Charmed mesons in cold nuclear matter from chiral effective model

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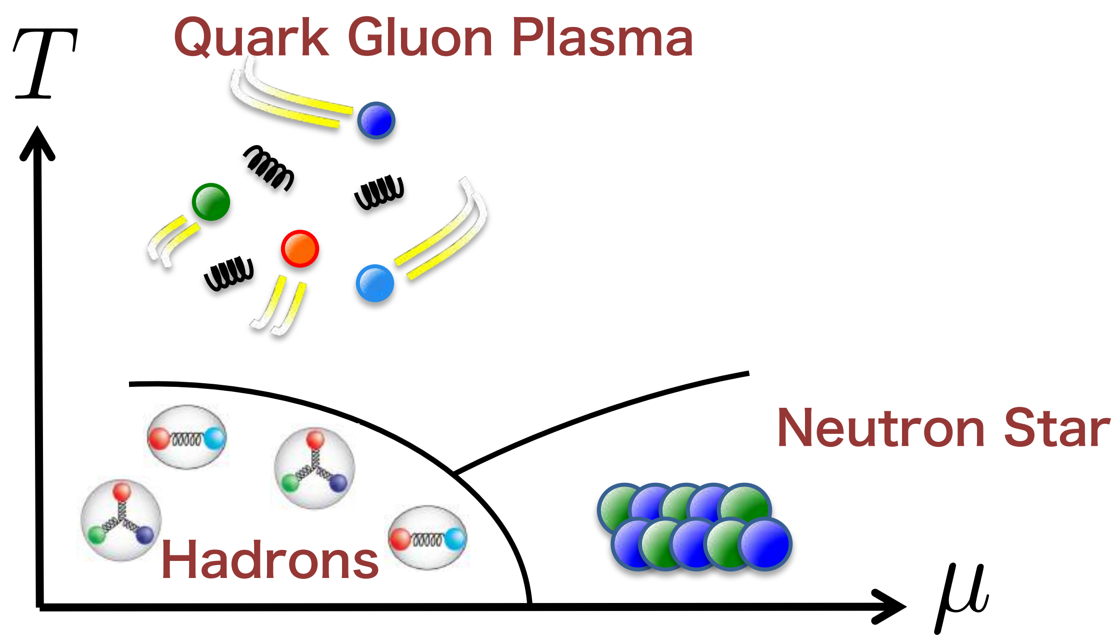
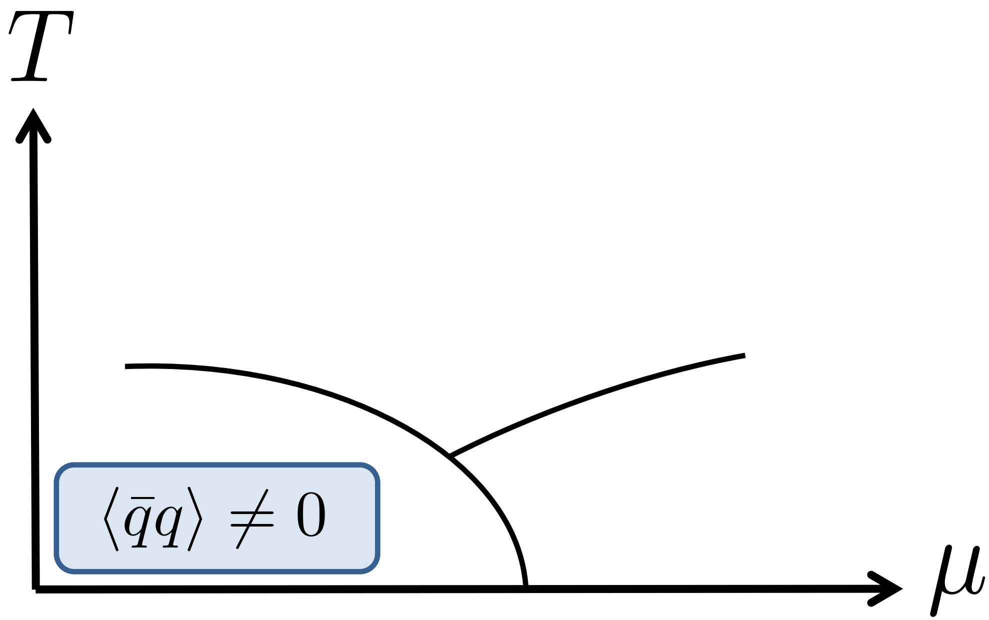
1. Introduction

