Heavy quark spin in nuclear medium

Shigehiro YASUI

Tokyo Institute of Technology

HHiNM
Heavy Hadrons in Nuclear Matter

第１０回「高エネルギーQCD・核子構造勉強会」@東京工業大学, 12 Oct. 2016

1. Multi-flavor nucleus

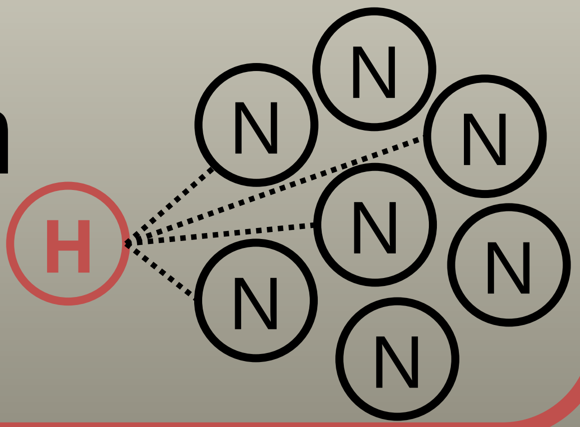
Nucleus meets Flavor

HiggsTan.com

charge	1st	2nd	3rd
Q=+2/3	up 	charm 	top 
	2 MeV	1300 MeV	173000 MeV
Q=−1/3	down 	strange 	bottom 
	5 MeV	100 MeV	4200 MeV

Nucleus meets Flavor

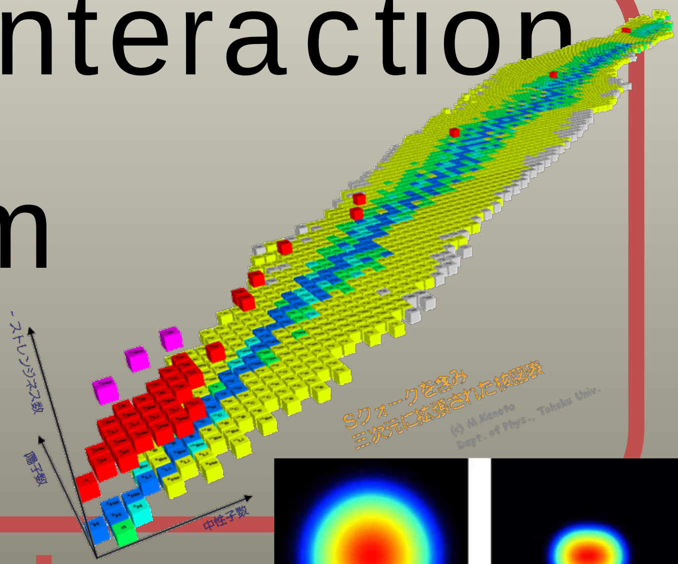
1. Hadron-nucleon interaction
2. Hadron in medium
3. Nuclear structure

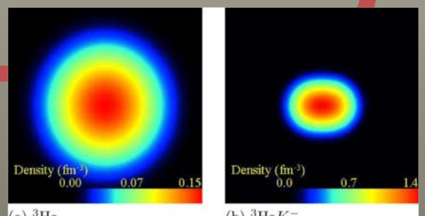


Impurity Physics

Nucleus + Strangeness

1. Hadron-nucleon interaction
2. Hadron in medium
3. Nuclear structure





(a) ^{3}He (b) ^{3}HeK^{-}

Impurity Physics

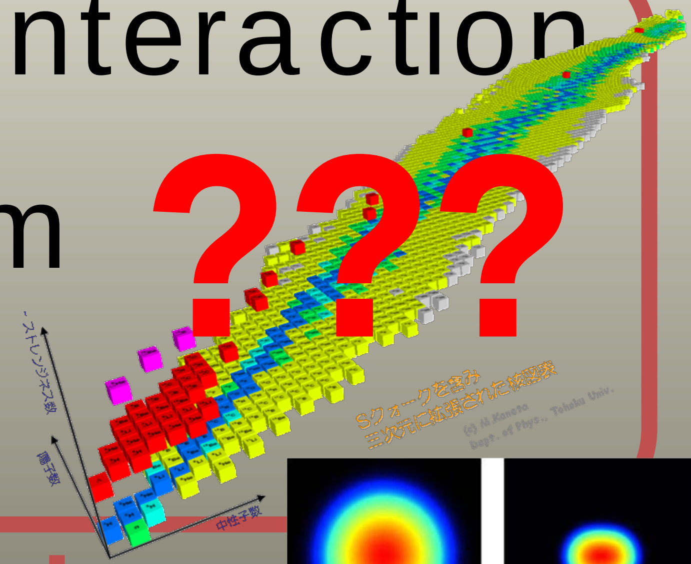
Nucleus + **Charm**

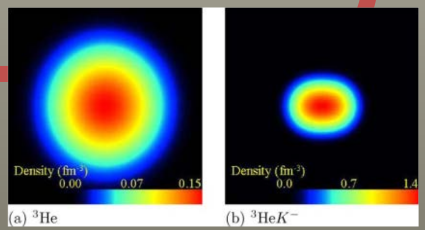
Mass hierarchy ($m_c >> \Lambda_{QCD}$)

~1.2 GeV ~0.2 GeV

1. Hadron-nucleon interaction
2. Hadron in medium
3. Nuclear structure

???



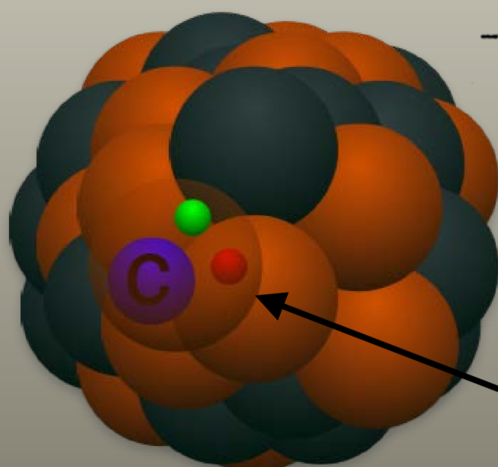


Impurity Physics

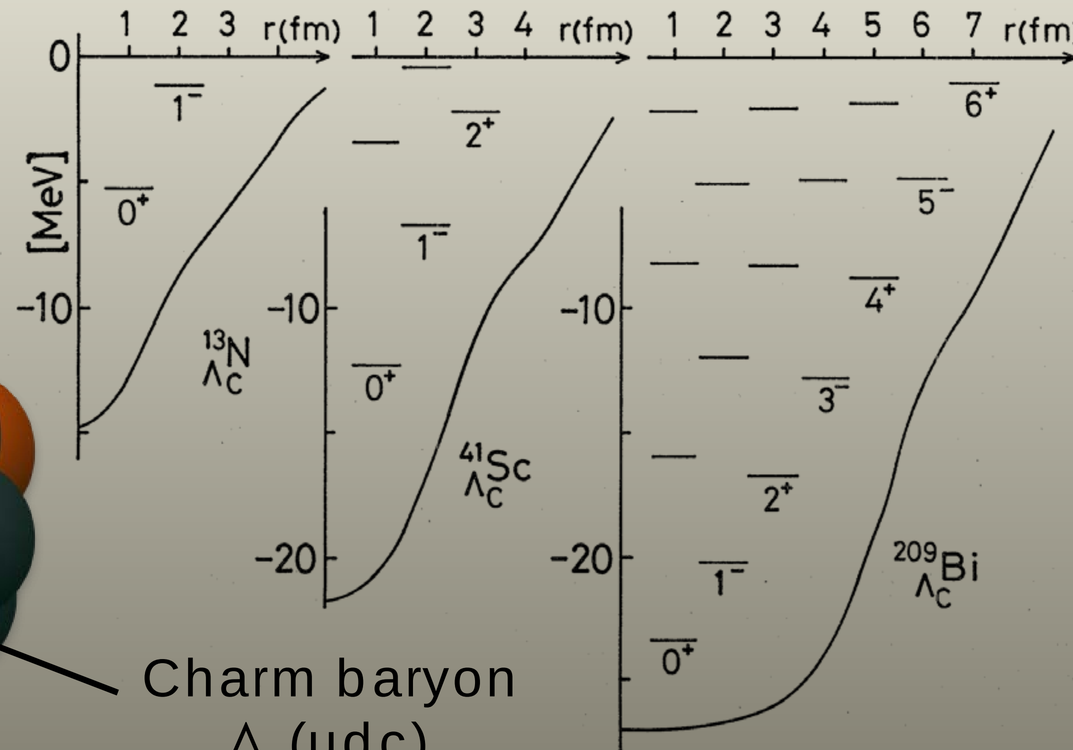
1. Multi-flavor nucleus

Strangeness | Charm

$$\Lambda(uds) \rightarrow \Lambda_c(udc)$$



Charm baryon
$\Lambda_c(udc)$



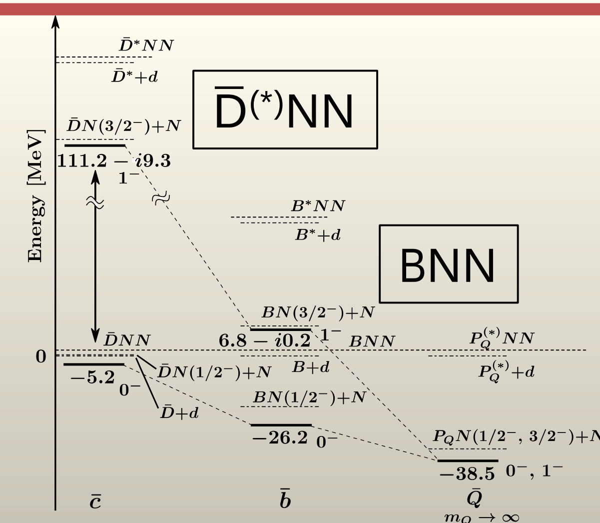
H.Bando, "Flavor Nuclei", PTP Suppl. 81, 197 (1985)

1. Multi-flavor nucleus
Charm/bottom "light" nuclei

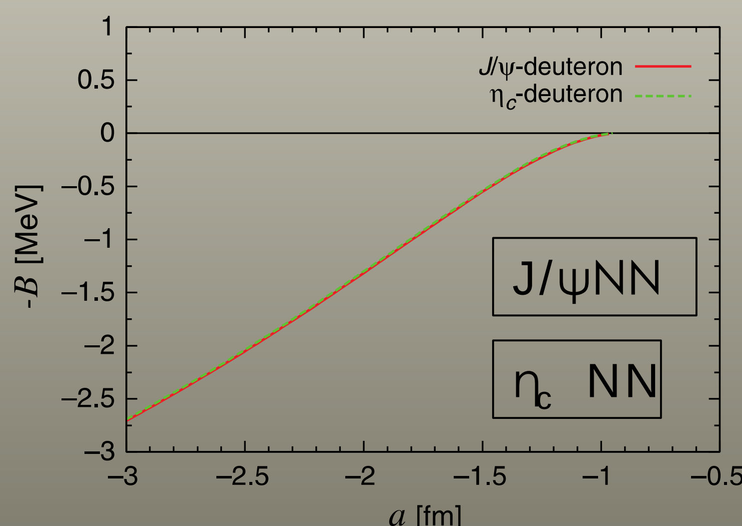
DNN

	HN1R $J=1$	$J=0$	Minnesota $J=0$	Av18 $J=0$
	Unbound	Bound	Bound	Bound
B	208	225	251	209
M_B	3537	3520	3494	3536
$\Gamma_{\pi Y_c N}$	—	26	38	22
$E_{\rm kin}$	338	352	438	335
$V(NN)$	0	−2	19	−5
$V(DN)$	−546	−575	−708	−540
$T_{\rm nuc}$	113	126	162	117
E_{NN}	113	124	181	113
P(odd)	75.0%	14.4%	7.4%	18.9%

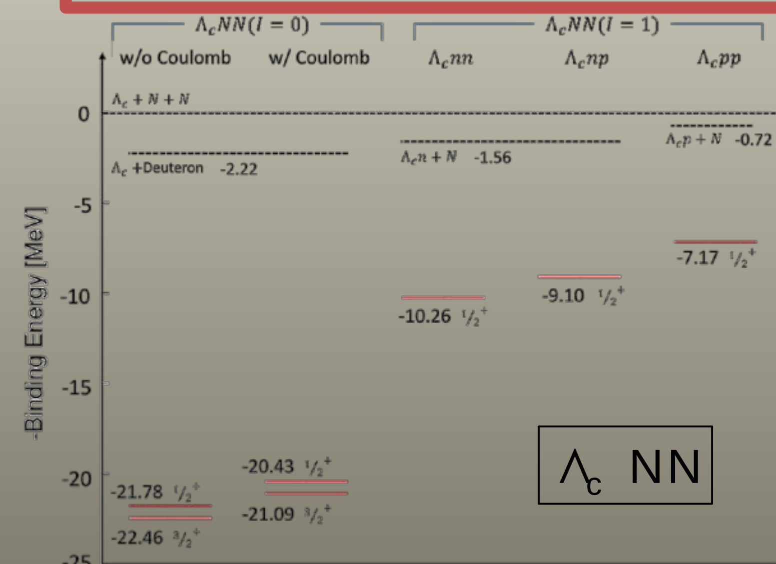
M. Bayer, C. W. Xiao, T. Hyodo, A. Dote, M. Oka, E. Oset, Phys. Rev. C86, 044004 (2012)



Y. Yamaguchi, S.Y., A. Hosaka, Nucl. Phys. A927, 110 (2014)



A. Yokota, E. Hiyama, M. Oka, Pog. Ther. Exp. Phys. 2013, 113D01



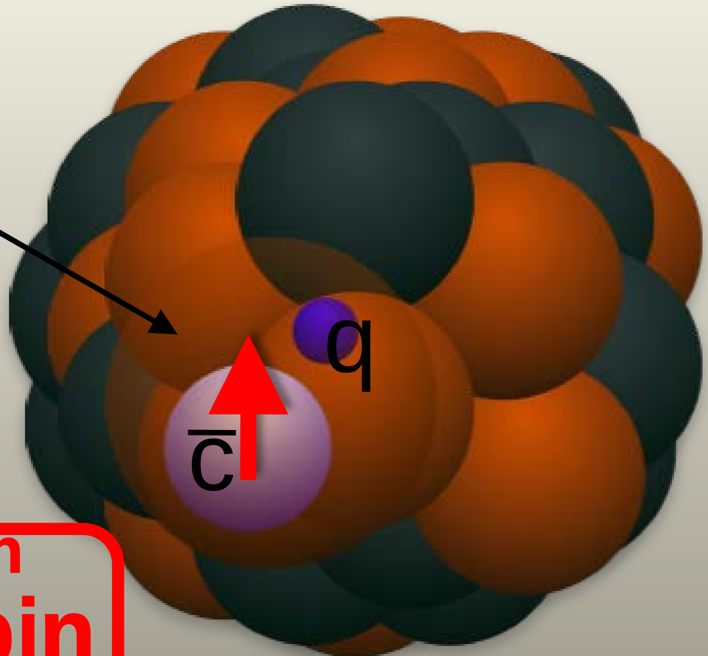
S. Maeda, M. Oka, A. Yokota, E. Hiyama, Y-R. Liu, Pog. Ther. Exp. Phys. 2016, 023D02

1. Multi-flavor nucleus

$\bar{D}$ (B) meson in nuclear matter

Quark-meson coupling model, QCD sum rules, hadronic interactions (mean-field approach, channel coupling, pion interaction), ...

