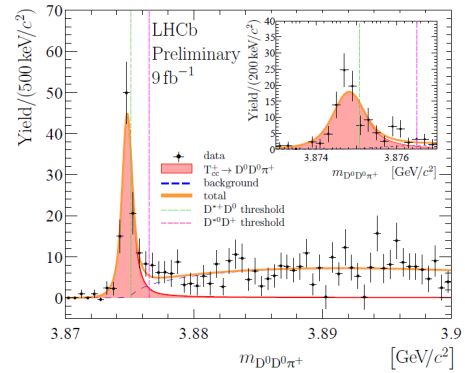
P_c



$X(6900)$



T_{cc}



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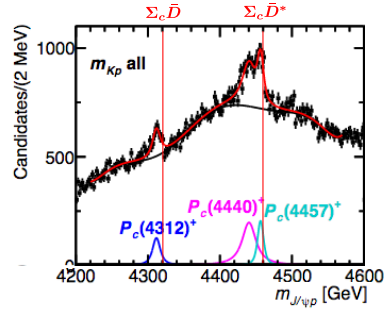

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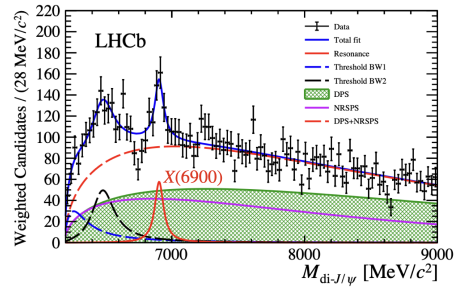

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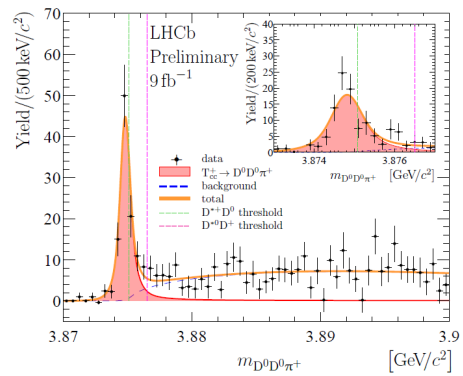
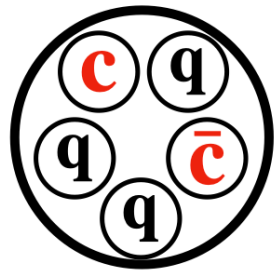


Candidates of Exotic structures?

Compact multiquarks



Tetraquark

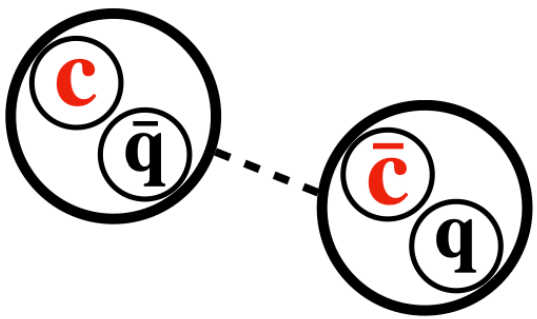


Pentaquark

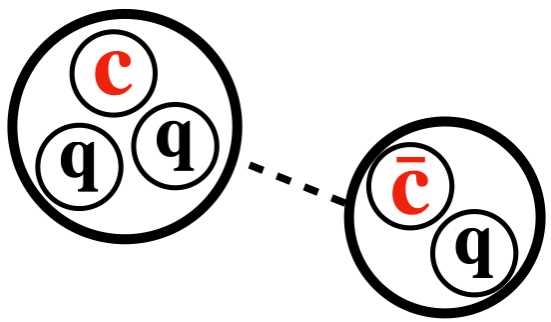
- Exotics as multiquarks
- Mixture of compact and molecular states has also been studied

Hadronic molecules

Near thresholds?



Meson-Meson



Meson-Baryon

Triangle Singularity

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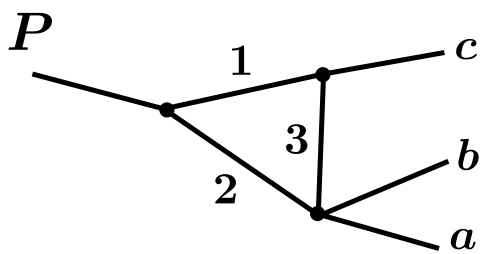

(w/o Resonance)

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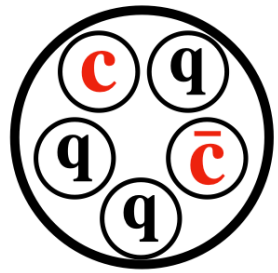

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- Triangle singularity producing a peak structure $\neq$ a resonance

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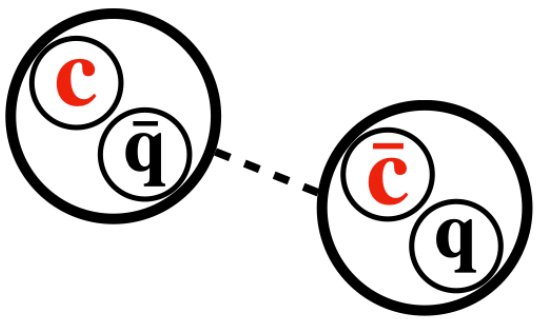

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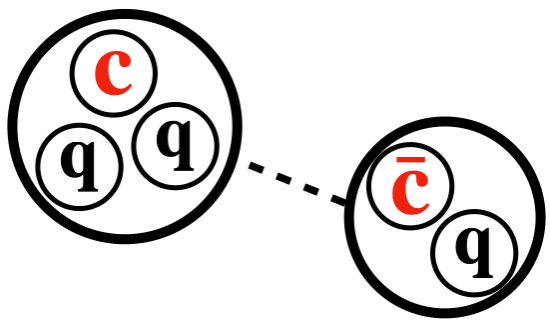

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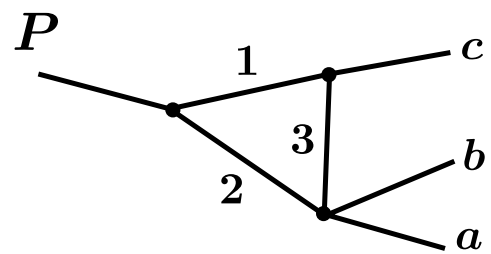

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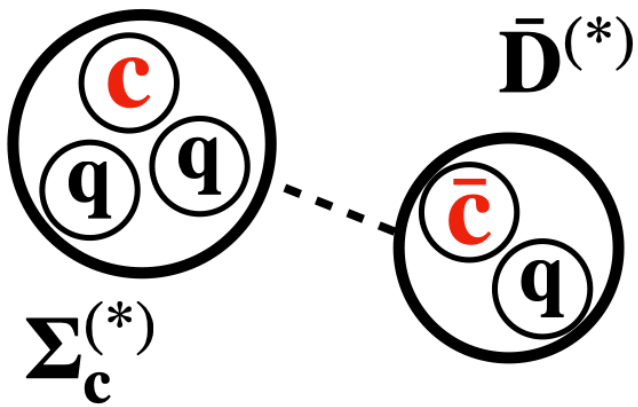
Hadronic molecules?

- Exotics as Hadronic molecule $\Rightarrow$ Hadron (quasi) bound state

$\rightarrow$ expected **near the thresholds**



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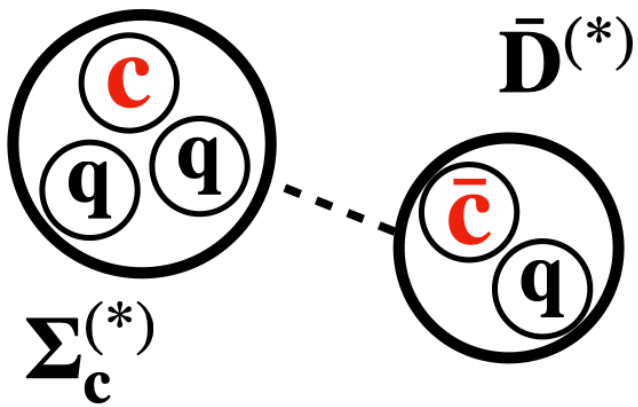
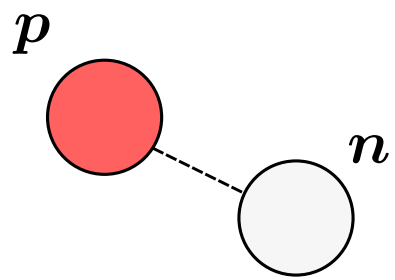


Analogous to Deuteron



$B = 2.2$ MeV

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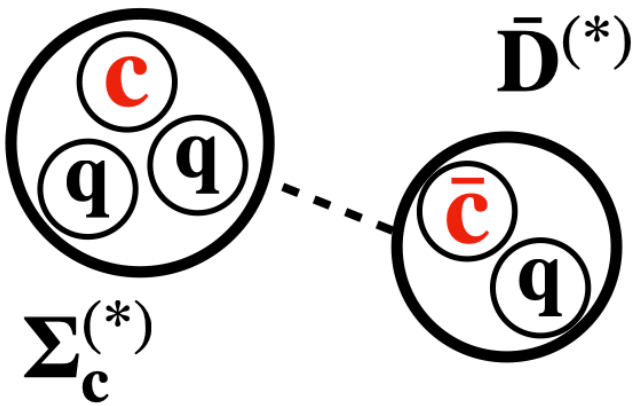
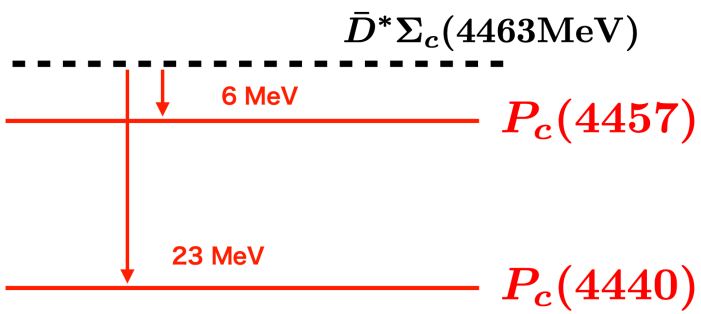
$P_c = \bar{D}^{(*)}\Sigma_c^{(*)}$ molecules?





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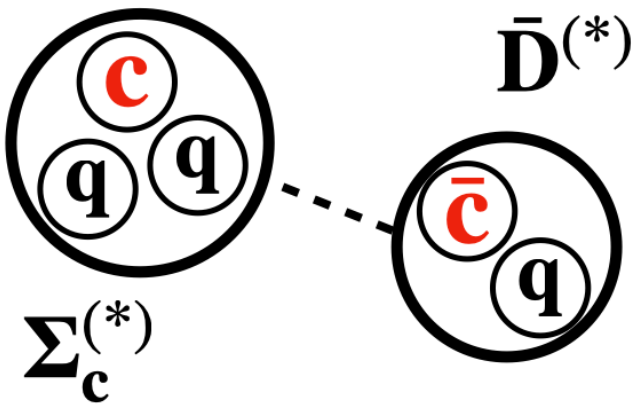

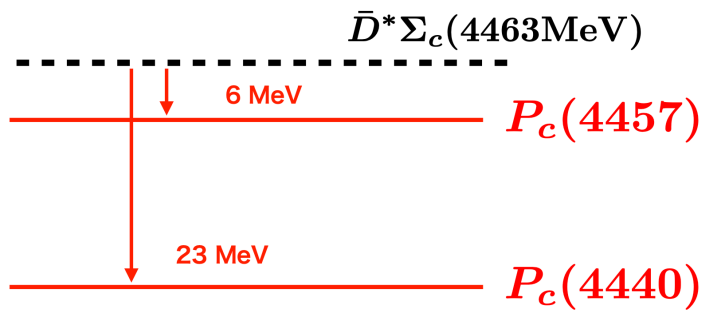

- Exotic hadrons near thresholds
  - $D\bar{D}^*$: $X(3872)$, $Z_c(3900)$,..., DD^*: T_{cc}
  - $B\bar{B}^*$: Z_b, $Z_b{}'$
  - $\bar{D}^{(*)}\Sigma_c^{(*)}$: P_c F. K. Guo, *et. al.*, Rev.Mod.Phys.**90**(2018)015004,Y. Y., *et. al.*, J.Phys.G**47**(2020)053001,...