- **Chiral symmetry in medium**
  - QCD phase diagram



1. Introduction

- **Chiral symmetry in medium**
  - QCD phase diagram **in terms of chiral symmetry**



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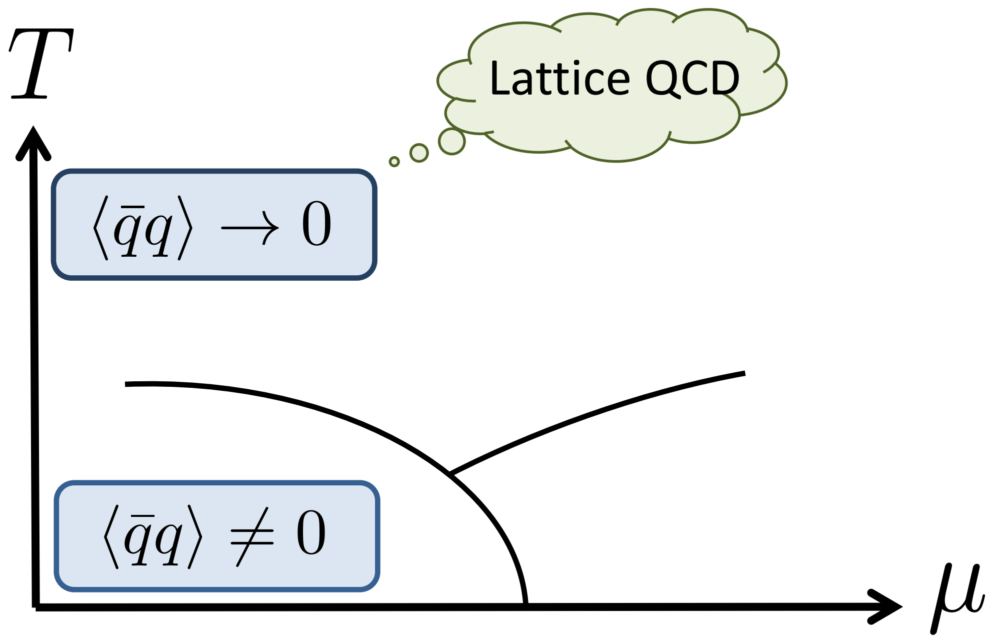

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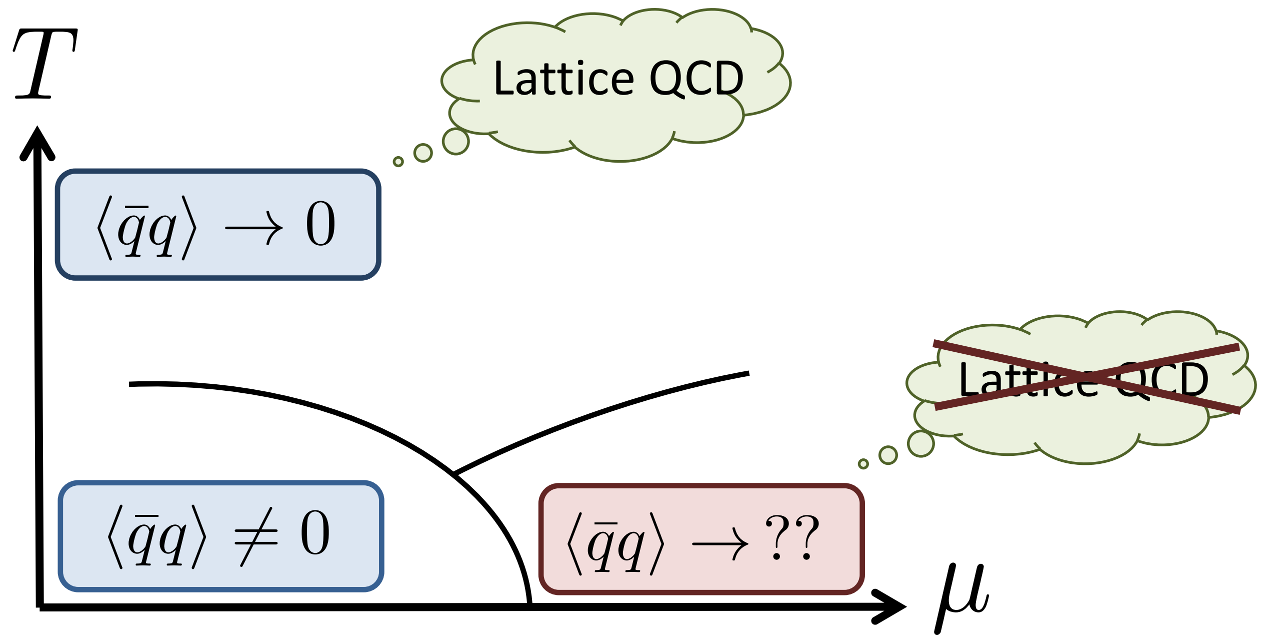