$\bar{D}$, $\bar{D}^*$



Nucleus

- Binding energy
- Dispersion relation
- Spectral function
- Reaction
- Restoration of χSB
- Nuclear structure
- etc.

Heavy quark spin

$m_c \gg \Lambda_{QCD}$

Charm nucleus mass spectroscopy

1. Multi-flavor nucleus

$\bar{D}$ (B) meson in nuclear matter

Quark-meson coupling model, QCD sum rules, hadronic interactions (mean-field approach, channel coupling, pion interaction), ...

Binding energy in nuclear matter [MeV]

	Quark-meson coupling model	QCD rum rule	Hadron dynamics: Mean field	Hadron dynamics: WT-type coupling	π exchange
$\bar{D}$ meson	$-$(10-35) (in ^{208}Pb) [6] $\simeq$ +20 [7]	+(65-75) [15] -50 MeV [27] +30 MeV [28] -66 MeV [29]	$\simeq$ $-$(100-180) [18] $-$30 [21] $-$27 [22, 24]	+18 [19] +(11-20) [20] +(27-35) [23] $\simeq$ $-$(20-27) [25]	$-$35.1 [26]
D^* meson					$-153.9 - i170.1$
B meson		+(125-155) [15]			$-$106.9
B^* meson					$-203.3 - i117.5$

~ a few ten MeV

(Repulsive? Attractive?)

[6] K. Tsushima, D. -H. Lu, A. W. Thomas, K. Saito and R. H. Landau, Phys. Rev. C 59, 2824 (1999).
[7] A. Sibirtsev, K. Tsushima and A. W. Thomas, Eur. Phys. J. A 6, 351 (1999).
[15] T. Hilger, R. Thomas and B. Kampfer, Phys. Rev. C 79, 025202 (2009).
[16] T. Hilger, R. Schulze and B. Kampfer, J. Phys. G G 37, 094054 (2010).
[17] Z. -G. Wang and T. Huang, Phys. Rev. C 84, 048201 (2011).
[18] A. Mishra, E. L. Bratkovskaya, J. Schaffner-Bielich, S. Schramm and H. Stoecker, Phys. Rev. C 69, 015202 (2004).
[19] M. F. M. Lutz and C. L. Korpa, Phys. Lett. B 633, 43 (2006).
[20] L. Tolos, A. Ramos and T. Mizutani, Phys. Rev. C 77, 015207 (2008).
[21] A. Mishra and A. Mazumdar, Phys. Rev. C 79, 024908 (2009).
[22] A. Kumar and A. Mishra, Phys. Rev. C 81, 065204 (2010).
[23] C. E. Jimenez-Tejero, A. Ramos, L. Tolos and I. Vidana, Phys. Rev. C 84, 015208 (2011).
[24] A. Kumar and A. Mishra, Eur. Phys. J. A 47, 164 (2011).
[25] C. Garcia-Recio, J. Nieves, L. L. Salcedo and L. Tolos, Phys. Rev. C 85, 025203 (2012).
[26] S. Yasui, K. Sudoh, Phys. Rev. C87, 015202 (2013).
[27] A. Hayashigaki, Phys. Lett. B487, 96 (2000)
[28] K. Suzuki, P. Gubler, M. Oka, Pos Hadron2013, 179 (2014).
[29] K. Azzi, N. Er, H. Sundu, Eur. Phys. J. C74, 3021 (2014).

1. Multi-flavor nucleus

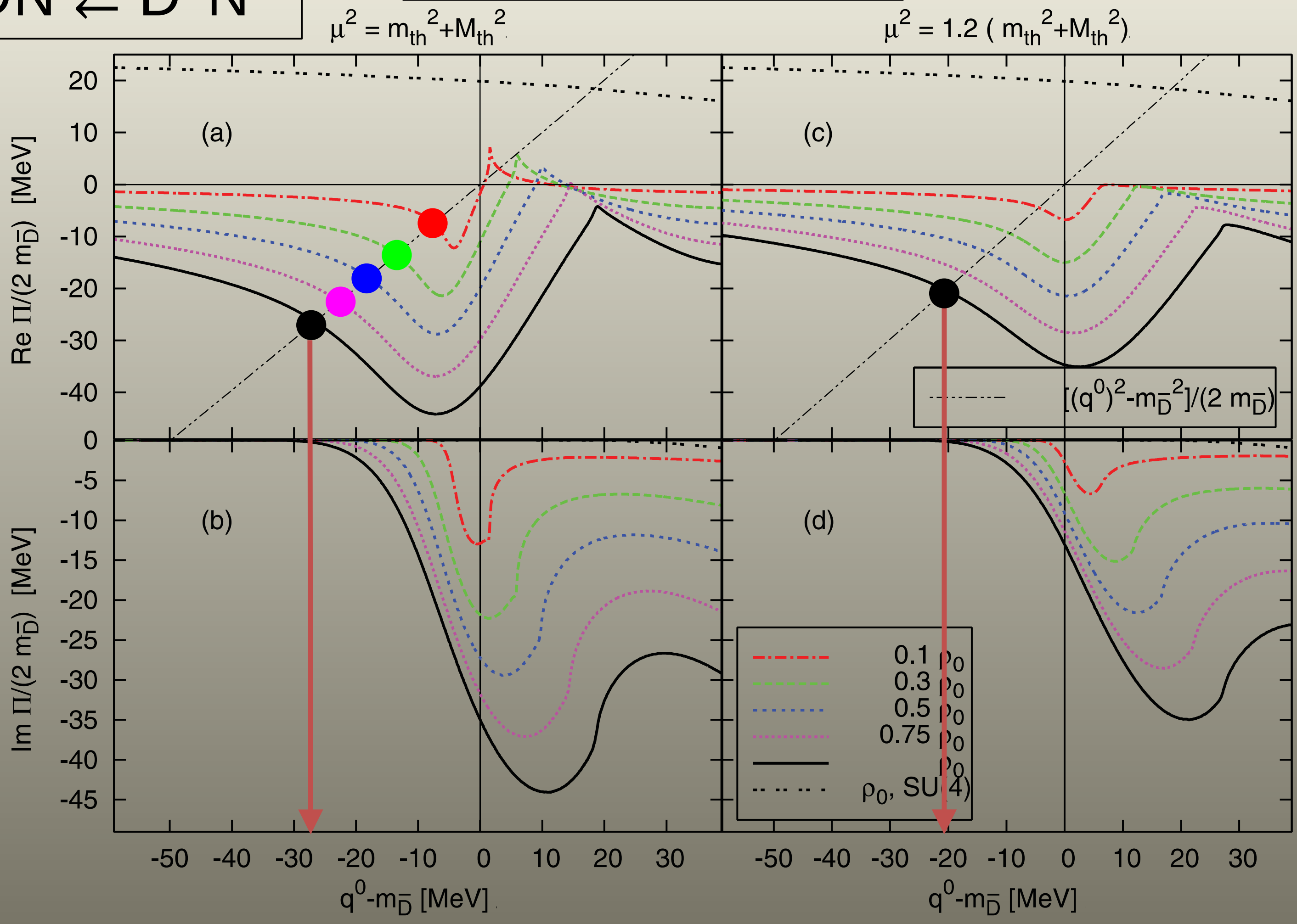
$\bar{D}$ (B) meson in nuclear matter

Quark-meson coupling model, QCD sum rules, hadronic interactions (mean-field approach, channel coupling, pion interaction), ...

Heavy quark symmetry
$\bar{D}N \rightleftarrows \bar{D}^*N$

Hadronic model

C. Garcia-Recio, J. Nieves, L. L. Salcedo, L. Tolos, Phys. Rev. C 85, 025203 (2012)



1. Multi-flavor nucleus

$\bar{D}$ (B) meson in nuclear matter

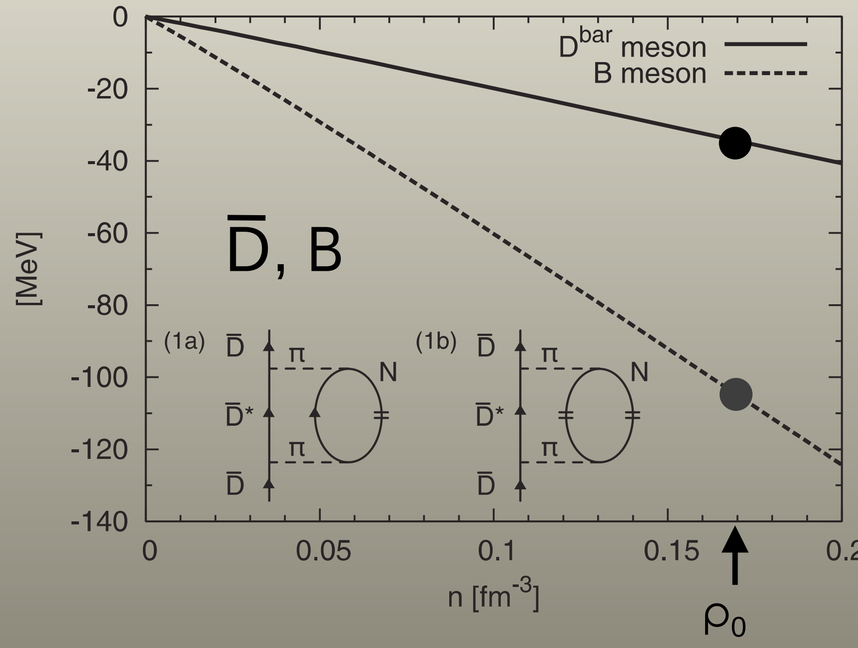
Quark-meson coupling model, QCD sum rules, hadronic interactions (mean-field approach, channel coupling, pion interaction), ...

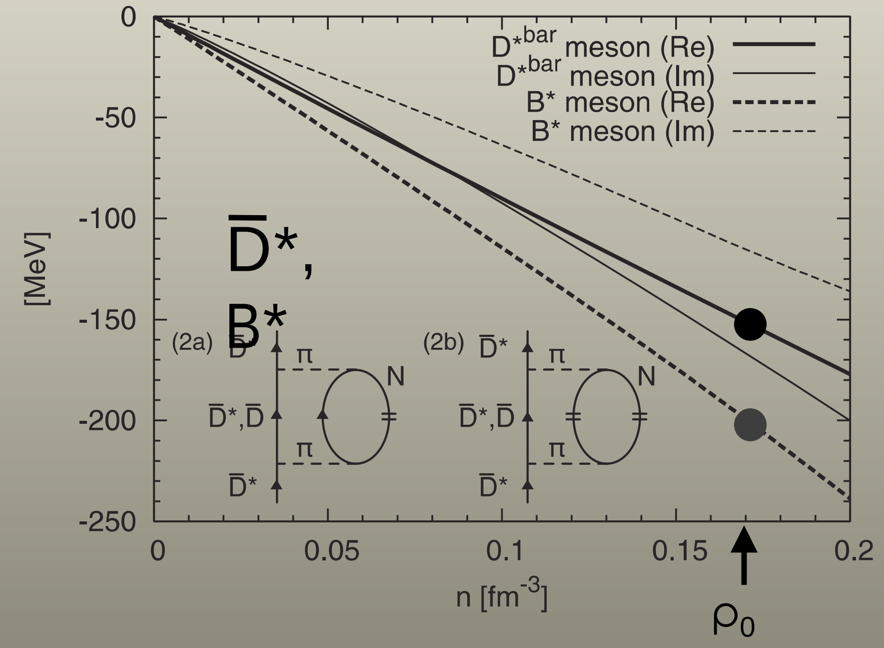
Heavy quark symmetry
$\bar{D}N \rightleftarrows \bar{D}^*N$