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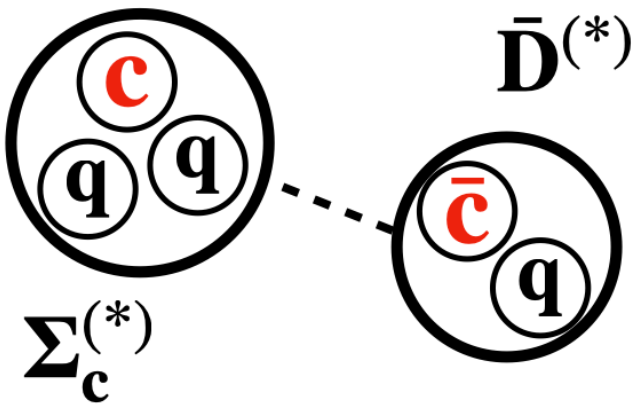

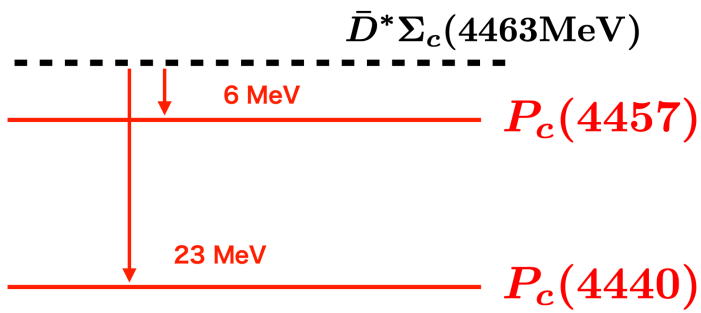

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Q. What is an interaction binding the constituent hadrons?

Hadron interactions

Problem Hadron interactions are **NOT established** yet...
due to the lack of the hadron-scattering data

($\leftrightarrow$ Lattice QCD, Femtoscopy, etc near future!)

How can we describe hadron interactions?

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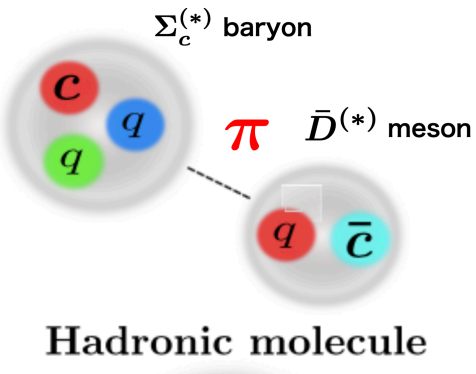
- Long-range int. known in the nuclear force !
- Chiral and Heavy quark spin symmetries



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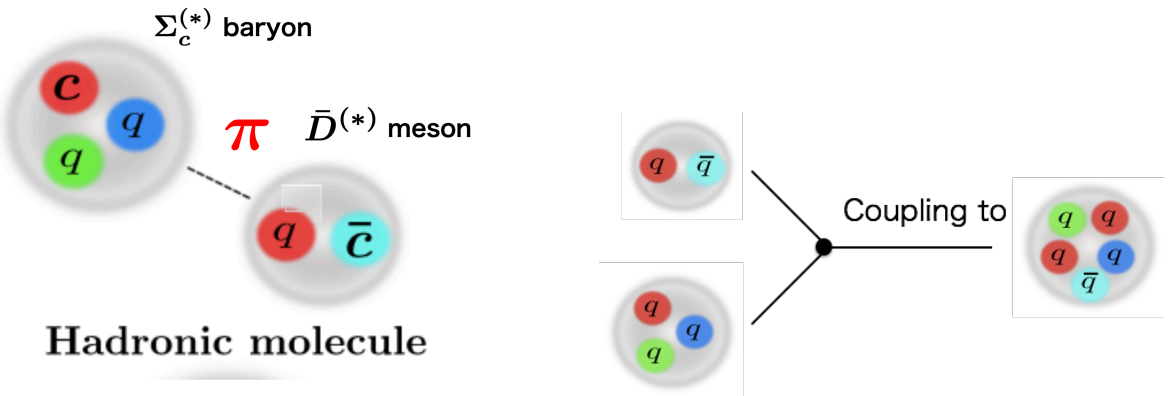
Short-range int. Many models

- ρ, ω, σ meson exchanges (analogy to Nuclear force)
- Quark exchanges, Mixing of Compact state, etc.



Hadronic molecules of $D^{(*)}$ mesons

- **Hadronic moleule** as an exotic hadron
  = Hadron-hadron bound state near thresholds?

  Reviews: Y.Y *et.al.*,J.Phys.G**47**(2020)053001, H.-X. Chen, *et.al.*, Rept. Prog. Phys. **86** (2023), 026201 ,...

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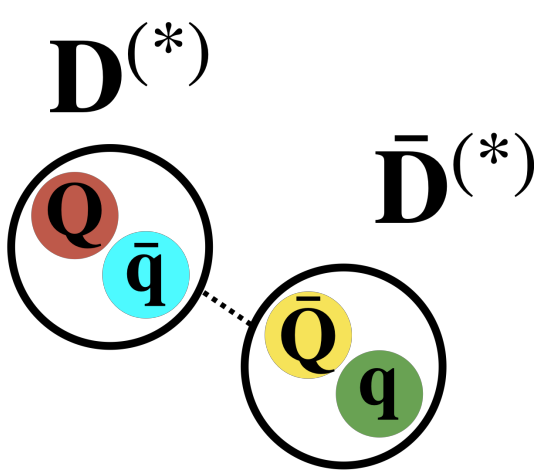
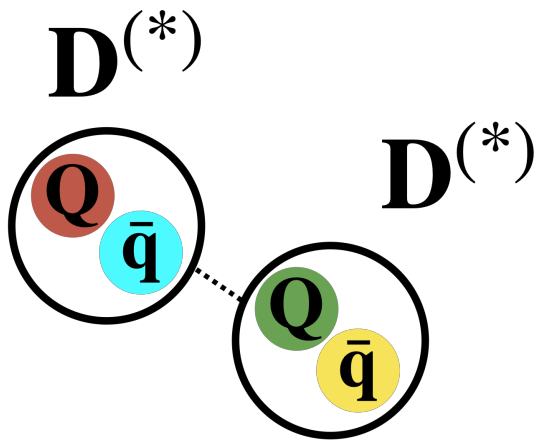


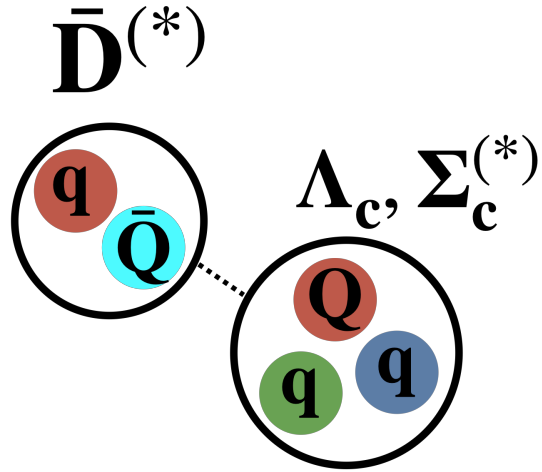
Hidden-charm tetraquark

XYZ



Doubly-charmed tetraquark

T_{cc}



Hidden-charm pentaquark

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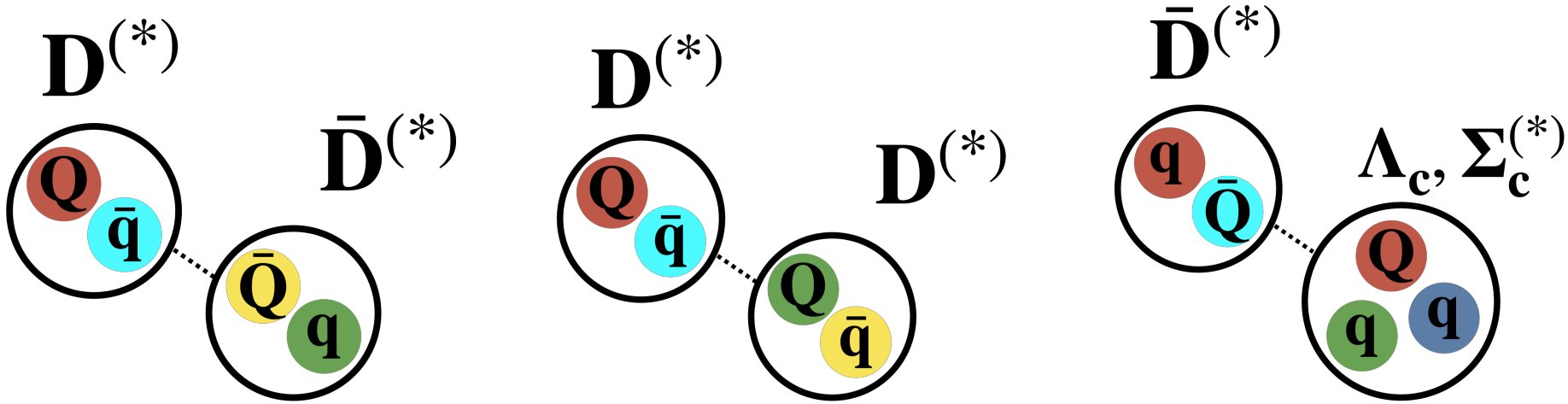


Hidden-charm tetraquark XYZ

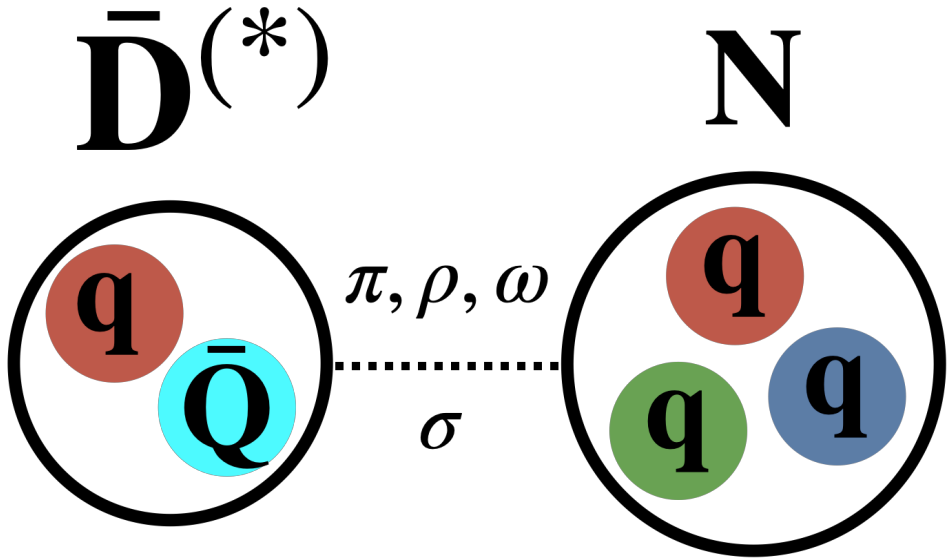
Doubly-charmed tetraquark T_{cc}

Hidden-charm pentaquark P_c, P_{cs}

- **Importance of the D meson interactions!**

  $\Leftrightarrow$ K interactions, Hyperon interactions,... **in the strangeness sector**