– Chiral symmetry at density is not understood well. . .

1. Introduction

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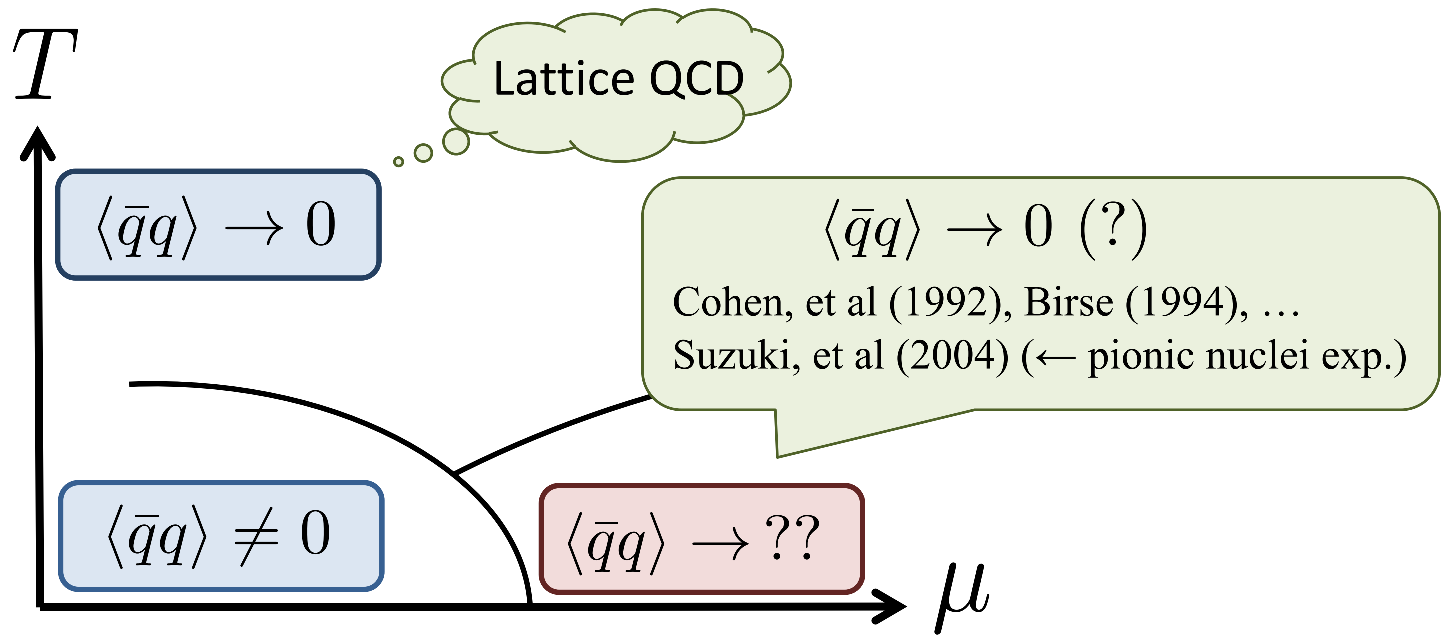
  - QCD phase diagram **in terms of chiral symmetry**

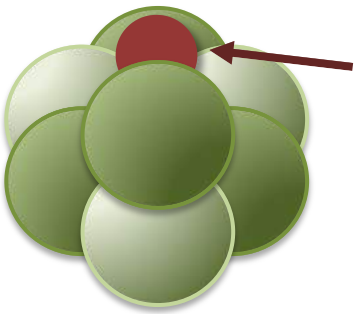


– Chiral symmetry at density is not understood well. . .