Hadronic model

S. Y. , K. Sudoh, Phys Rev. C87, 015202 (2013)

π meson exchange between $\bar{D}$ ($\bar{D}^*$) and N



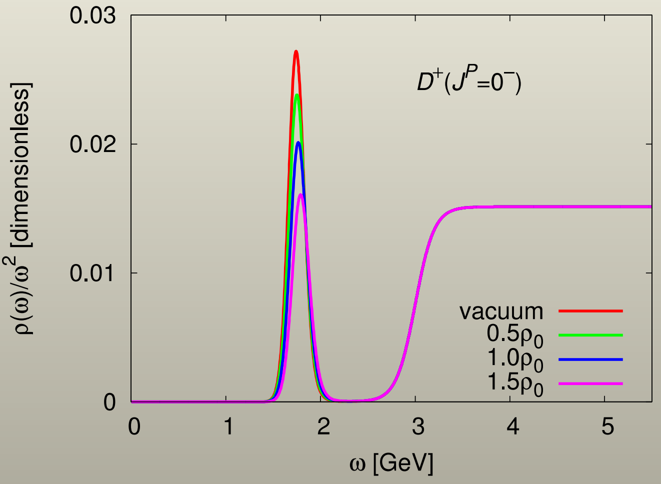


1. Multi-flavor nucleus

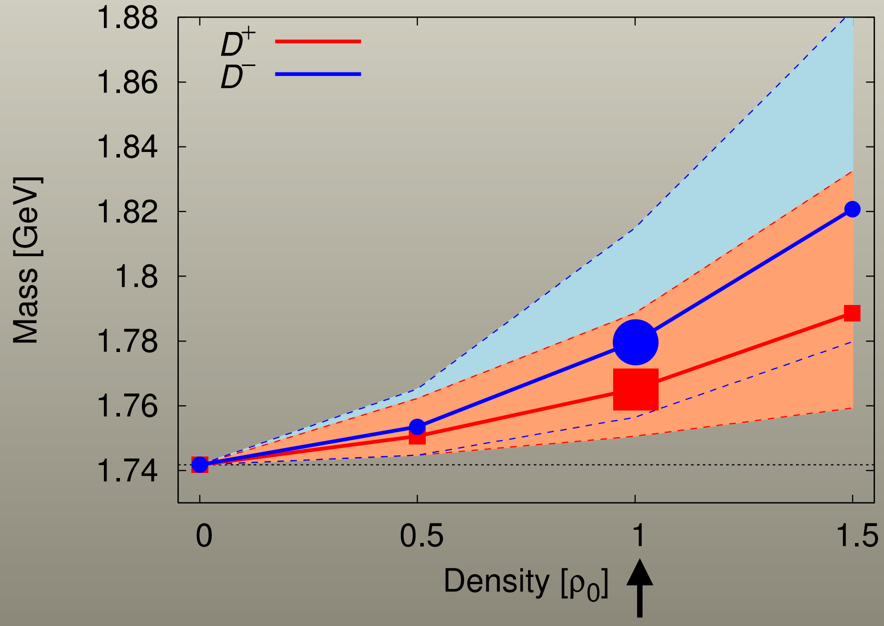
$\bar{D}$ (B) meson in nuclear matter

Quark-meson coupling model, QCD sum rules, hadronic interactions (mean-field approach, channel coupling, pion interaction), ...

QCD sum rule



K. Suzuki, P. Gubler, M. Oka, arXiv:1511.04513 [hep-ph]



Cf. Quark confinement picture
A. Park. P. Gubler, M. Harada, S. H. Lee, C. Nonaka, W. Park, arXiv:1602.01250 [nucl-th]

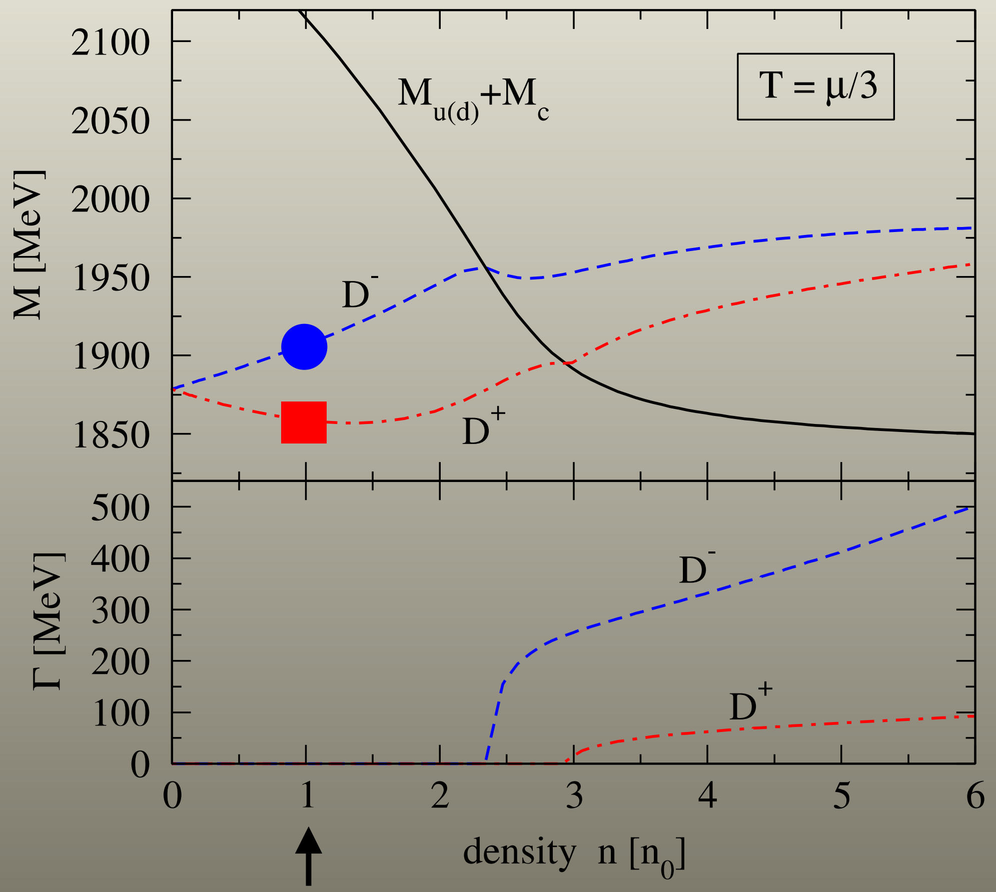
1. Multi-flavor nucleus

$\bar{D}$ (B) meson in nuclear matter

Quark-meson coupling model, QCD sum rules, hadronic interactions (mean-field approach, channel coupling, pion interaction), ...

PNJL model

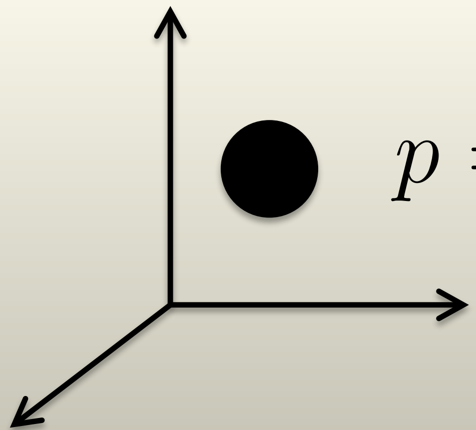
D. Blaschke, P. Costa, Y-L. Kalinovsky, Phys. Rev. D85, 034005 (2012)



Contents

2. Heavy quark symmetry

Introduction to “velocity-frame”



$$p = m_{\mathrm{Q}} v + k$$

$$v^2 = 1 \quad v^\mu = (1,0,0,0)$$

Propagator:

$$\frac{i}{\not{p} - m_{\mathrm{Q}} + i\varepsilon} = \frac{i(\not{p} + m_{\mathrm{Q}})}{p^2 - m_{\mathrm{Q}}^2 + i\varepsilon}$$

$$= \frac{i(m_{\mathrm{Q}}\not{v} + \not{k} + m_{\mathrm{Q}})}{(m_{\mathrm{Q}} v + k)^2 - m_{\mathrm{Q}}^2 + i\varepsilon}$$

$$= \frac{i(m_{\mathrm{Q}}\not{v} + \not{k} + m_{\mathrm{Q}})}{2m_{\mathrm{Q}} v\cdot k + k^2 + i\varepsilon}$$

$$= \frac{i(\not{v} + \not{k}/m_{\mathrm{Q}} + 1)}{2v\cdot k + k^2/m_{\mathrm{Q}} + i\varepsilon}$$

$$= \frac{\not{v} + 1}{2}\frac{i}{v\cdot k + i\varepsilon} + \mathcal{O}(1/m_{\mathrm{Q}})$$

2. Heavy quark symmetry

$$\mathcal{L}_{\text{heavy quark}} = \bar{Q}(i\not{D} - m_{\rm Q})Q \qquad D_\mu = \partial_\mu - igA^a_\mu T^a$$

1/m_Q expansion

(positive energy state Q_v with velocity v)

$$Q_v = e^{im_{\rm Q}v\cdot x}\frac{1+\not{v}}{2}Q$$

Manohar, Wise, Luke, Grinstein, ...

$$\mathcal{L}_{\rm HQET} = \boxed{\bar{Q}_v v\cdot iDQ_v} + \bar{Q}_v\frac{(iD_\perp)^2}{2m_{\rm Q}}Q_v - g_s\bar{Q}_v\frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_{\rm Q}}Q_v + \mathcal{O}(1/m_{\rm Q}^2)$$

LO

$$\gamma^\mu \to \frac{1+\not{v}}{2}\gamma^\mu\frac{1+\not{v}}{2} = v^\mu\frac{1+\not{v}}{2} \to v^\mu$$

Heavy quark spin in $m_Q \to \infty$ is <u>conserved</u>.

Heavy quark symmetry (HQS)

2. Heavy quark symmetry

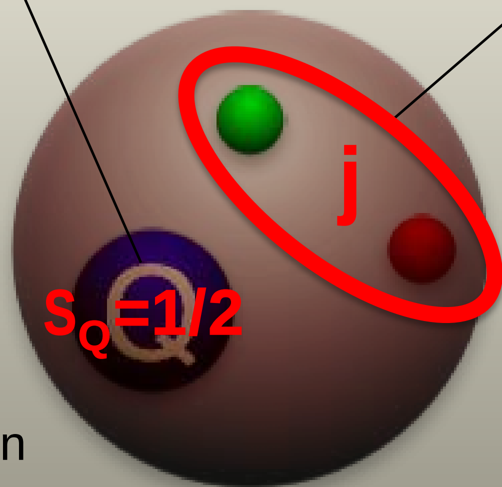
Heavy quark symmetry (HQS)

Normal hadrons, exotic hadrons, hadronic molecules, exotic nuclei, ...

Heavy quark spin × Light quark and gluon total spin

Brown muck

(Spin-complex)



Heavy hadron

→

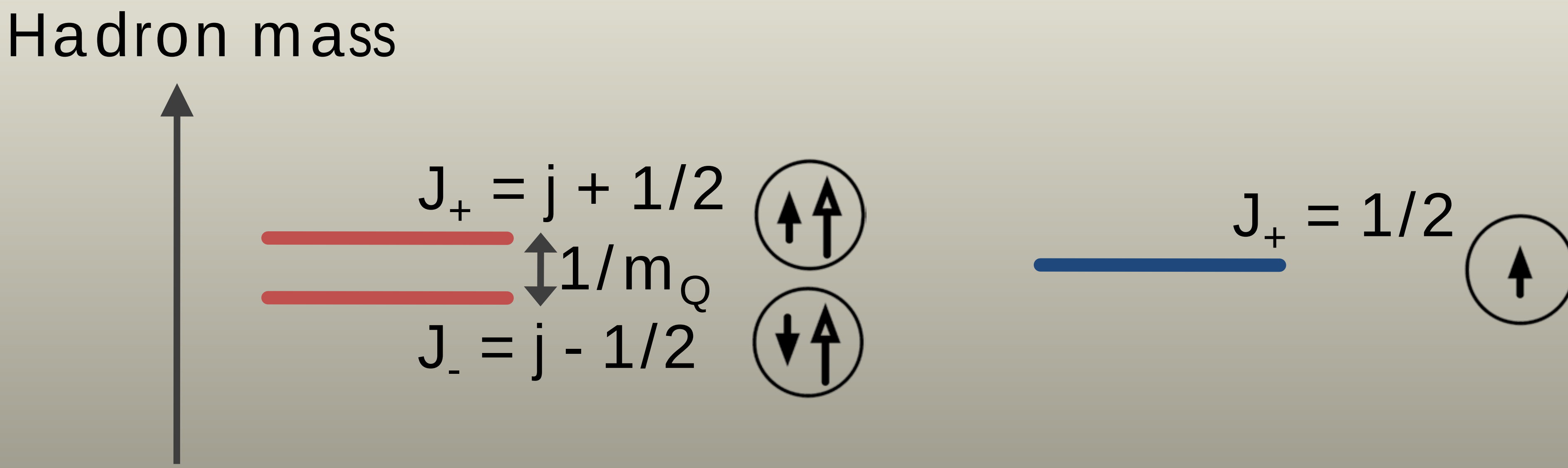
small spin-spin ($S_Q \cdot j$) interaction