$\bar{D}$ meson-Nucleon systems



$\bar{D}$ meson-Nucleon systems

- **Genuine Exotic pentaquark channel**

  $\bar{D}(\bar{c}q) + N(qqq) \Rightarrow$ Minimal quark content $\boldsymbol{\bar{c}qqqq}$ (No $q\bar{q}$ annihilation)

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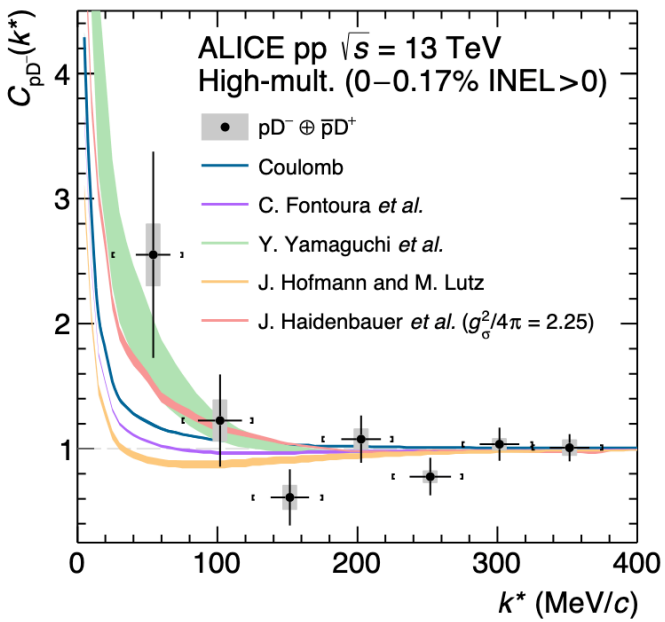

S. Acharya *et al.* [ALICE], Phys.Rev.D 106 (2022) 052010

Model	$a(I=0)$ [fm]	$a(I=1)$ [fm]	
Yamaguchi et al.	-4.38	-0.07	**Bound state**
Haidenbauer et al.	0.67	0.04	**Attractive**
Fontoura et al.	0.16	-0.25	**Attractive**
Hofmann and Lutz	-0.16	-0.26	**Repulsive**

- ALICE data is consistent with the attractive models?

$$a_{I=0}^{-1} \in [(-2.5)^{-1}, (1.1)^{-1}] \text{ fm}^{-1}$$

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  H1 Collaboration, Phys.Lett.B 588 (2004) 17

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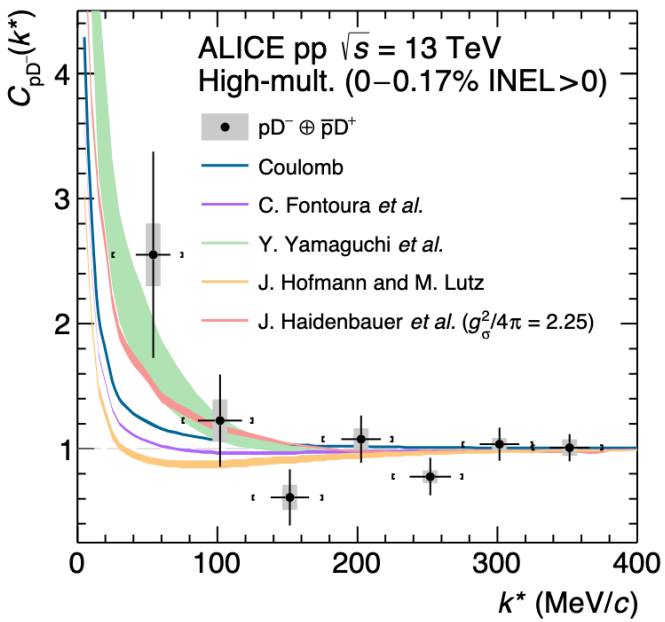


S. Acharya *et al.* [ALICE], Phys.Rev.D 106 (2022) 052010

Model	$a(I=0)$ [fm]	$a(I=1)$ [fm]	
Yamaguchi et al.	-4.38	-0.07	**Bound state**
Haidenbauer et al.	0.67	0.04	**Attractive**
Fontoura et al.	0.16	-0.25	**Attractive**
Hofmann and Lutz	-0.16	-0.26	**Repulsive**

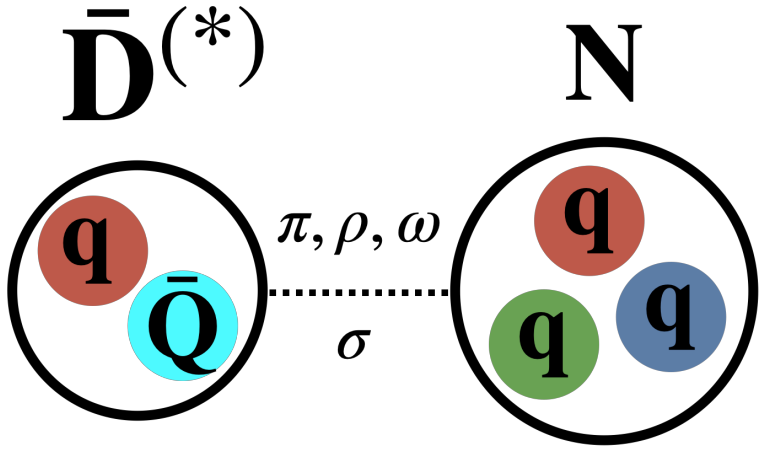
- ALICE data is consistent with the attractive models?

$$a_{I=0}^{-1} \in [(-2.5)^{-1}, (1.1)^{-1}] \text{ fm}^{-1}$$

- Recent Lattice QCD: $\bar{D}N$ potential by HALQCD

  W. Yamada *et al.*, arXiv:2603.12251 [hep-lat]

Construction of the $\bar{D}N$ interaction



- Heavy quark spin symmetry ($\bar{D} - \bar{D}^*$ mixing) + Realistic NN interaction

  Y.Y, Shigehiro Yasui, Atsushi Hosaka, Phys. Rev. D 106, 094001 (2022)

  - CD-Bonn potential as the NN int is employed R. Machleidt, PRC**63**(2001)024001

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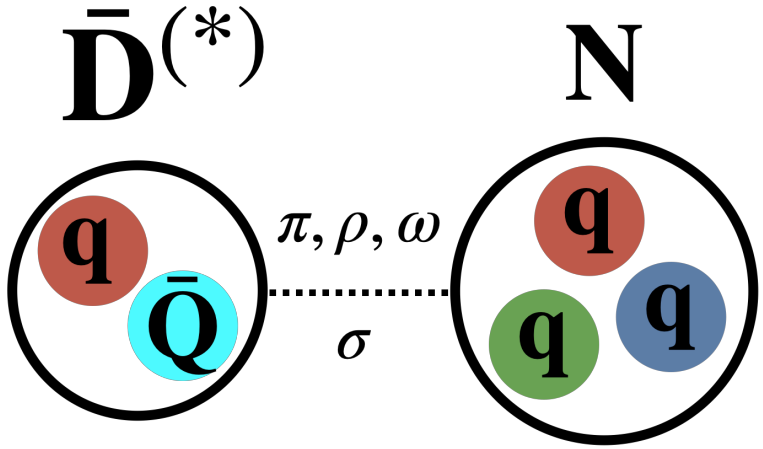

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  - CD-Bonn potential as the NN int is employed R. Machleidt, PRC**63**(2001)024001
  - $\pi + \rho, \omega, \sigma$ exchanges are introduced

    - **The π exchange (Tensor)** is the driving force to bind Deuteron

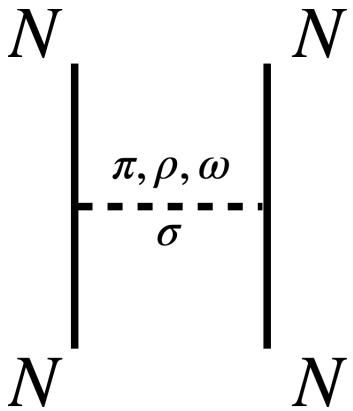
    - **The σ exchange** also generates the attraction $\rightarrow$ important to explain both $I = 0, 1$ NN scattering data simultaneously,

    while there is **ambiguity in V_σ.**

CD-Bonn potential $\longrightarrow$ Simplified CD-Bonn

R. Machleidt, PRC**63**(2001)024001

- Realistic NN potential having the meson exchanges $\pi, \rho, \omega, \sigma$
- Complicated structures of the CD-Bonn, introducing light and heavy "σ_I's", Non-locality,... σ_0 for $I = 0$ and σ_1 for $I = 1$



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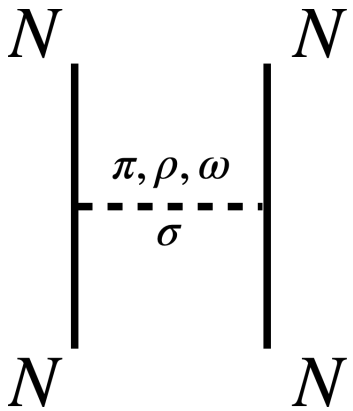

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$\Rightarrow$ Obtaining a simplified NN potential in this work,

- employing the light "σ" and the local approximation
- Keeping the coupling constants, but rescaling the cutoffs $\Lambda_N \rightarrow \kappa_I \Lambda_N$

CD-Bonn parameters

Mesons	Masses [MeV]	$\frac{g^2_{\alpha NN}}{4\pi}$	$\frac{f_{\alpha NN}}{g_{\alpha NN}}$	Λ_N [MeV]	
				$I=0$	$I=1$
π	138.04	13.6	—	1384	1330
ρ	769.68	0.84	6.1	1054	1013
ω	781.94	20	0.0	1207	1159
σ_0	350	0.51673	—	2011	—
σ_1	452	3.96451	—	—	1932

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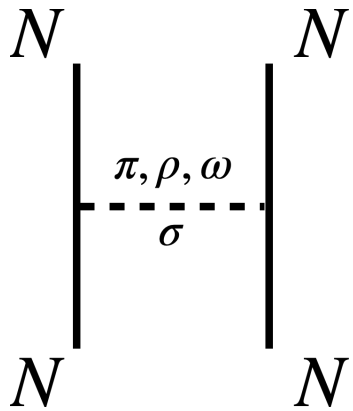

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$$\boldsymbol{\kappa_{I=0} = 0.80,\ \kappa_{I=1} = 0.77}$$

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Results of the Simplified CD-Bonn

	Simplified CD-Bonn	Exp
B_d [MeV]	2.23 (input)	2.23
a_0 [fm]	5.30	5.42
r_{e0} [fm]	1.56	1.75
a_1 [fm]	-23.7 (input)	-23.7
r_{e1} [fm]	2.34	2.77

The NN properties are reproduced!