1. Introduction

- **Our proposal**

  - $\bar{D}\ (\sim \bar{c}q)$ mesons can be good probes



$\bar{D}$ mesons in nuclear matter

D. Suenaga, et. al, PRC (2014); D.Suenaga, et al, PRD (2015)
D. Suenaga and M. Harada PRD (2016); M. Harada, et al, PTEP (2017)
D. Suenaga, et. al, PRC96 (2017); D. Suenaga, 1805.01709 (2018)

Advantages

– $\bar{D}$ mesons have large masses compared to Λ_{QCD}

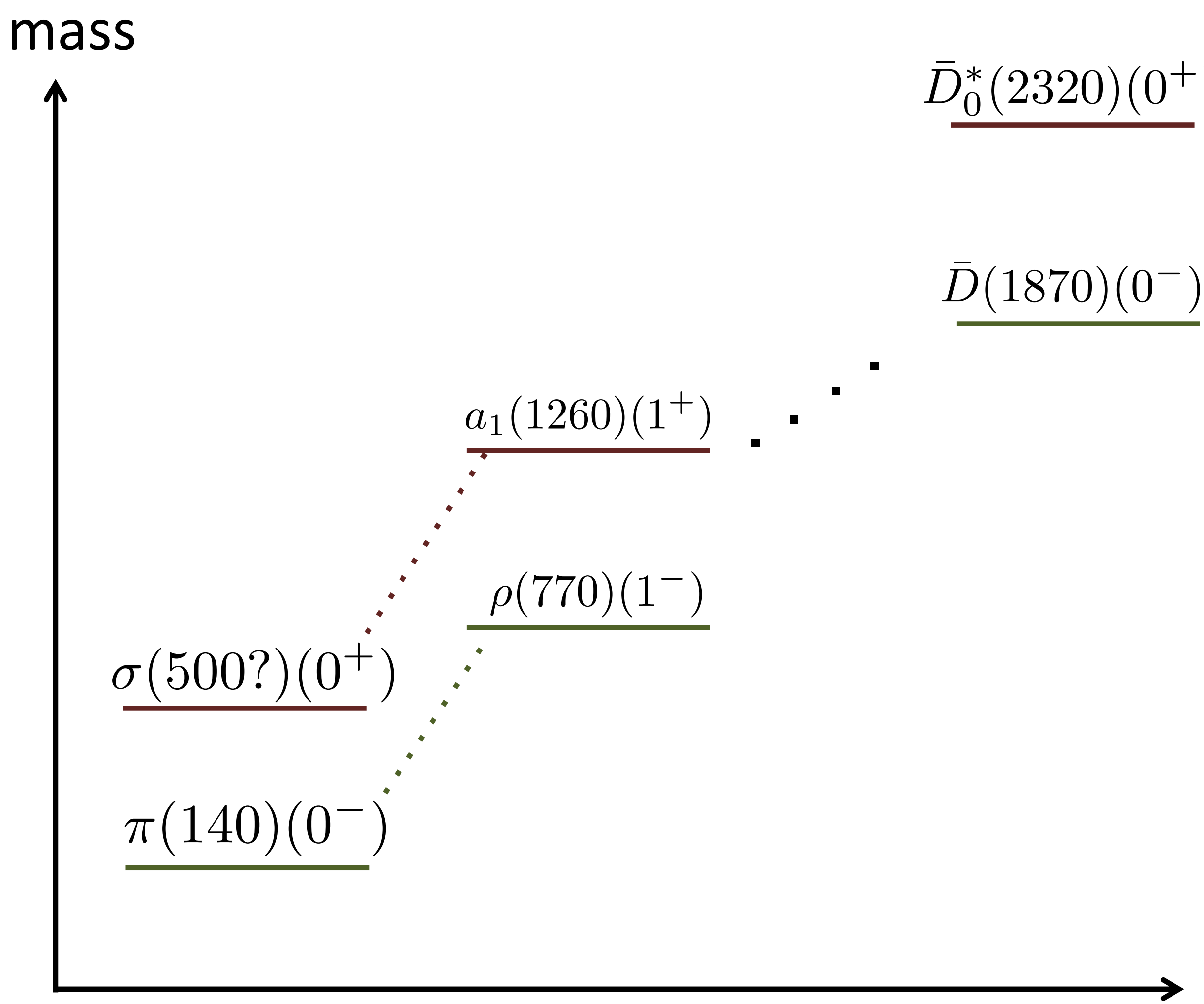
⟹ $SU(2)_S$ **heavy quark spin symmetry**