$\sim \Lambda_{QCD}/m_Q << 1$

Total spin = j ± 1/2: degenerate

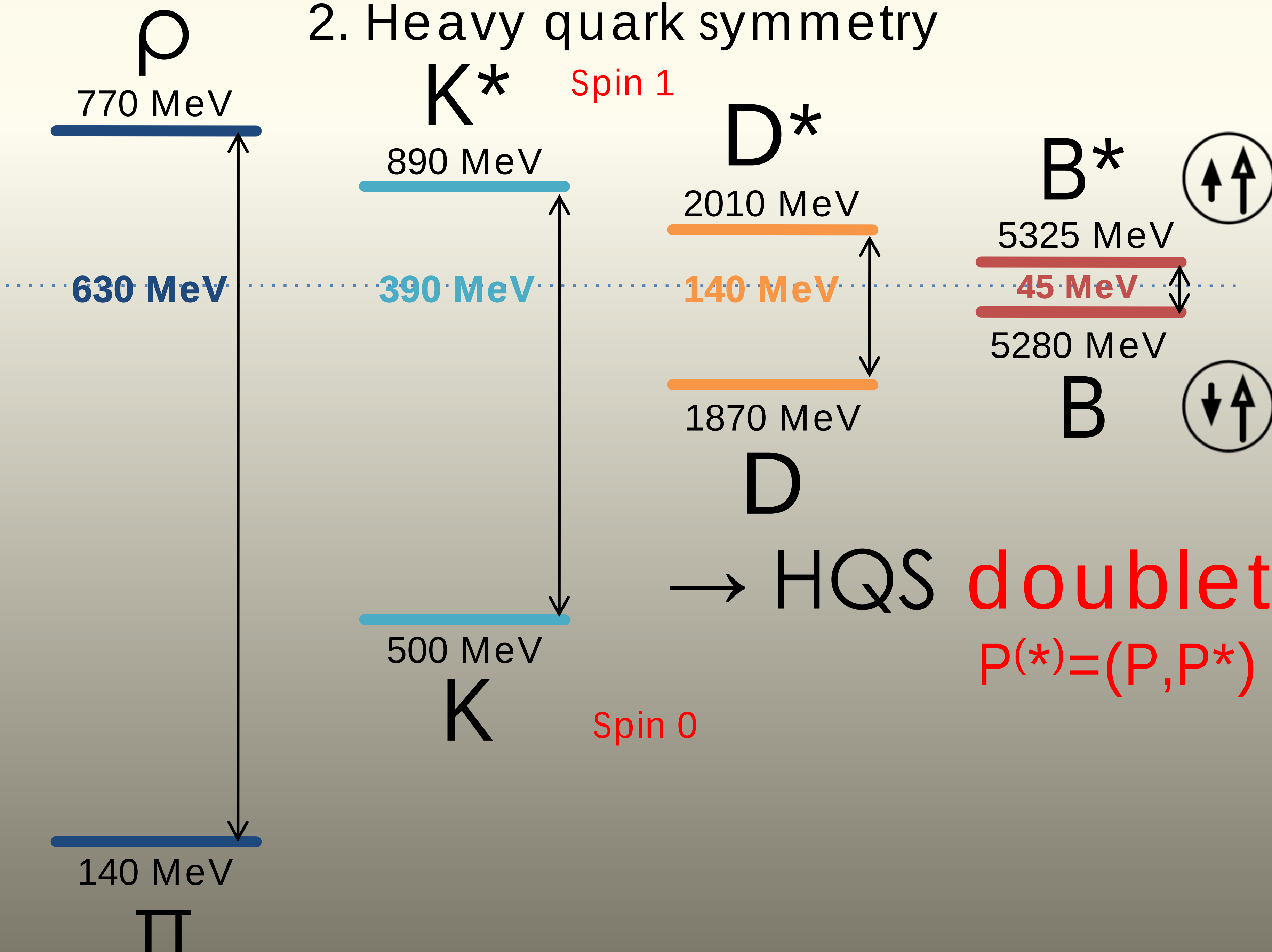
Heavy quark symmetry (HQS)

Normal hadrons, exotic hadrons, hadronic molecules, exotic nuclei, ...



HQS **doublet** ($j \neq 0$) OR HQS **singlet** ($j = 0$)

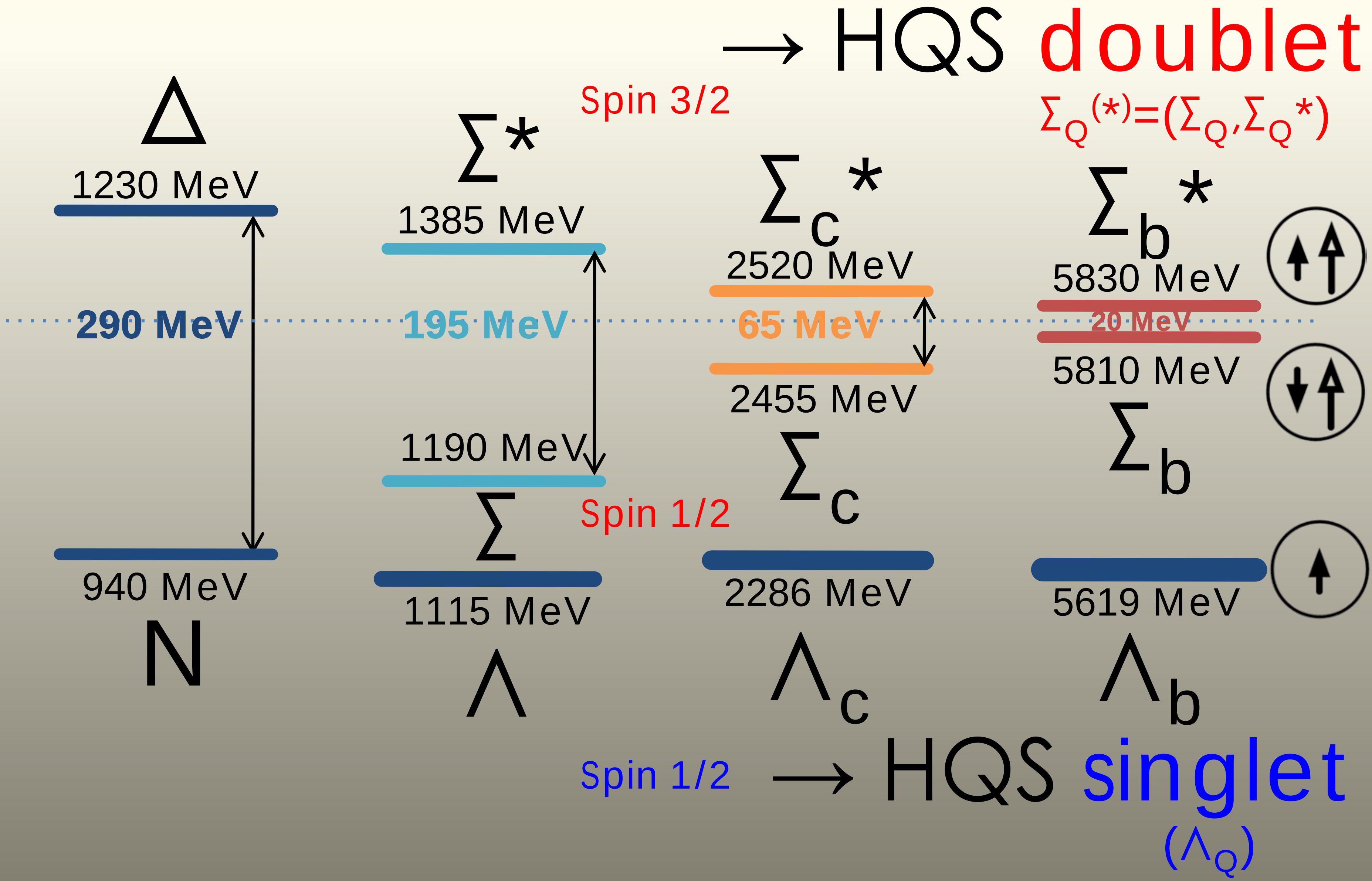
2. Heavy quark symmetry



→ HQS doublet

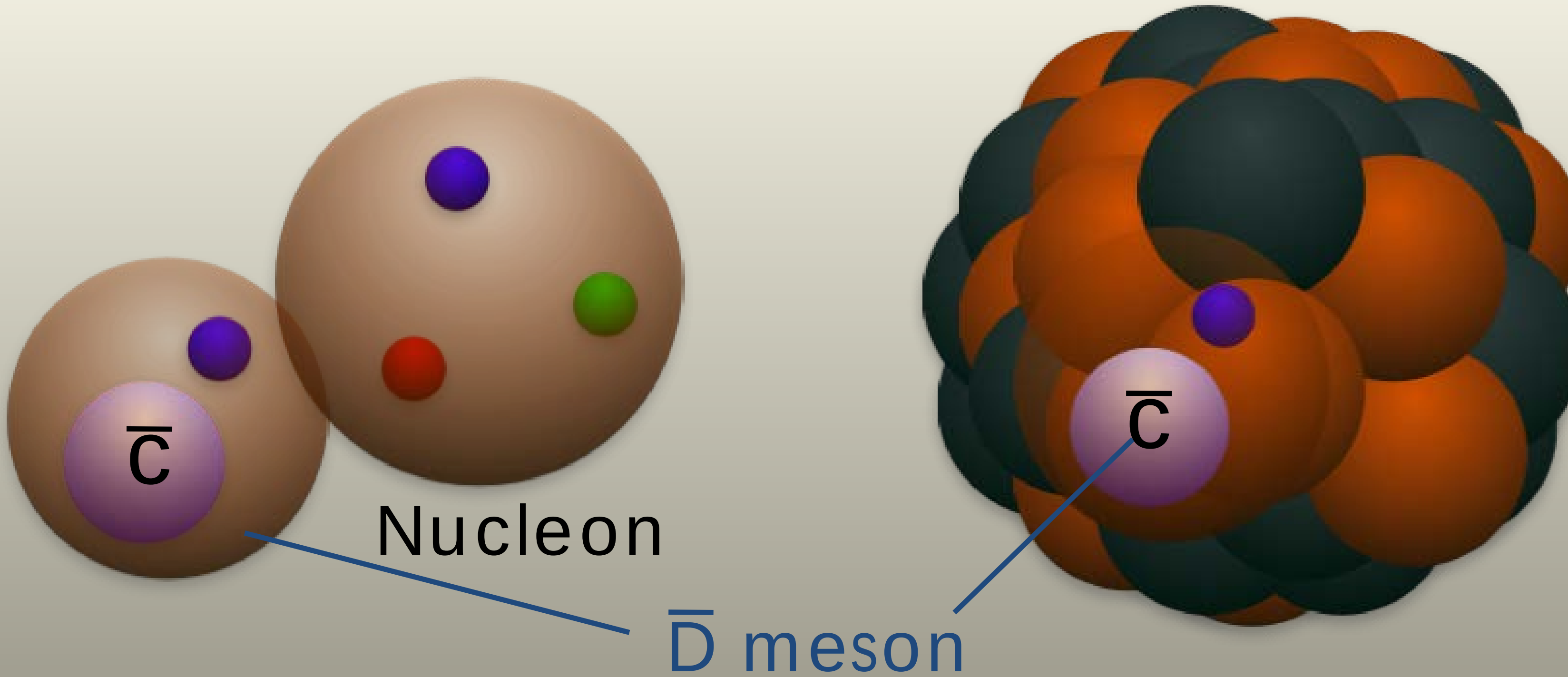
$P^{(*)} = (P, P^*)$

2. Heavy quark symmetry



Question

Charm (bottom) exotic hadrons and nuclei



Hadronic molecule (A=1)

Nucleus (A: large)

HQS doublet or singlet?

Answer

HQS doublet!!

3. Application 1: Leading order in $1/m_Q$ expansion

Heavy hadron effective theory

LO in $1/m_Q$ expansion

3. Application 1: Leading order in $1/m_Q$ expansion

$Q\bar{q}$

$\uparrow\downarrow \quad \uparrow$

$P^{(*)} = P^* \ \uparrow\uparrow$ or $P \ \downarrow\uparrow$

1^- same mass 0^-

$Q=b$ ($Q=c$) $\bar{B}^*$ (D^*) $\bar{B}$ (D)

H.Georgi, Phys. Lett. B240, 447 (1990)
A.F.Falk, H.Georgi, B.Grinstein, Nucl. Phys. B343, 1 (1990)

3. Application 1: Leading order in $1/m_Q$ expansion

$Q\bar{q}$

$$H_v(x) = \frac{1+\not v}{2}\left[P^{*\mu}_v(x)\gamma_\mu + i\gamma_5 P_v(x)\right]$$

1^- 0^-

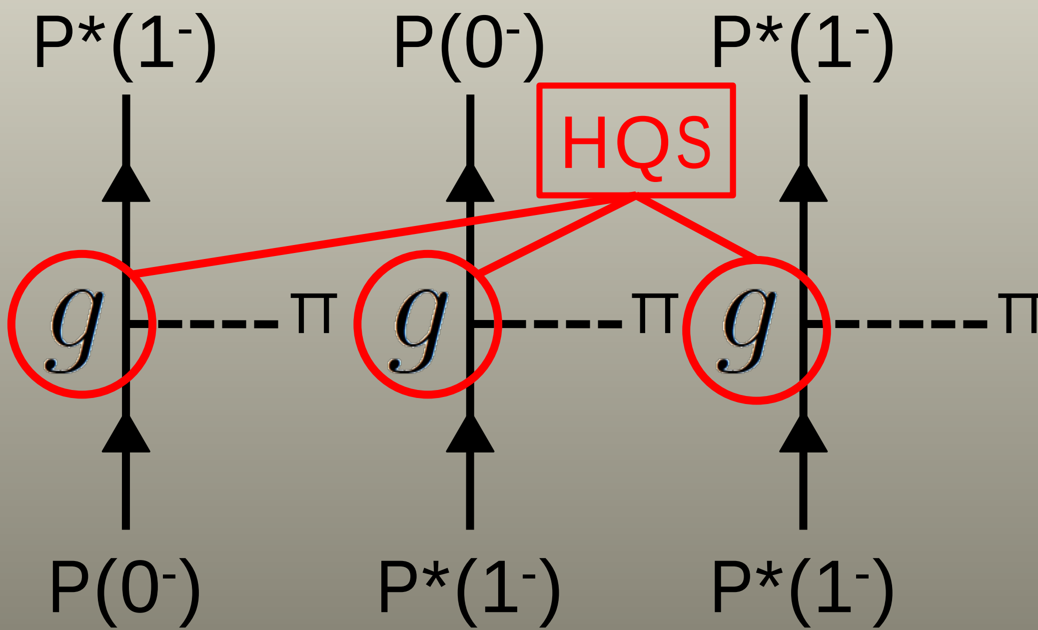
H.Georgi, Phys. Lett. B240, 447 (1990)
A.F.Falk, H.Georgi, B.Grinstein, Nucl. Phys. B343, 1 (1990)