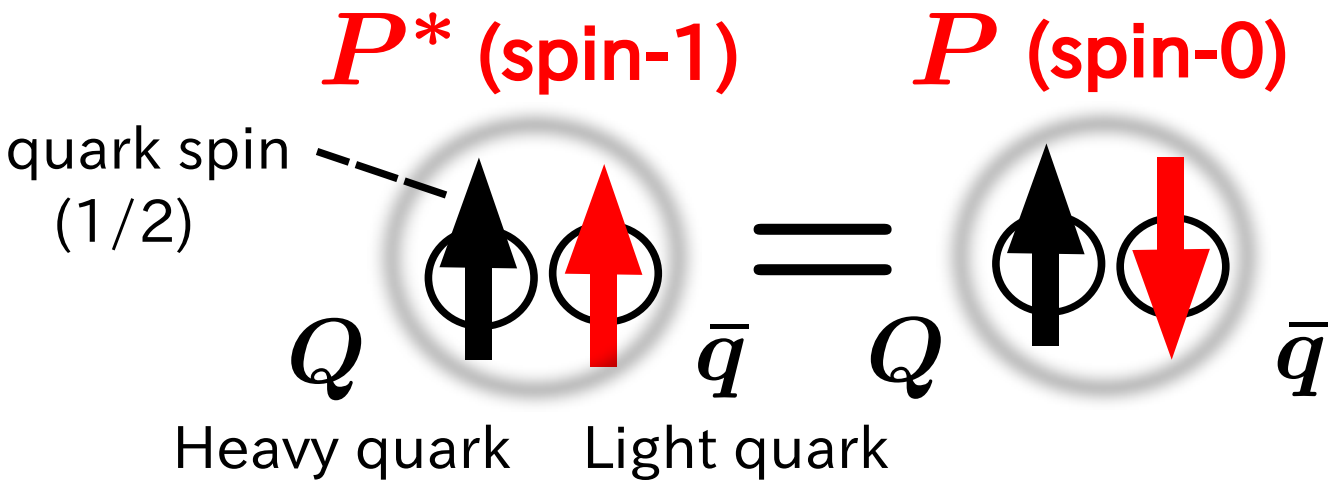
Heavy Quark Spin Symmetry and Mass degeneracy

Heavy Quark Spin Symmetry (HQS) N.Isgur,M.B.Wise,PLB**232**(1989)113

- **Suppression of Spin-spin force** in $m_Q \to \infty$.

  $\Rightarrow$ **Mass degeneracy** of hadrons with the different J

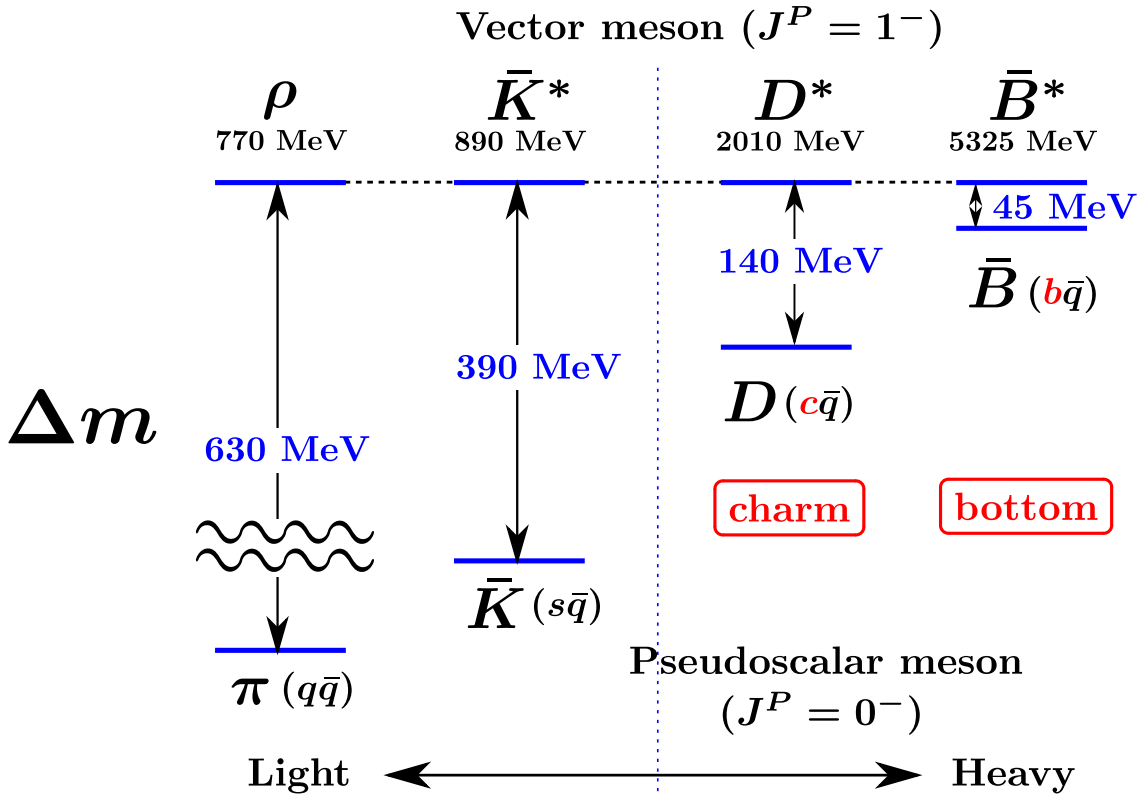
- e.g. $Q\bar{q}$ meson



$\Rightarrow$ Mass degeneracy of spin-0 and spin-1 states!

Mass degeneracy of heavy hadrons

- Mass difference between vector and pseudoscalar mesons. $(Q\bar{q},\ q = u, d)$



- Δm decreases when the quark mass increases.

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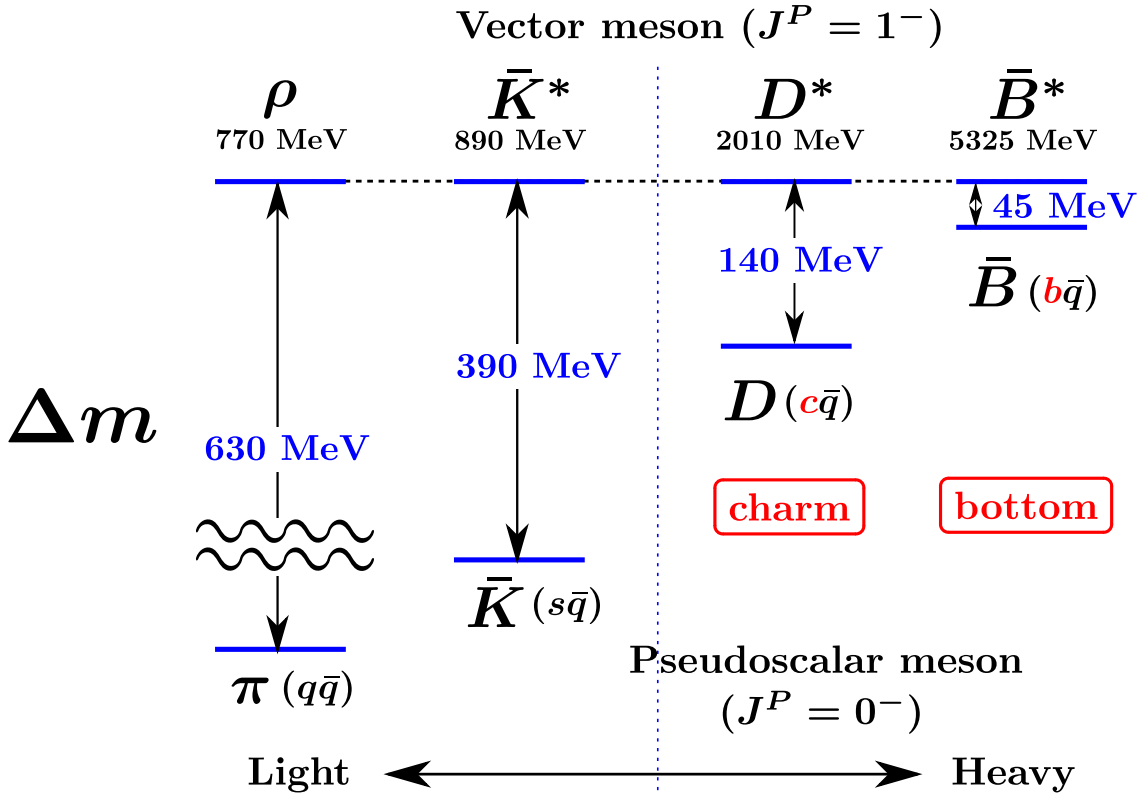


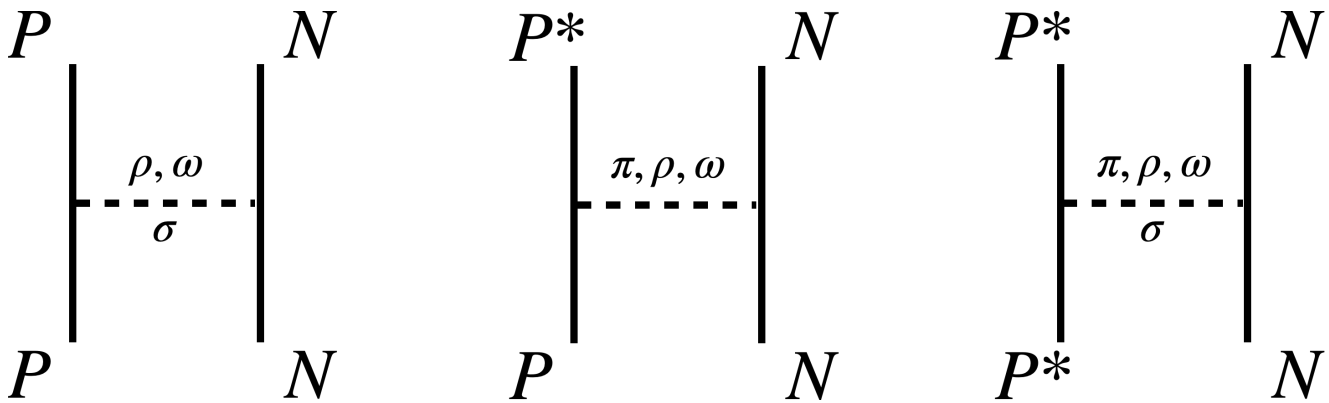
- Δm decreases when the quark mass increases.
  $\Rightarrow$ **Degeneracy of Heavy hadrons!**

Heavy Quark Spin Symmetry $\Rightarrow$ $D - D^*$ **mixing is induced!**

Heavy meson-Nucleon interactions

- $DD\pi$ vertex is forbidden due to the parity conservation. $\rightarrow$ No OPEP in the $\bar{D}N$ int.
- Small $\Delta m_{\bar{D}\bar{D}^*} \sim 140$ MeV (Heavy quark spin symmetry) induces the $\bar{D}N - \bar{D}^*N$ channel-coupling interactions $\rightarrow$ enhancing the **π exchange**