– $\bar{D}$ mesons contain only one light quark

⟹ **fundamental rep. of** $SU(2)_L \times SU(2)_R$ **chiral group**

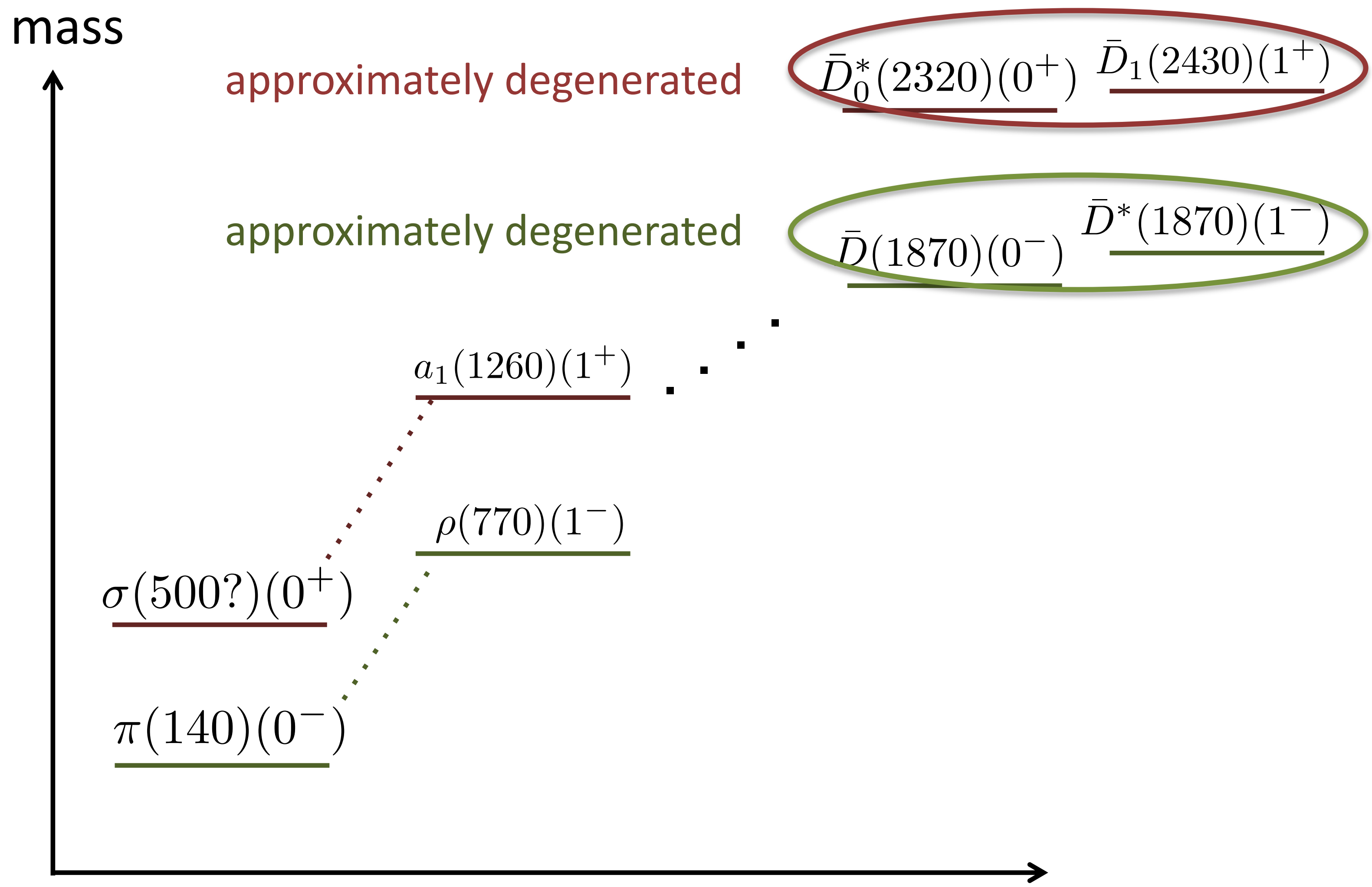