3. Application 1: Leading order in $1/m_Q$ expansion

Interaction of $P(0^-)$, $P^*(1^-)$ meson and pion field with chiral symmetry + HQS

$$\mathcal{L}^{(0)}_{\mathrm{HMET}} = \underbrace{-\mathrm{Tr}\overline{H}_v v\cdot iDH_v}_{\text{kinetic term}} + \underbrace{g\,\mathrm{Tr}\overline{H}_v H_v \gamma_\mu \gamma_5 A^\mu}_{\text{interaction with pion}} + \mathcal{O}(1/M)$$

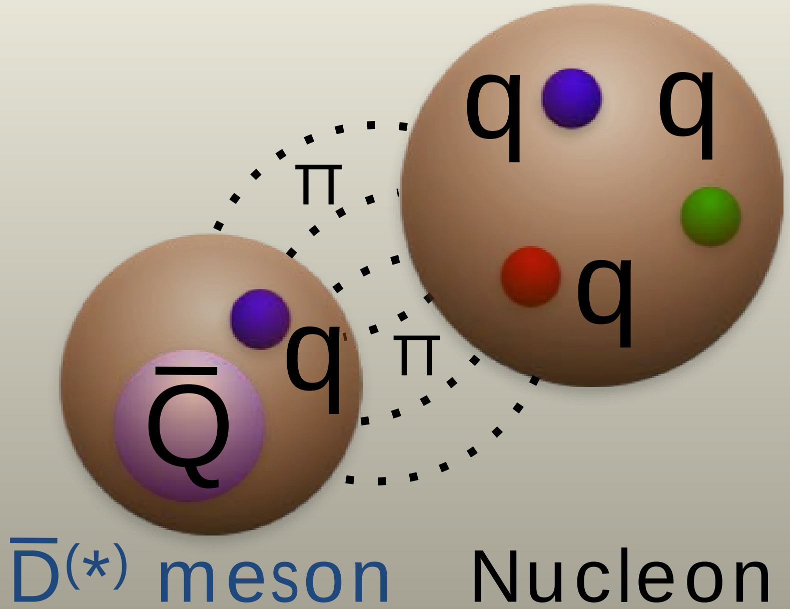
$$A_\mu = -\partial_\mu \pi$$



H.Georgi, Phys. Lett. B240, 447 (1990)
A.F.Falk, H.Georgi, B.Grinstein, Nucl. Phys. B343, 1 (1990)

3. Application 1: Leading order in $1/m_Q$ expansion

$$\bar{Q}q = \bar{P}^{(*)}$$



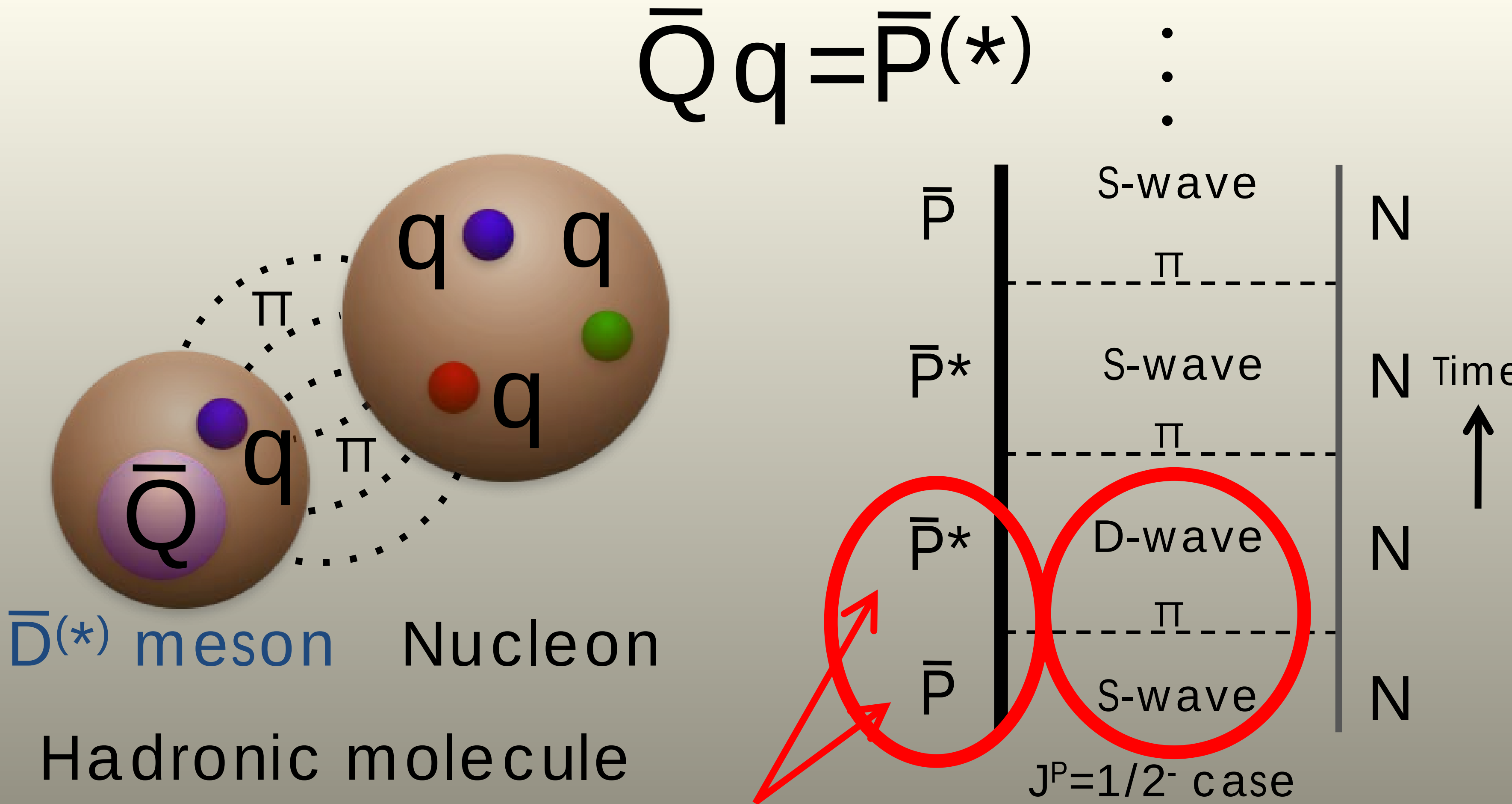
① No *quark-antiquark* annihilation
(very simple system!)

② Relation for interaction vertices:
$g_{PP^*\pi} = g_{P^*P^*\pi}$ (heavy quark symmetry)

Hadronic molecule

HQS doublet or singlet?

3. Application 1: Leading order in $1/m_Q$ expansion

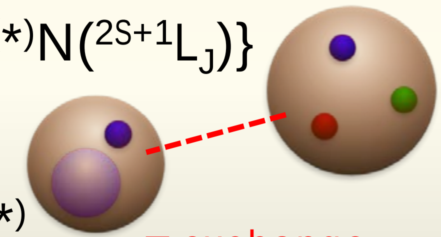


$\bar{P}(0^-)$-$\bar{P}^*(1^-)$ mixing and Tensor force are important!

(mixing of S-wave and D-wave, like in deuteron)

3. Application 1: Leading order in $1/m_Q$ expansion

$J^P = 1/2^-, 3/2^-$



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

$$H_{1/2^-} = \begin{pmatrix} K_0 & \sqrt{3}C & -\sqrt{6}T \\ \sqrt{3}C & K_0-2C & -\sqrt{2}T \\ -\sqrt{6}T & -\sqrt{2}T & K_2+(C-2T) \end{pmatrix} \rightarrow \begin{pmatrix} K_0-3C & 0 & 0 \\ 0 & K_0+C & -2\sqrt{2}T \\ 0 & -2\sqrt{2}T & K_2+(C-2T) \end{pmatrix}$$

HQS singlet

Unitary transformation
(Heavy quark + Brown muck)

HQS doublet
(tensor potential)

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

$$H_{3/2^-} = \begin{pmatrix} K_2 & \sqrt{3}T & -\sqrt{3}T & \sqrt{3}C \\ \sqrt{3}T & K_0+C & 2T & T \\ -\sqrt{3}T & 2T & K_2+C & -T \\ \sqrt{3}C & T & -T & K_2-2C \end{pmatrix} \rightarrow \begin{pmatrix} K_0+C & 2\sqrt{2}T & 0 & 0 \\ 2\sqrt{2}T & K_2+(C-2T) & 0 & 0 \\ 0 & 0 & K_2-3C & 0 \\ 0 & 0 & 0 & K_2+(C+2T) \end{pmatrix}$$

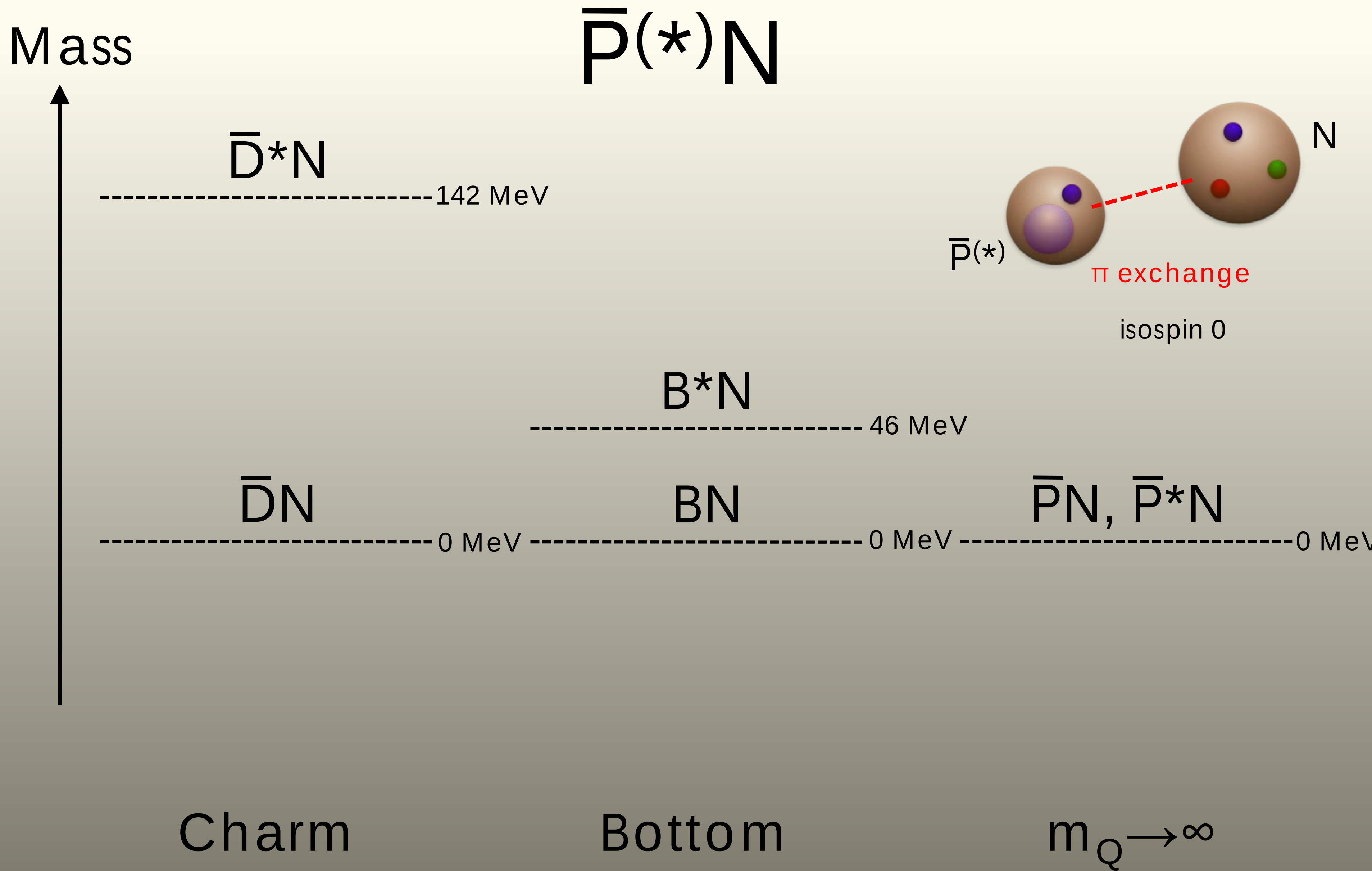
Unitary transformation
(Heavy quark + Brown muck)