T. D. Cohen, P. M. Hohler and R. F. Lebed, PRD **72**(2005)074010, S. Yasui and K. Sudoh, PRD **80**(2009)034008.



ρ, ω, σ exchanges **π exchange!**

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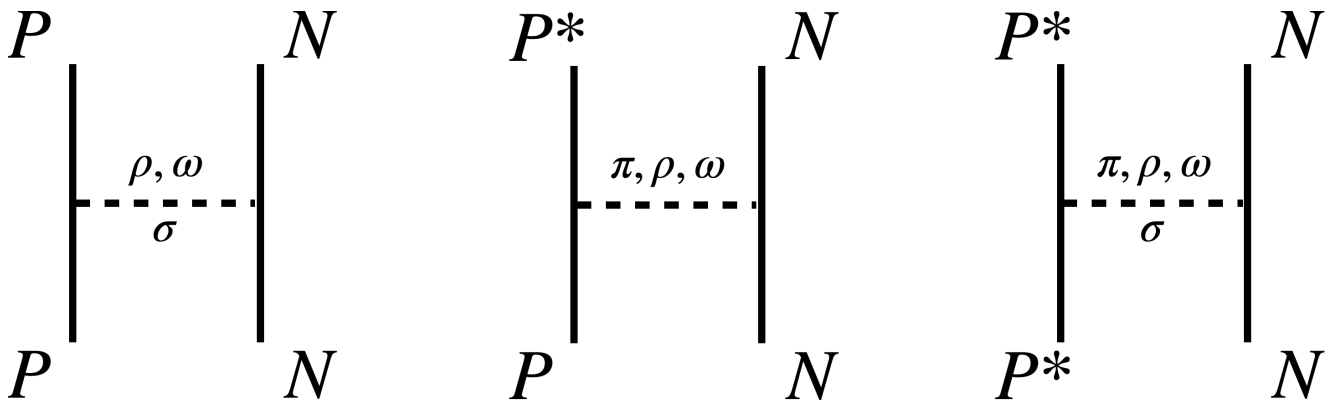
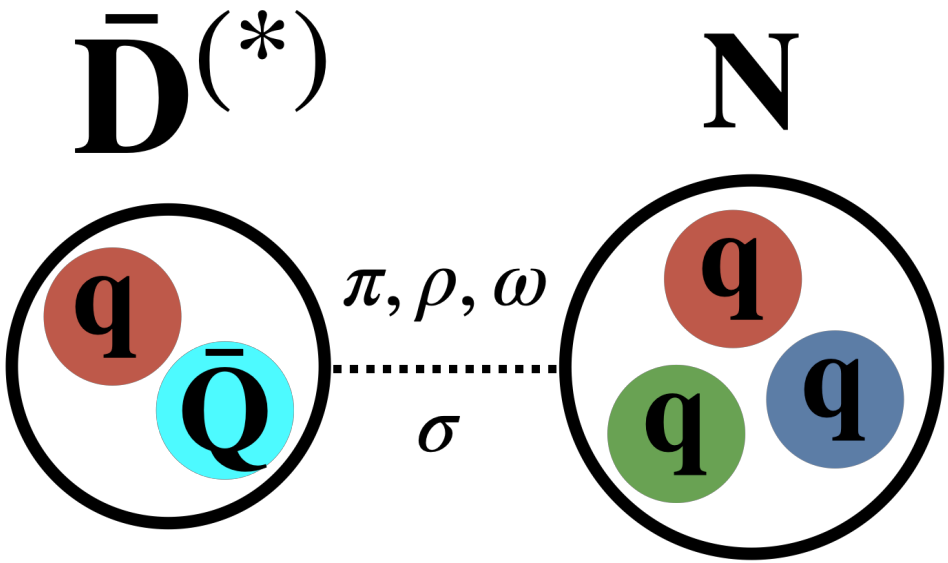


ρ, ω, σ exchanges **π exchange!**

- Parameters
  - $g_{\pi D} = 0.59$ ($D^* \rightarrow D\pi$), $\beta_v = 0.9$, $\lambda = 0.56$ [GeV^{-1}] (B decay)
  - $\boldsymbol{g_{\sigma D} = g_{\sigma NN}/3}$ (σ couples to q in $P(\bar{Q}q)$) $\rightarrow$ We will see the $g_{\sigma D}$ dependence
  - Cuttoff: $\Lambda_D = 1.35\Lambda_N$ from the hadron size

Numerical results



- Solving the coupled-channel Schrödinger equations with the constructed meson exchange potentials.

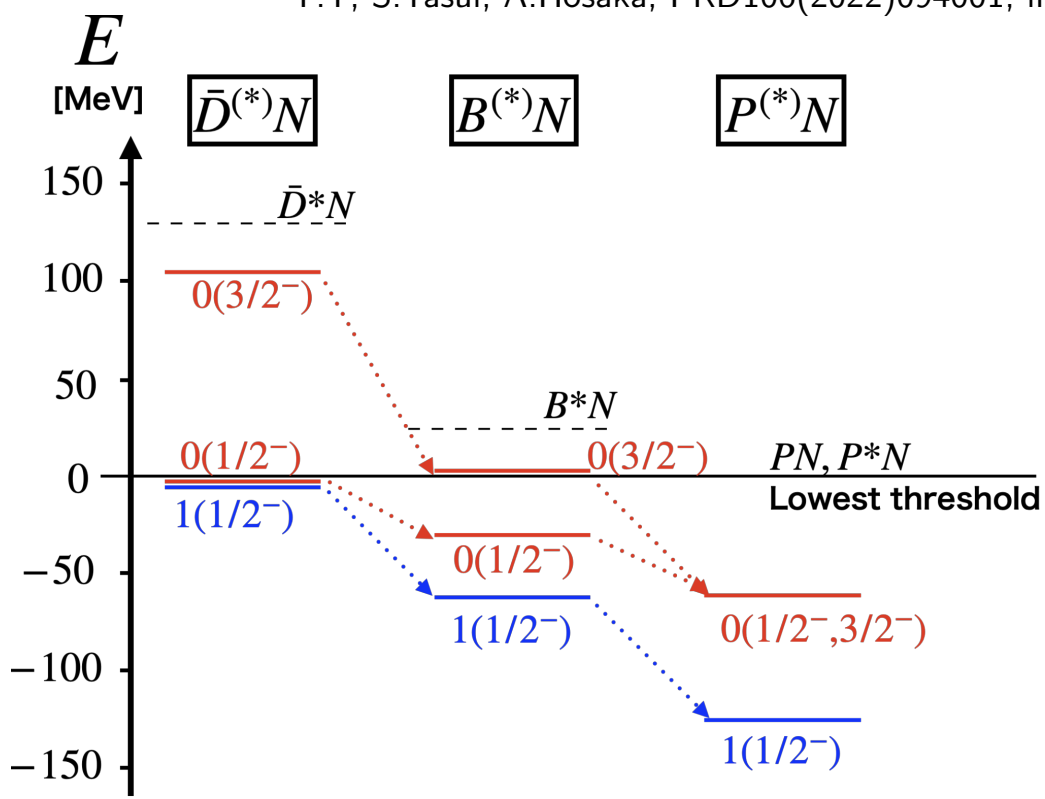
  $J^P = 1/2^-$: $\bar{D}N(^2S_{1/2}), \bar{D}^*N(^2S_{1/2}, ^4D_{1/2})$ **3 channels**

  $J^P = 3/2^-$: $\bar{D}N(^2D_{3/2}), \bar{D}^*N(^4S_{3/2}, ^4D_{3/2}, ^2D_{3/2})$ **4 channels**

- Studying Bound and Resonant states for $\bar{D}N$, BN and PN (heavy quark limit) systems

Summary of numerical results for $\bar{D}N$, BN and PN

Y.Y, S.Yasui, A.Hosaka, PRD106(2022)094001, in preparation



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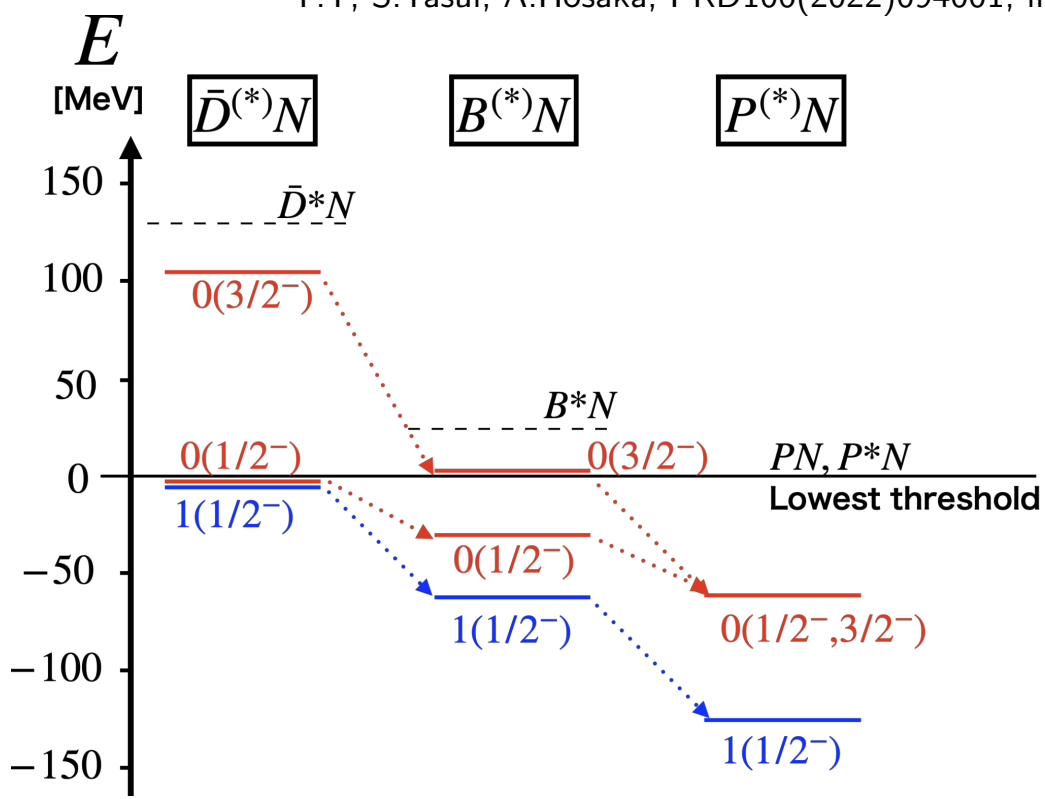

- For $I = 0$, **$1/2^-$ bound states and $3/2^-$ Feshbach resonances** are obtained in $\bar{D}N$ and BN

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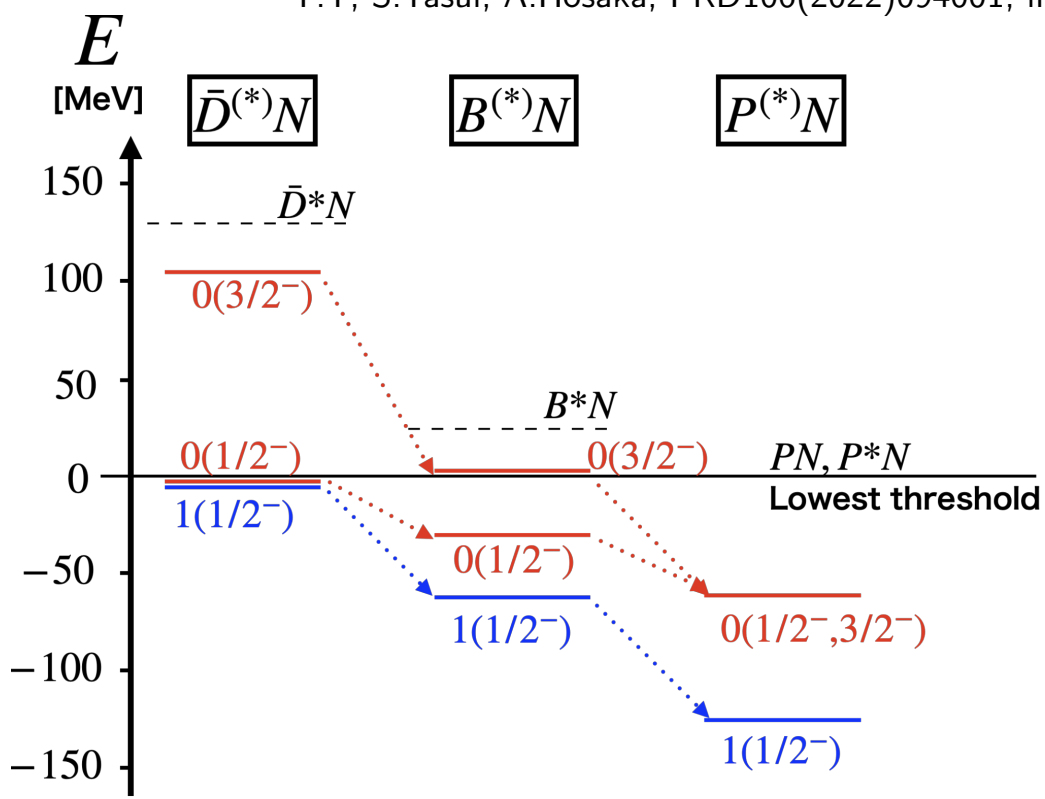

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$\Rightarrow$ Degenerate in the heavy quark limit $(PN) \to$ **HQS doublet** with $j_\ell = 1$
(j_ℓ: the total angular momentum of the light cloud)

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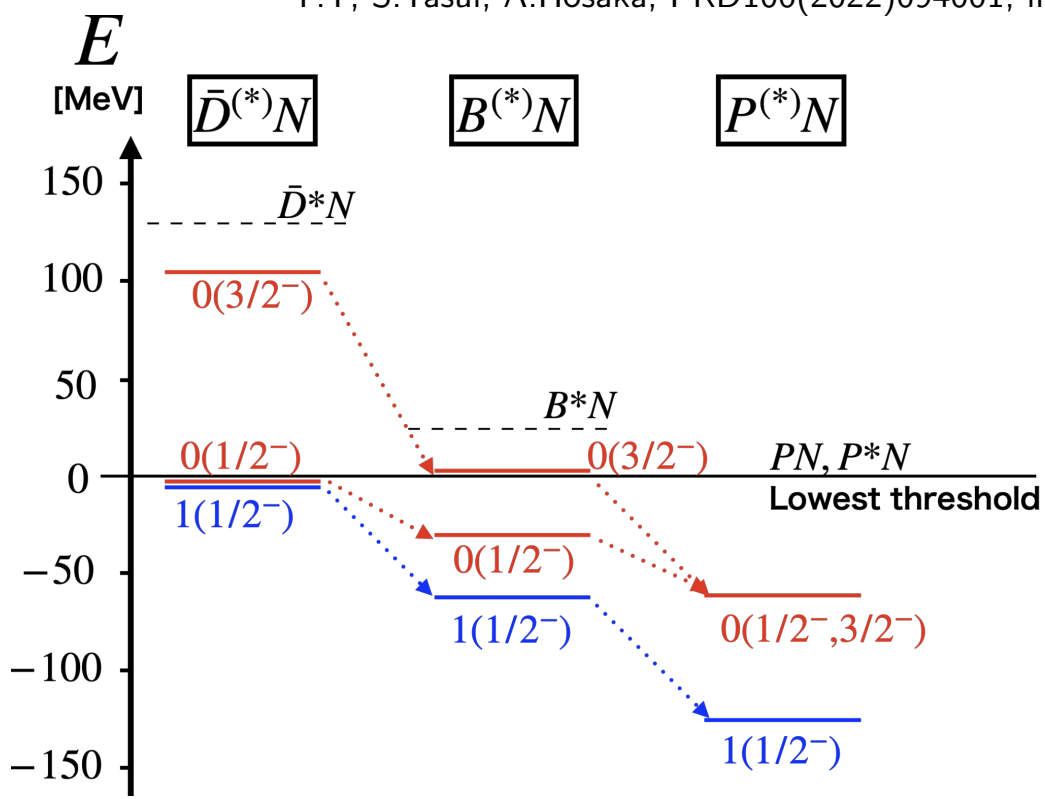

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(j_ℓ: the total angular momentum of the light cloud)

- For $I = 1$, **$1/2^-$ bound states $\Rightarrow$ HQS singlet** with $j_\ell = 0$

Numerical results of the $\bar{D}^{(*)}N$ state for $I(J^P) = 0(1/2^-)$

- Bound state

Numerical results of the $\bar{D}^{(*)}N$ state for $I(J^P) = 0(1/2^-)$

- Bound state **is found!** $\rightarrow$ Binding energy $=$ **1.38 MeV**
- Mixing ratio
  $\Rightarrow$ $\bar{D}N(^2S_{1/2})$: 96.1%, $\bar{D}^*N(^2S_{1/2})$: 1.94%, $\bar{D}^*N(^4D_{1/2})$: 1.93%
  Major component **Not negligible**

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- Potential energy expectation values $\langle V \rangle$

$\langle V_\pi \rangle$ (-38.61)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	0.0	-0.79	-17.35
$\bar{D}^*N(^2S_{1/2})$	-0.79	0.28	-3.20
$\bar{D}^*N(^4D_{1/2})$	-17.35	-3.20	3.79

$\langle V_{\rho+\omega} \rangle$ (7.34)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	7.05	-3.89	2.62
$\bar{D}^*N(^2S_{1/2})$	-3.89	2.44	0.49
$\bar{D}^*N(^4D_{1/2})$	2.62	0.49	-0.58

$\langle V_\sigma \rangle$ (-5.25)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	-4.46	—	—
$\bar{D}^*N(^2S_{1/2})$	—	-0.48	—
$\bar{D}^*N(^4D_{1/2})$	—	—	-0.31

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V_π tensor

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V_ρ spin-spin

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V_σ

Phase shifts of the $J^P = 3/2^-$ states with $I = 0$

- $J^P = 3/2^-$: $\bar{D}N(^2D)$, $\bar{D}^*N(^4S)$, $\bar{D}^*N(^2D)$, $\bar{D}^*N(^4D)$

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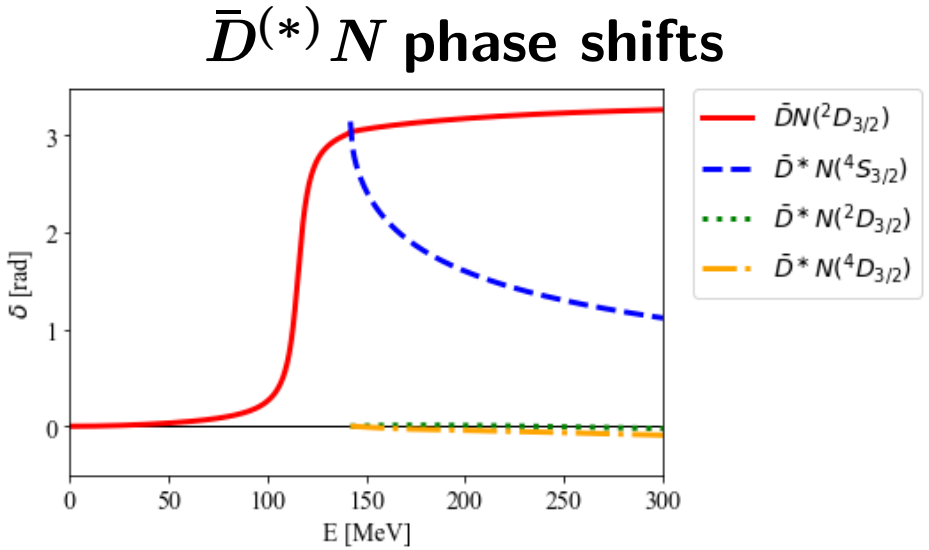

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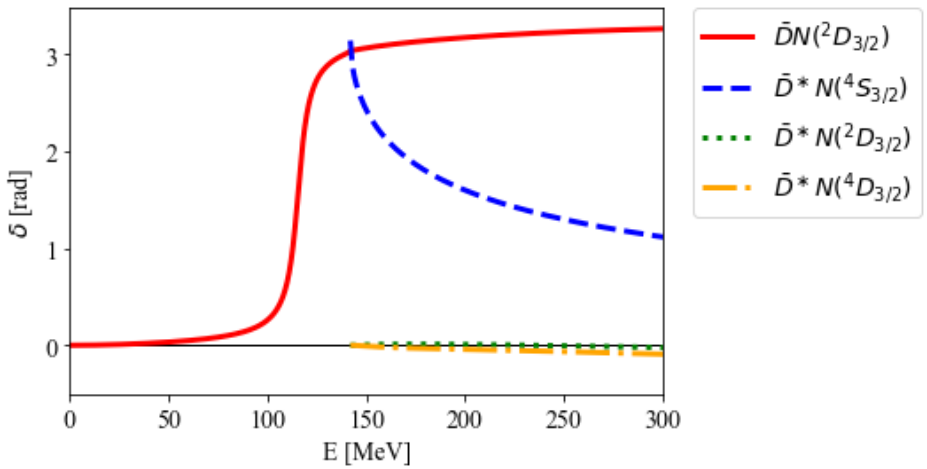
$\bar{D}^{(*)}N$ phase shifts



- $\bar{D}N(^2S)$ increasing beyond $\pi/2$

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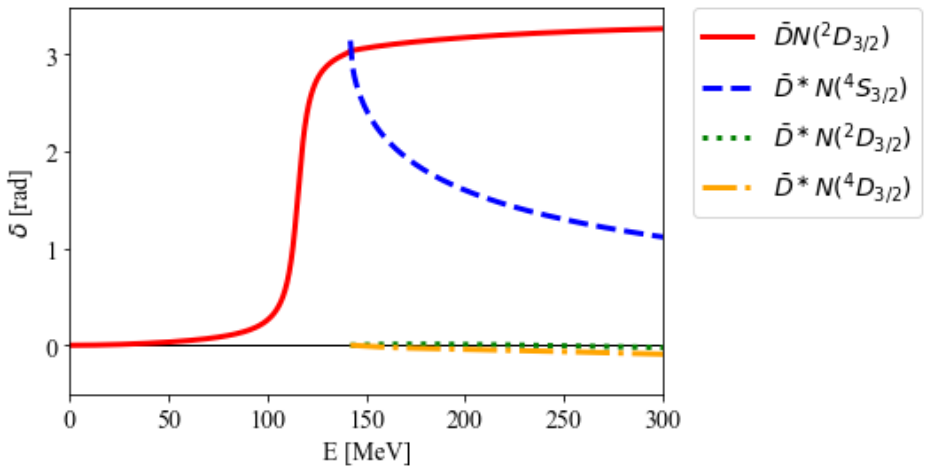

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$\Rightarrow$ **Resonance**
$(E_{re}, \Gamma) = (115.6, 8.42)$ MeV

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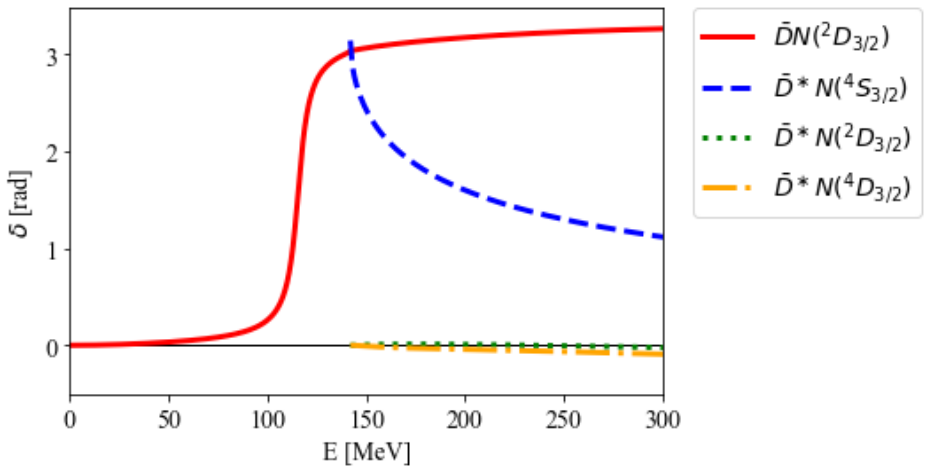