K_L: kinetic term
(angular momentum L)
C: central potential
T: tensor potential

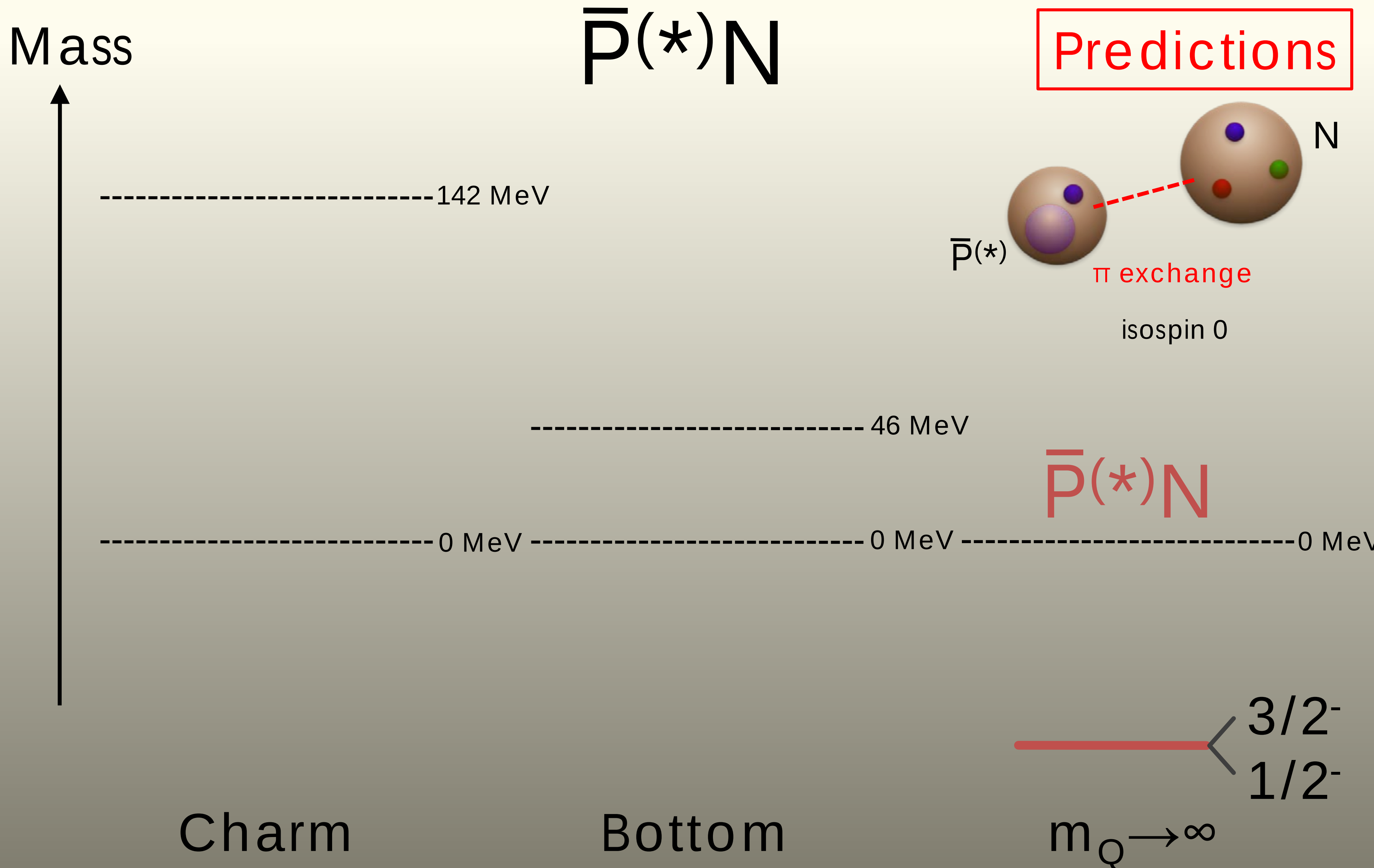
$1/2^-$ and $3/2^-$ are degenerate in mass.

HQS doublet

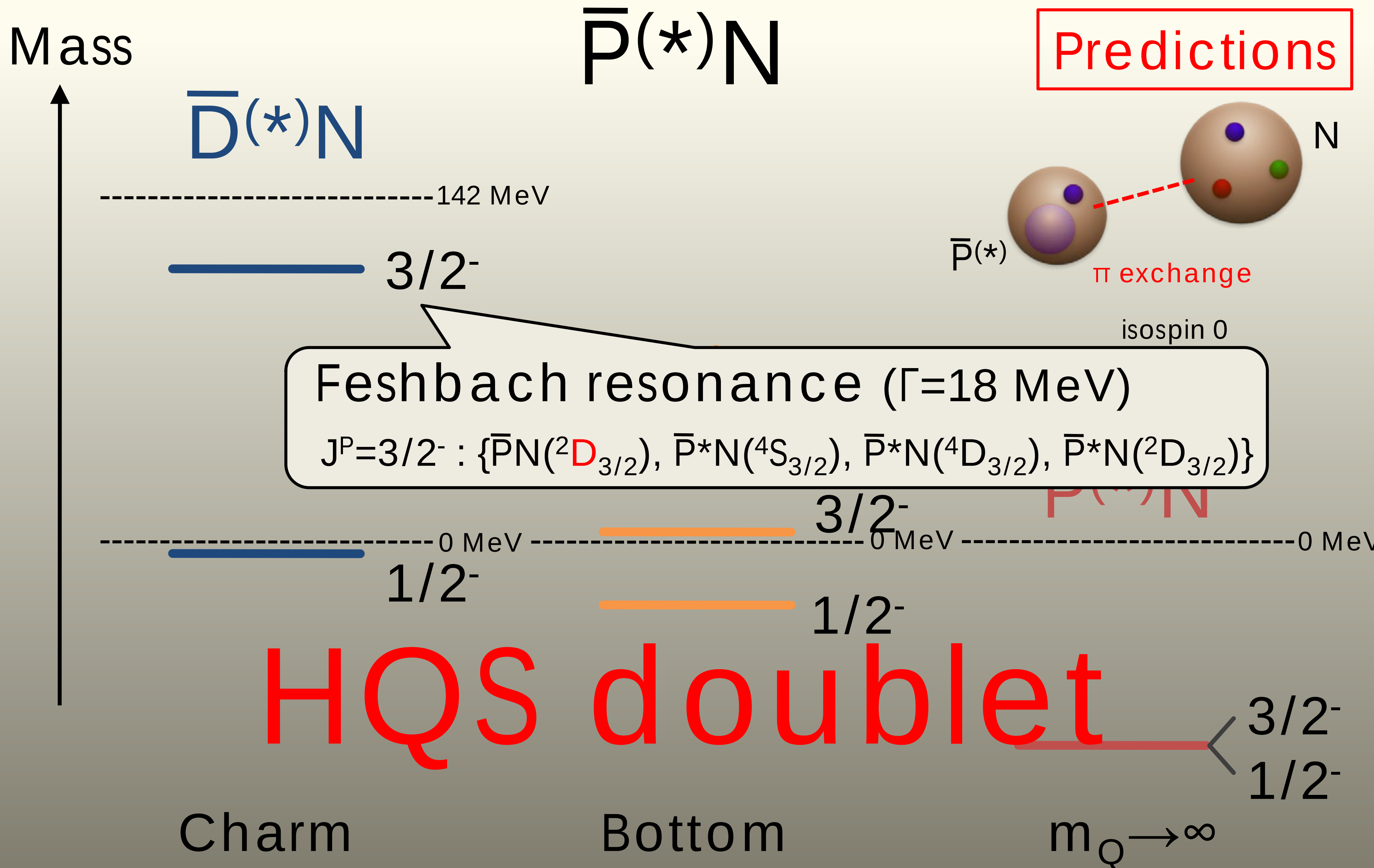
3. Application 1: Leading order in $1/m_Q$ expansion



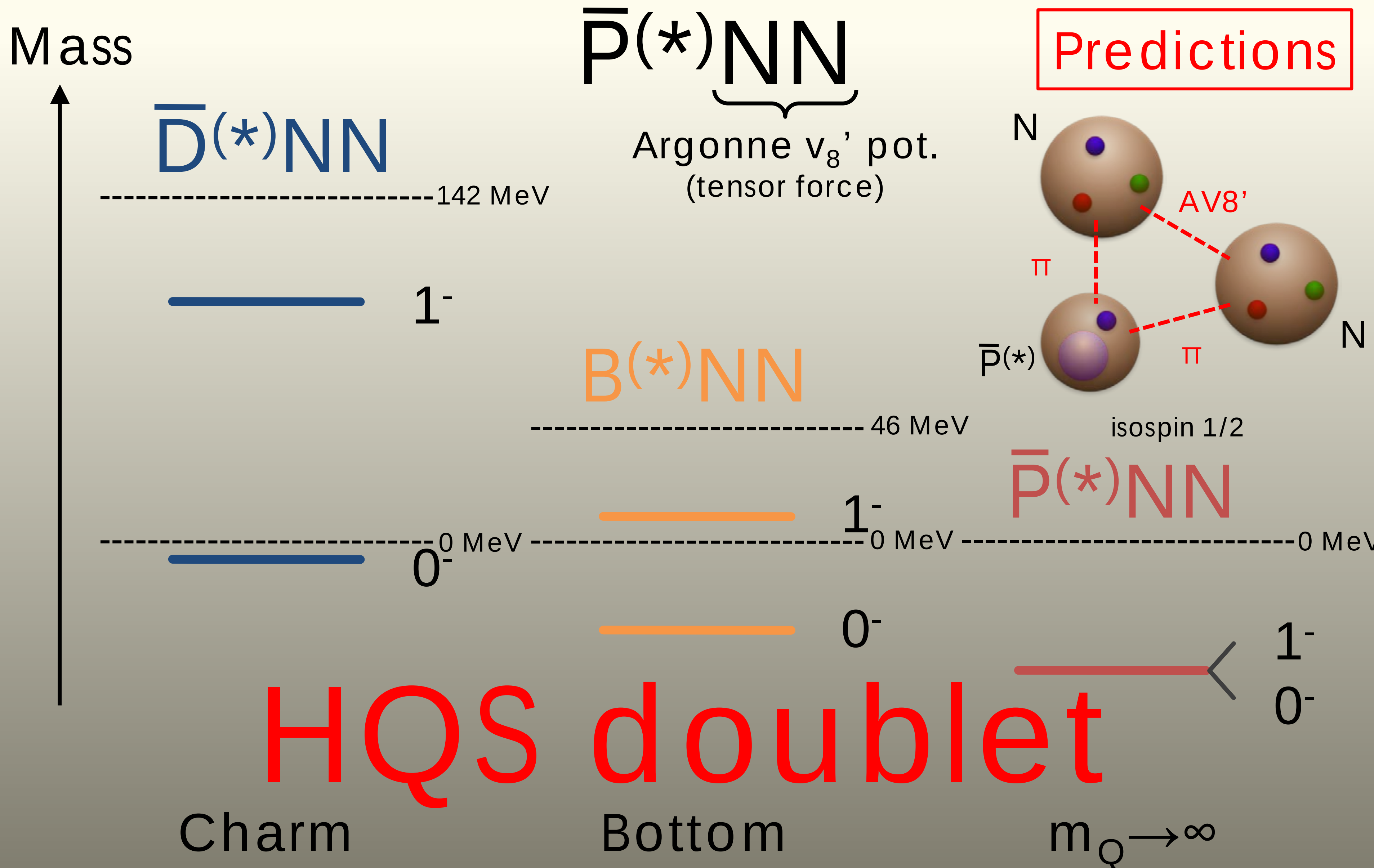
3. Application 1: Leading order in $1/m_Q$ expansion



3. Application 1: Leading order in $1/m_Q$ expansion

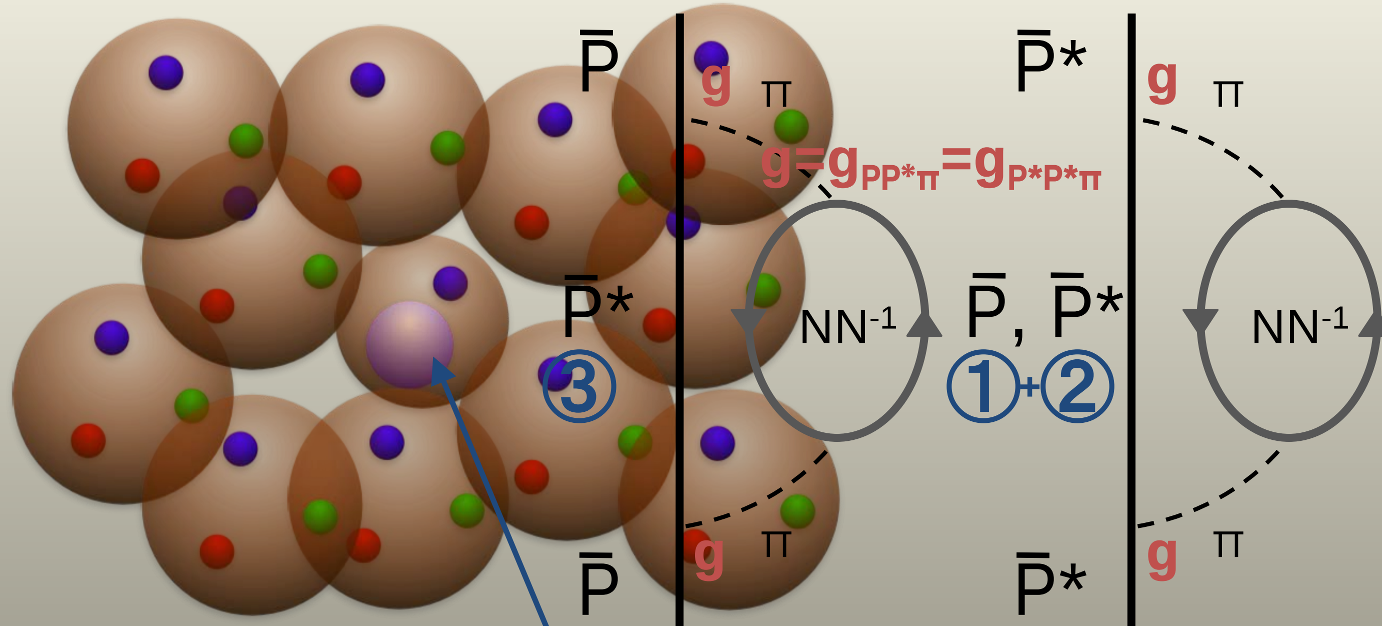


3. Application 1: Leading order in $1/m_Q$ expansion



3. Application 1: Leading order in $1/m_Q$ expansion

$\bar{P}^{(*)}$ in nuclear matter



$\bar{P}^{(*)}$ meson

In-medium mass of $\bar{P}$, $\bar{P}^*$ mesons in nuclear matter.