- $\bar{D}N(^2S)$ increasing beyond $\pi/2$

$\Rightarrow$ **Resonance**
$(E_{re}, \Gamma) = (115.6, 8.42)$ MeV

- Quasi bound state in $\bar{D}^*N(^4S)$

$\Rightarrow$ **Feshbach resonance**

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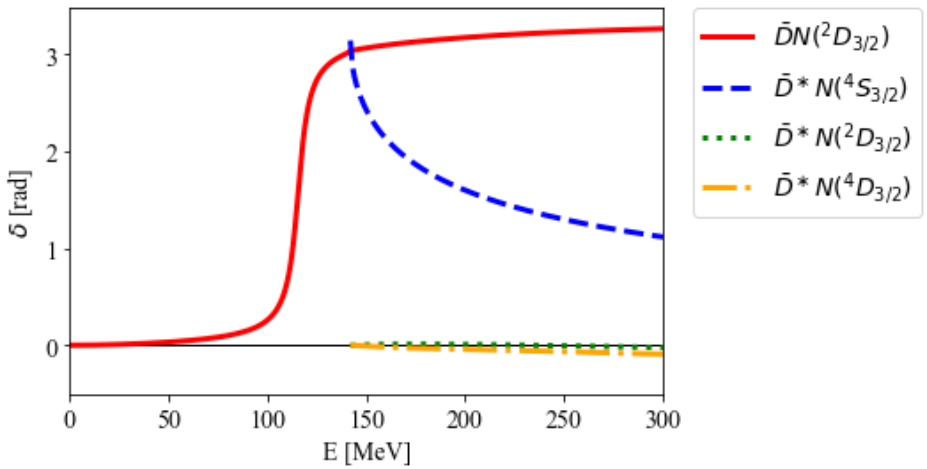
$\bar{D}^{(*)}N$ phase shifts



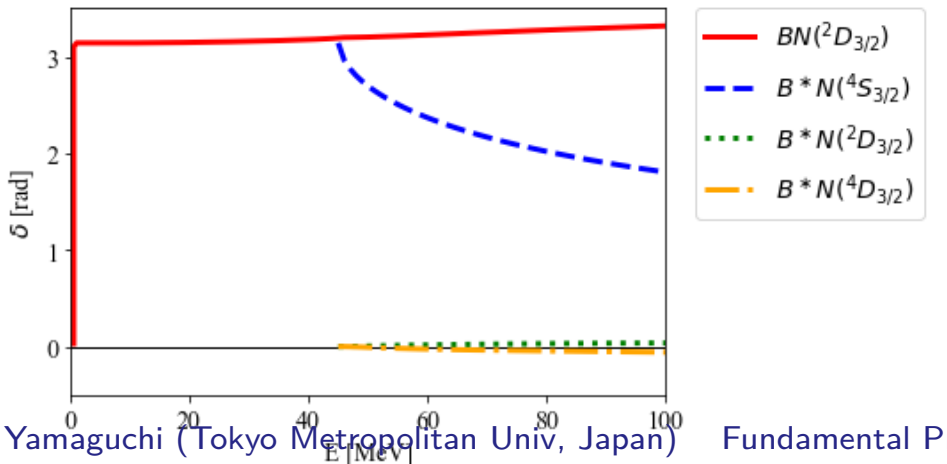
- $\bar{D}N(^2S)$ increasing beyond $\pi/2$

$\Rightarrow$ **Resonance**
$(E_{re}, \Gamma) = (115.6, 8.42)$ MeV

- Quasi bound state in $\bar{D}^*N(^4S)$

$\Rightarrow$ **Feshbach resonance**

$B^{(*)}N$ phase shifts



- $BN(^2D)$ resonance slightly above the BN threshold

$(E_{re}, \Gamma) = (0.515, 5.09 \times 10^{-5})$ MeV

- Quasi bound state in $B^*N(^4S)$

Numerical results for $I = 1$ $(J^P = 1/2^-)$

- Bound state

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- Mixing ratio
  $\Rightarrow$ $\bar{D}N(^2S_{1/2})$: 88.9%, $\bar{D}^*N(^2S_{1/2})$: 10.9%, $\bar{D}^*N(^4D_{1/2})$: 0.106%
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$\langle V_\pi \rangle$ (-4.81)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	0.0	-0.95	-1.60
$\bar{D}^*N(^2S_{1/2})$	-0.95	-0.66	0.51
$\bar{D}^*N(^4D_{1/2})$	-1.60	0.51	-5.04×10^{-2}
$\langle V_{\rho+\omega} \rangle$ (2.02)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	29.45	-14.85	0.75
$\bar{D}^*N(^2S_{1/2})$	-14.85	1.18	-0.25
$\bar{D}^*N(^4D_{1/2})$	0.75	-0.25	8.10×10^{-2}
$\langle V_\sigma \rangle$ (-79.32)	$\bar{D}N(^2S_{1/2})$	$\bar{D}^*N(^2S_{1/2})$	$\bar{D}^*N(^4D_{1/2})$
$\bar{D}N(^2S_{1/2})$	-55.59	—	—
$\bar{D}^*N(^2S_{1/2})$	—	-23.66	—
$\bar{D}^*N(^4D_{1/2})$	—	—	-7.21×10^{-2}

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Small contribution

$\vec{\tau}_1 \cdot \vec{\tau}_2 = +1$

$\leftrightarrow I = 0 : \vec{\tau}_1 \cdot \vec{\tau}_2 = -3$

V_σ dominant contribution

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Phase shifts of the $J^P = 3/2^-$ states with $I = 1$

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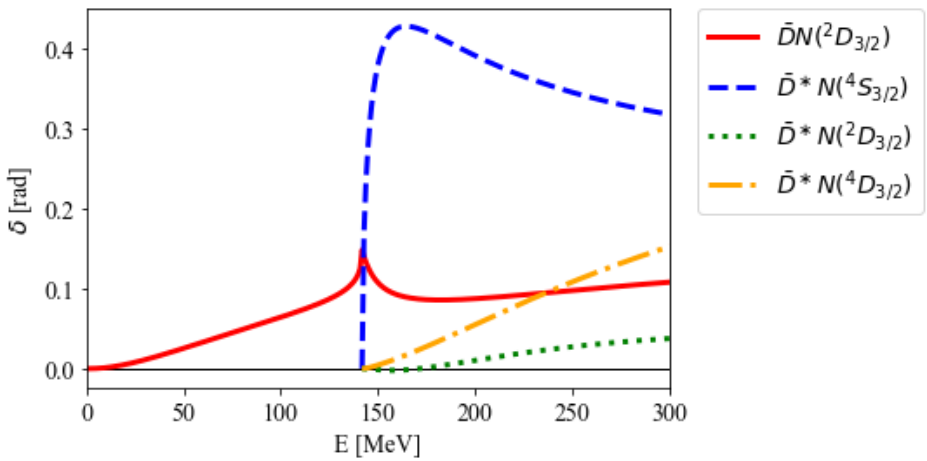
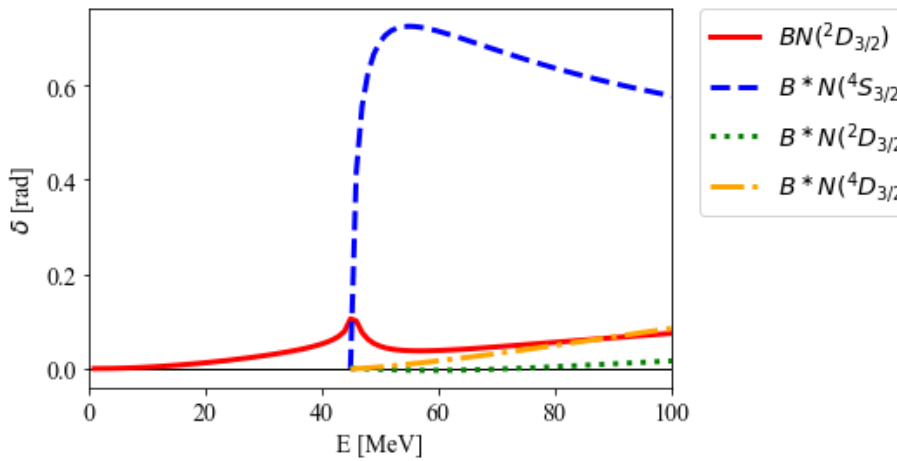
$\bar{D}^{(*)}N$



$B^{(*)}N$



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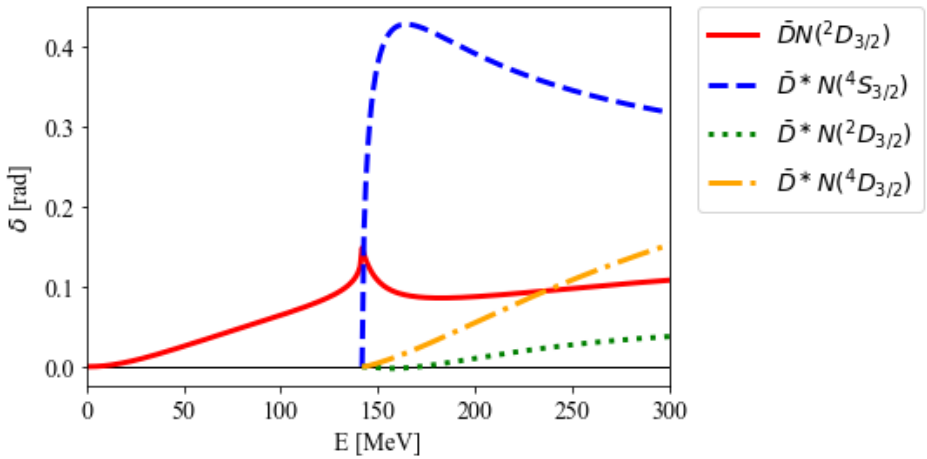

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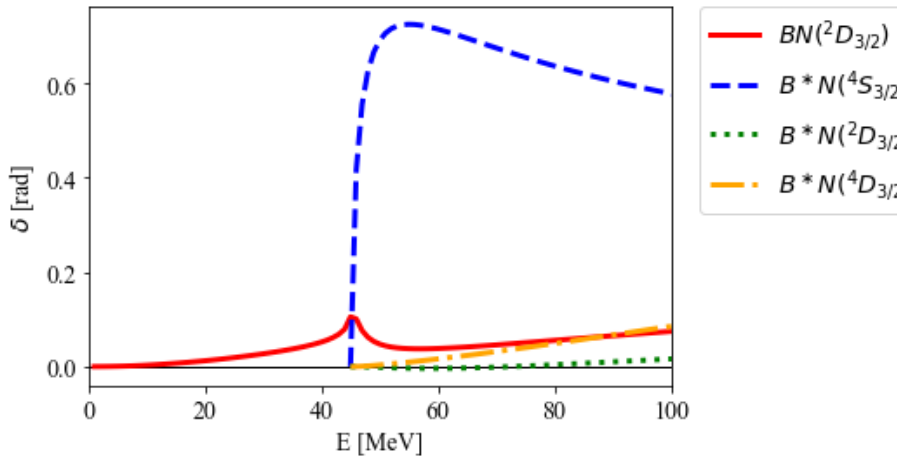
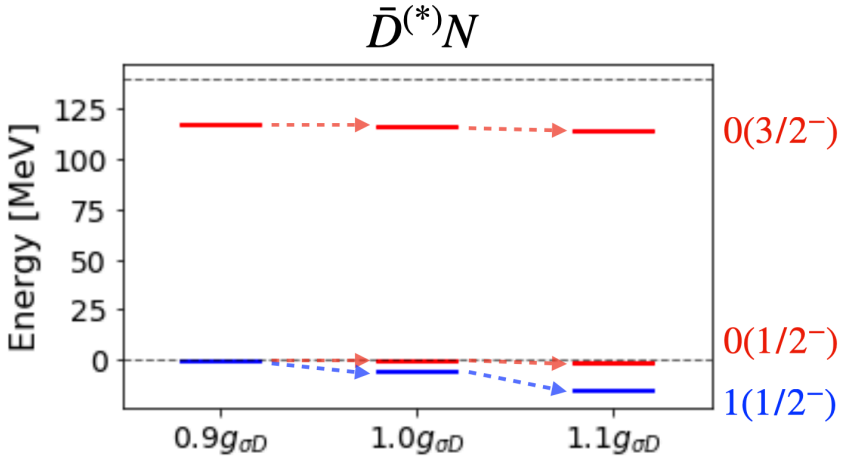


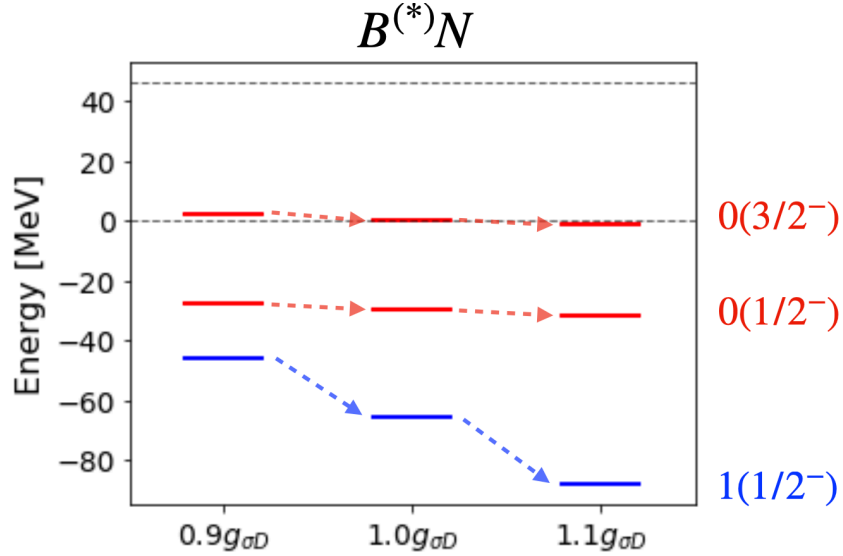
- No (quasi) bound state

$\Leftrightarrow$ **Bound states for $I(J^P) = 1(1/2^-)$**

- $\rho + \omega$ produce a strong repulsion
- The $1(1/2^-)$ bound state is in the HQS singlet (with $j_\ell = 0$),
  while $1(3/2^-)$ belongs to another HQS multiplet (with $j_\ell = 1$ **or** 2)

Sensitivity to the σ coupling ($g_{\sigma D}$ vs E)





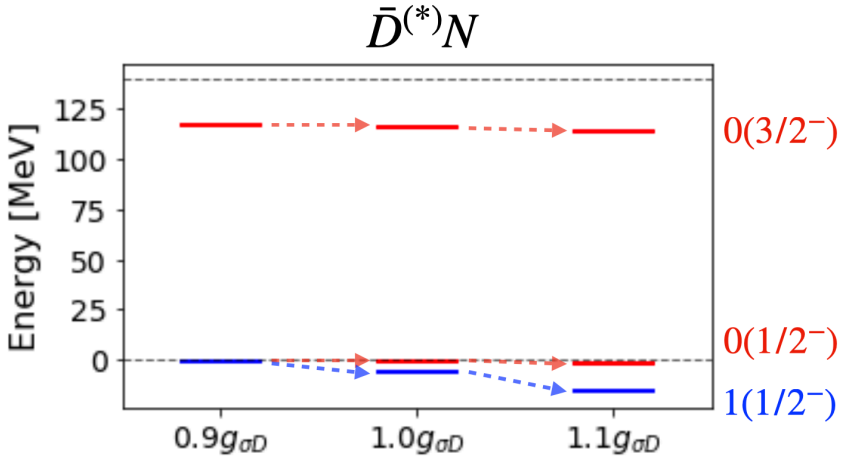
$I = 0$:

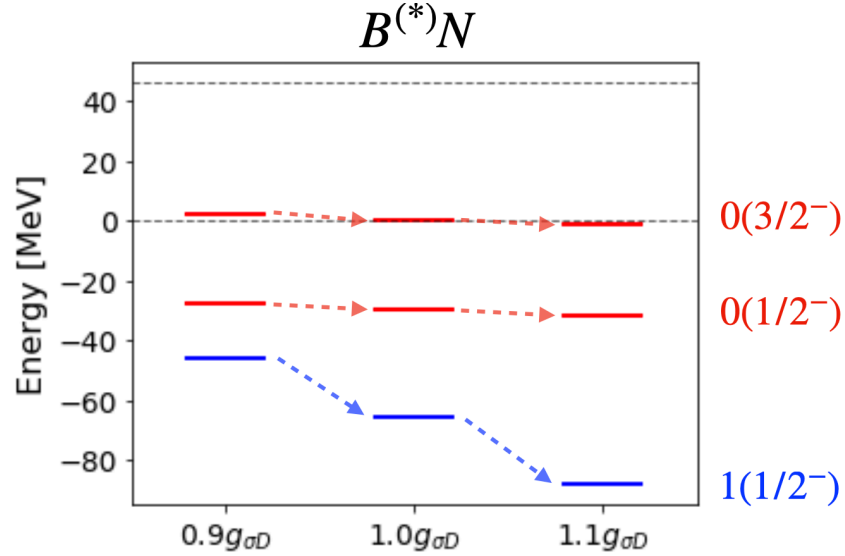
Stable against g_σ changing

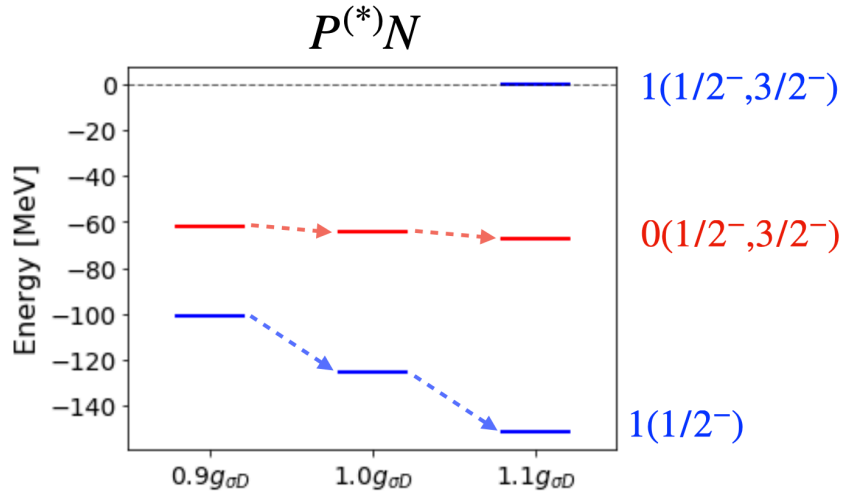
$I = 1$:

Strongly depending on g_σ

Sensitivity to the σ coupling ($g_{\sigma D}$ vs E)







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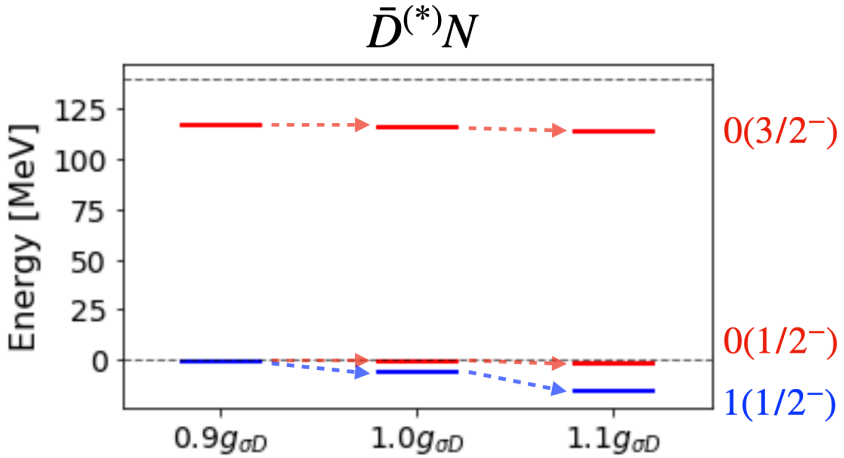

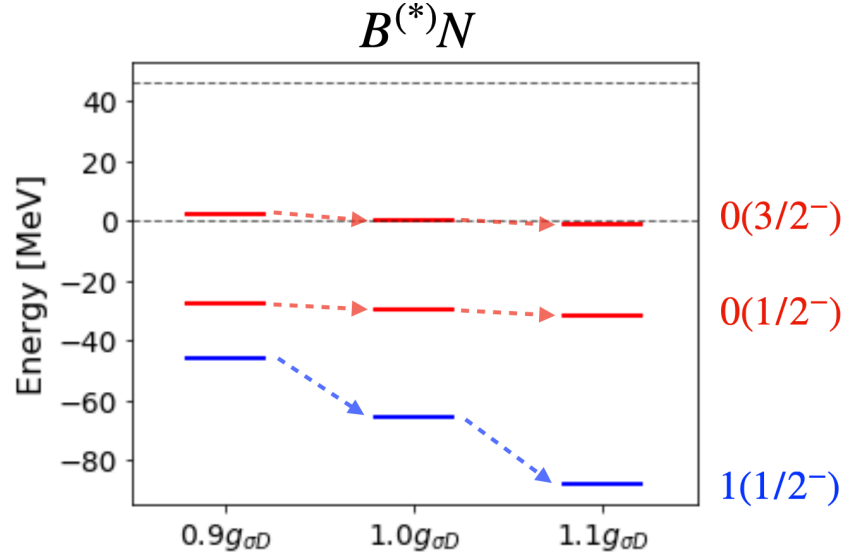

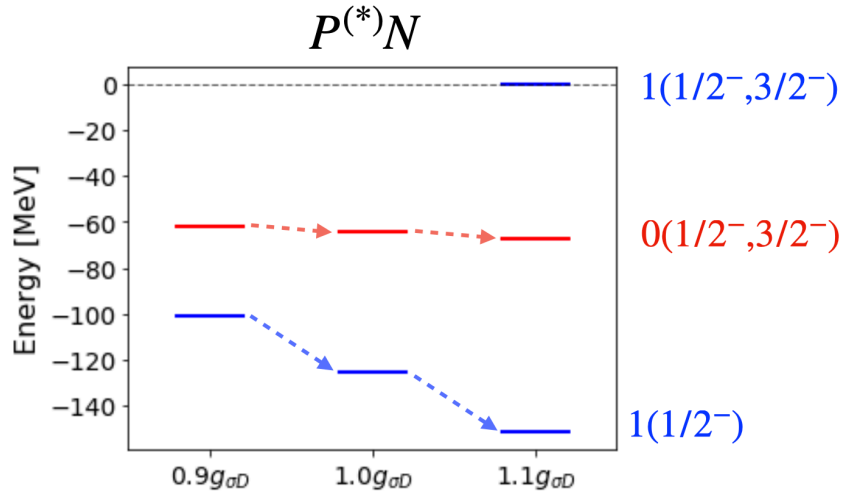

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Strongly depending on g_σ

For PN, Another **HQS doublet** $(1(1/2^-, 3/2^-))$ appears with the strong attraction

Summary

- Investigation of the $\bar{D}N$ interactions
  - Genuine open-charm pentaquark
  - Correlation function obtained by ALICE
- Constructing Meson exchange potentials based on CD-Bonn and Heavy quark symmetry
- Studying $J^P = 1/2^-, 3/2^-$ states
  - Bound states and Resonances are found
  - For $I = 0$, the $1/2^-$ bound states and the $3/2^-$ resonances, belonging to the HQS doublet
    $\rightarrow$ The OPEP tensor force is dominant. The states are stable against the g_σ changing.
  - For $I = 1$, the $1/2^-$ bound state, being the HQS singlet
    $\rightarrow$The σ exchange is dominant. The states strongly depend on $g_{\sigma D}$

Y.Y, Shigehiro Yasui, Atsushi Hosaka, Phys. Rev. D 106, 094001 (2022), in preparation

Thank you for your kind attention.