HQS doublet

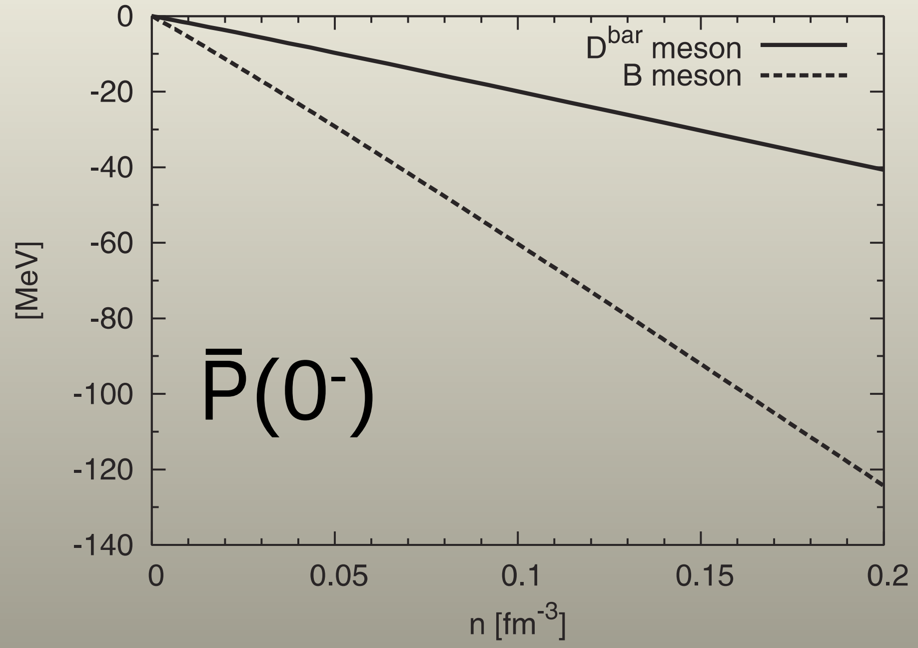
$\mathrm{Mass}(\bar{P}) = \mathrm{Mass}(\bar{P}^*)$

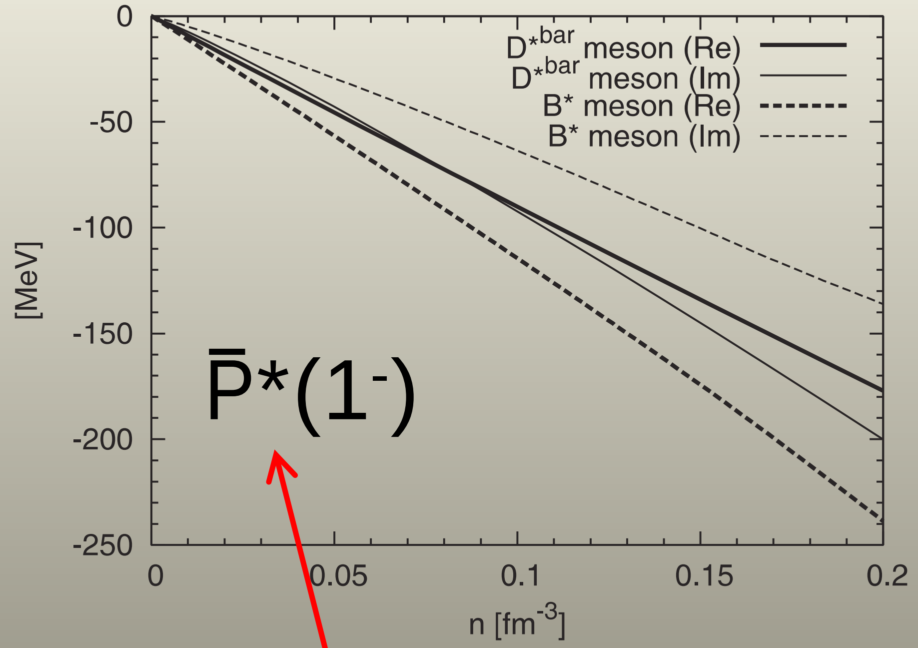
Cf. HQS singlet in "pion condensate" (Suenaga, He, Ma, Harada, PRC89, 068201 (2014))

3. Application 1: Leading order in $1/m_Q$ expansion

Numerical results for cutoff momentum 800 MeV

$P(0^-)$, $P^*(1^-)$ self-energy in nuclear medium





1. Imaginary parts
2. Large mass drop

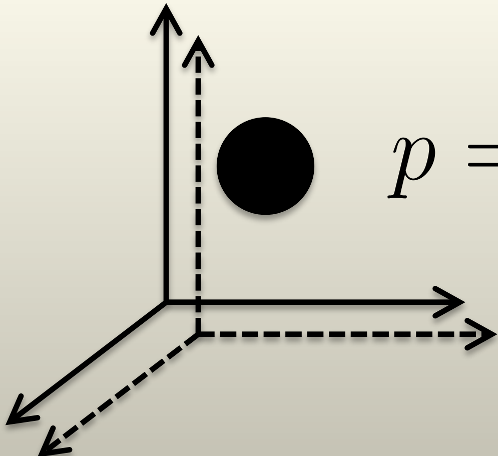
4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

$1/m_Q$ expansion

LO + NLO

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

Change of “velocity-frame”



$$p = m_Q v + k$$

$$w^\mu = v^\mu - (k' - k)^\mu / m_Q$$

$$p = m_Q w + k'$$

velocity-rearrangement

$$v \to v + q/m_Q$$

Effective field

$$Q_v \to e^{iq\cdot x}\left(1 + \frac{\not{q}}{2m_Q}\right) Q_v$$

Ex. Heavy Quark Effective Theory

$$\mathcal{L}_0 = \bar{Q}_v iv\cdot D Q_v \qquad \mathcal{L}_1 = \bar{Q}_v \frac{(iD_\perp)^2}{2m_Q} Q_v - g_s \bar{Q}_v \frac{\sigma_{\mu\nu}G^{\mu\nu}}{4m_Q} Q_v$$

$$\mathcal{L}_0 \to \mathcal{L}_0 + \frac{1}{m_Q}\bar{Q}_v iq\cdot D Q_v \qquad \mathcal{L}_1 \to \mathcal{L}_1 - \frac{1}{m_Q}\bar{Q}_v iq\cdot D Q_v$$

$L_0 + L_1$: invariant

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

Heavy hadron mass "parametrization"

$1/m_Q$ expansion

$$M_H(\rho) = m_Q + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_Q} + 4\vec{S}\cdot\vec{j}\,\frac{\lambda_2(\rho;m_Q)}{2m_Q} + \mathcal{O}(1/m_Q^2)$$

ρ: nuclear matter density

at NLO

$$\frac{\lambda_1(\rho)}{m_Q} = -\left\langle H_{v_r}(\rho)\right|\overline{Q}_{v_r} g_s \vec{x}\cdot\vec{E} Q_{v_r}\left|H_{v_r}(\rho)\right\rangle$$

M.Neubert, Phys. Lett. B322, 419 (1994)

Color **electric** gluon

$$8\vec{S}\cdot\vec{j}\,\lambda_2(\rho;m_Q) = \frac{1}{2}c(\mu)\left\langle H_{v_r}(\rho)\right|\overline{Q}_{v_r} g_s \vec{\sigma}\cdot\vec{B} Q_{v_r}\left|H_{v_r}(\rho)\right\rangle$$

Color **magnetic** gluon

"Non-perturbative" gluon

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

Can we calculate hadron w.f.

in nuclear medium from ***QCD***?

Very difficult, but...

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

$$M_{\mathrm{H}}(\rho) = m_{\mathrm{Q}} + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_{\mathrm{Q}}} + 4\vec{S}\cdot\vec{j}\,\frac{\lambda_2(\rho;m_{\mathrm{Q}})}{2m_{\mathrm{Q}}} + \mathcal{O}(1/m_{\mathrm{Q}}^2)$$

Heavy hadron effective theory

LO + NLO

$1/m_Q$ expansion in quark ⇄ $1/M$ expansion in hadron

$M = m_Q + \Lambda + 1/m_Q + \mathcal{O}(1/m_Q^2)$

$1/M = 1/m_Q + \mathcal{O}(1/m_Q^2)$

Question: what is NLO?

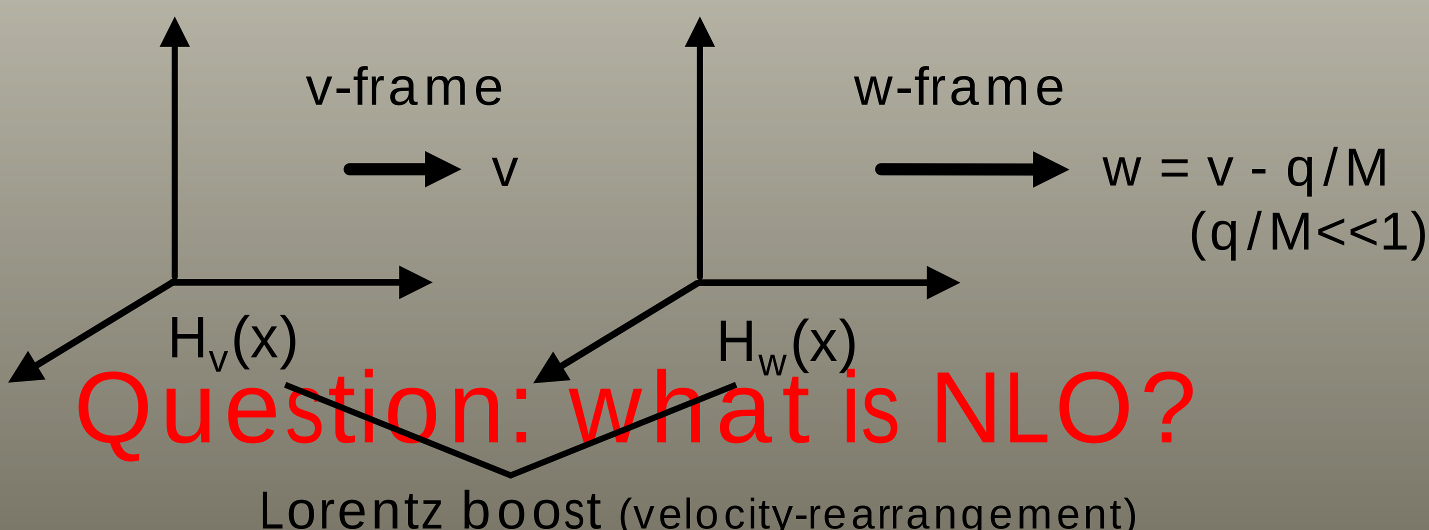
4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

How to construct effective Lagrangian?

1. Heavy quark symmetry is conserved at O(1).

2. Invariance under Lorentz boost at O(1)+O(1/M).

Luke, Manohar, PLB286, 348 (1992), Kitazawa, Kurimoto, PLB323, 65 (1994)



Question: what is NLO?

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

How to construct effective Lagrangian?

1. Heavy quark symmetry is conserved at O(1).

2. Invariance under Lorentz boost at O(1)+O(1/M).

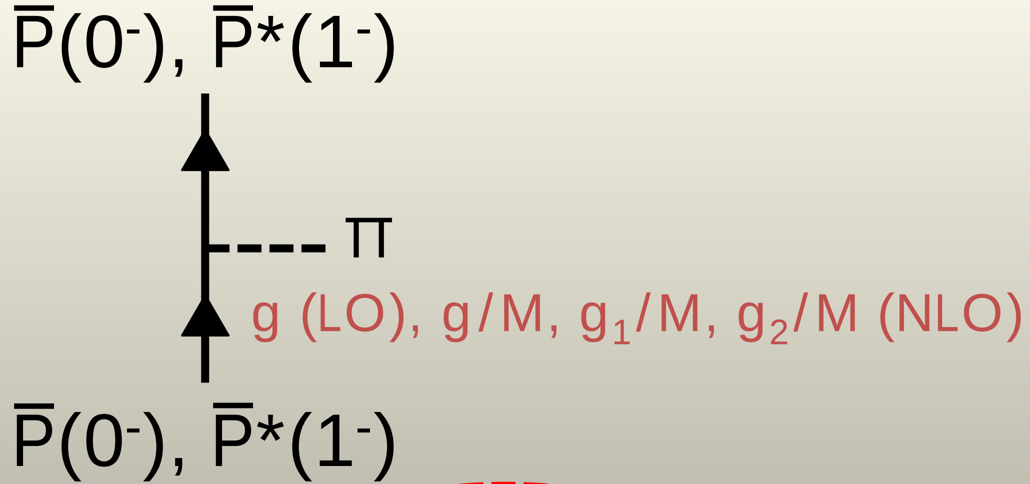
Luke, Manohar, PLB286, 348 (1992), Kitazawa, Kurimoto, PLB323, 65 (1994)

3. Heavy quark symmetry breaking terms at O(1/M).

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

Kitazawa, Kurimoto, PLB323, 65 (1994)

Heavy meson effective theory with 1/M corrections



$$\mathcal{L}_{\rm HMET}^{\rm LO+NLO} = -{\rm Tr}\overline{\mathcal{H}}_v v\cdot iD\mathcal{H}_v + \frac{\lambda}{M}{\rm Tr}\overline{\mathcal{H}}_v\sigma^{\mu\nu}\mathcal{H}_v\sigma_{\mu\nu}$$

spin-flip (1/M)

$$+\left(g+\frac{g_1}{M}\right){\rm Tr}\overline{\mathcal{H}}_v\mathcal{H}_v\gamma_\mu\gamma_5A^\mu + \frac{g_2}{M}{\rm Tr}\overline{\mathcal{H}}_v\gamma_\mu\gamma_5\mathcal{H}_vA^\mu$$

$$+\mathcal{O}(1/M^2)$$

"Covariant" field for velocity-rearrangement

$$\mathcal{H}_v = H_v + \frac{1}{2M}(i\overrightarrow{\not{D}}H_v - H_v i\overleftarrow{\not{D}} - 2v\,iDH_v) + \mathcal{O}(1/M^2)$$

4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

$$M_{\mathrm{H}}(\rho) = m_{\mathrm{Q}} + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_{\mathrm{Q}}} + 4\vec{S}\cdot\vec{j}\,\frac{\lambda_2(\rho; m_{\mathrm{Q}})}{2m_{\mathrm{Q}}} + \mathcal{O}(1/m_{\mathrm{Q}}^2)$$

$\bar{P}^{(*)}$ in nuclear matter

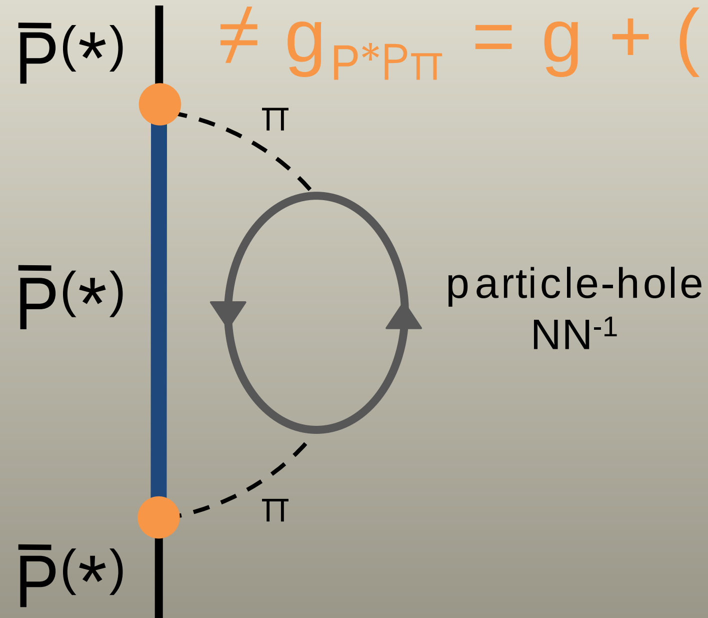
with breaking of HQS

$g_{P^*P^*\pi} = g + (g_1+\mathbf{g_2})/M$

$\neq g_{P^*P\pi} = g + (g_1-\mathbf{g_2})/M$

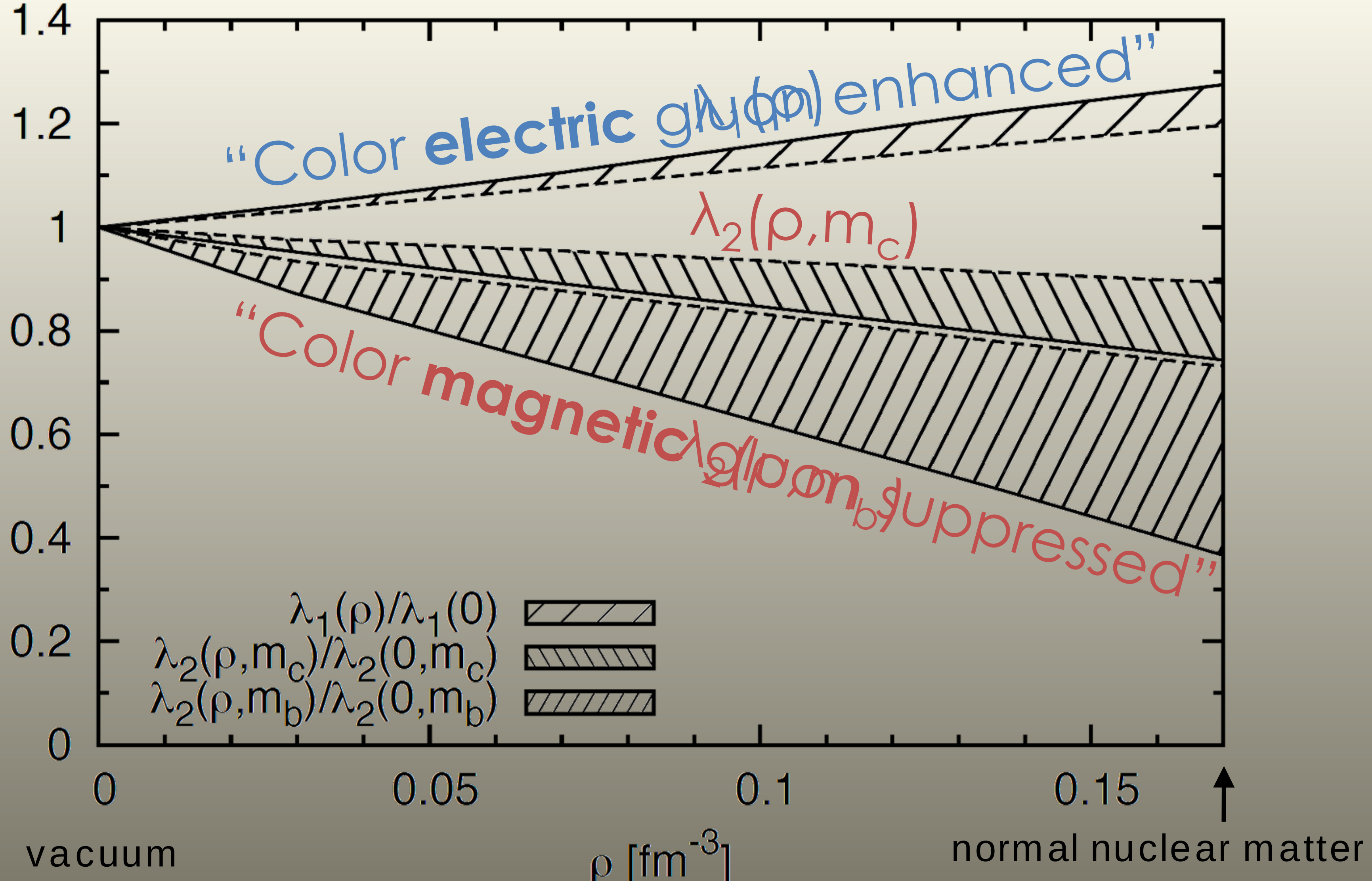
$M_{P^*} = M-2\boldsymbol{\lambda}/M$

$\neq M_P = M+6\boldsymbol{\lambda}/M$

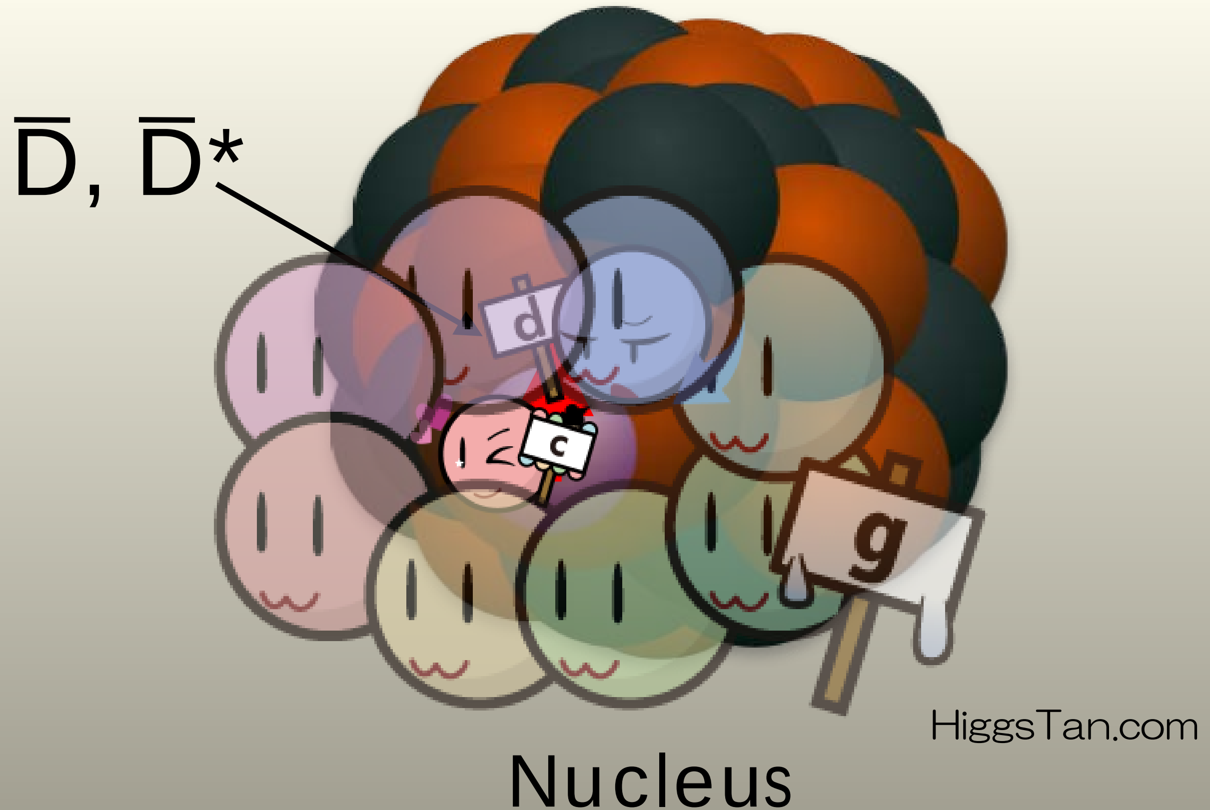


4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion

$$M_H(\rho) = m_Q + \bar{\Lambda}(\rho) - \frac{\lambda_1(\rho)}{2m_Q} + 4\vec{S}\cdot\vec{j}\,\frac{\lambda_2(\rho; m_Q)}{2m_Q} + \mathcal{O}(1/m_Q^2)$$



4. Appl.2: Next-to-Leading order in $1/m_Q$ expansion



Charm hadron → **Probing gluon fields**

5. Conclusion

1. We discuss heavy quark symmetry (HQS) at LO in $1/m_Q$ expansion.

2. HQS gives doublet/singlet in mass spectrum in exotic heavy hadrons and nuclei.

3. Mass modifications and splitting of $\bar{D}$ and $\bar{D}^*$ mesons are concerned with gluon in medium.

4. Toward experiments at J-PARC, GSI-FAIR, LHC, RHIC, etc.!!

5. Conclusion

Many open problems...

- Relation to other fundamental aspects of QCD？
  (Dynamical breaking of chiral symmetry, Quark Confinement, ...)

- Hadron-nucleon interaction？ Many-body physics？
  (Pion exchange, Mean field approximation, Symmetry restoration, ...)

- What about atomic nucleus with charm？

- Lattice QCD: what QCD says about charm nucleus？

- Production cross sections of charm nucleus？

- etc.

References

HQS doublet/singlet in exotic hadrons and nuclei

S.Y., K.Sudoh, Y.Yamaguchi, S.Ohkoda, A.Hosaka, T.Hyodo, Phys. Lett. B727, 185 (2013)

Y.Yamaguchi, S.Ohkoda, T.Hyodo, A.Hosaka, S.Y., Phys. Rev. D91, 034034 (2015)

$\bar{D}^{(*)}N$, $\bar{D}^{(*)}NN$ hadronic molecules

S.Y., K.Sudoh, Phys. Rev. D80, 034008 (2009)

Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D84, 014032 (2011)

Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D85, 054003 (2013)

Y.Yamaguchi, S.Y., A.Hosaka, Nucl. Phys. A927, 110 (2014)

$\bar{D}^{(*)}$ in nuclear matter and Kondo effects

S.Y., K.Sudoh, Phys. Rev. C87, 015202 (2013)

S.Y., K.Sudoh, Phys. Rev. C88, 015201 (2013)

NLO in $1/m_Q$ expansion for $\bar{D}^{(*)}$ in nuclear matter

S.Y., K.Sudoh, Phys. Rev. C89, 015201 (2014)

$D^{(*)}N$ hadronic molecules

Y.Yamaguchi, S.Ohkoda, S.Y., A.Hosaka, Phys. Rev. D87, 074019 (2013)