1. Introduction

- **What is $\bar{D}$ meson ?**

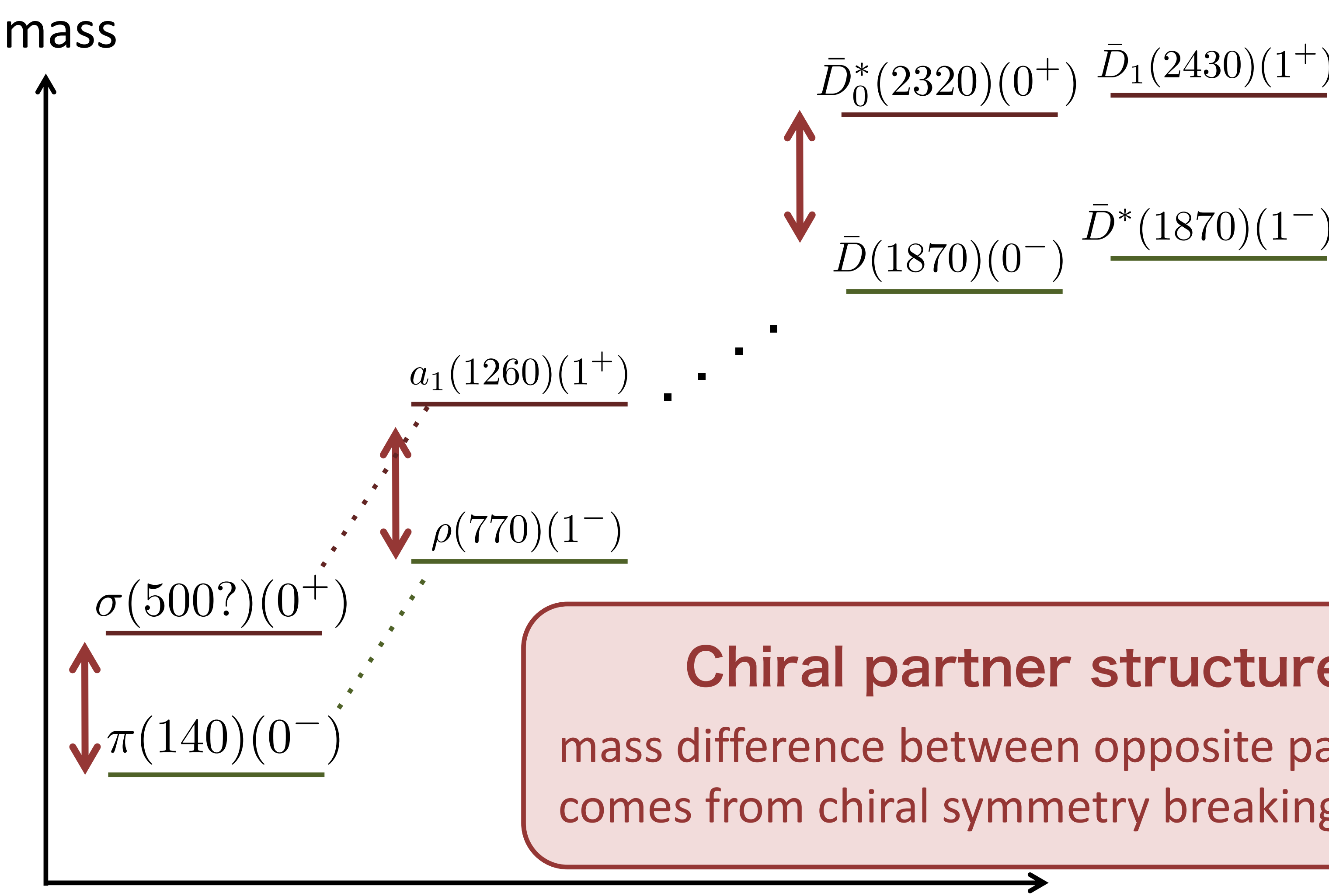


1. Introduction

- **What is $\bar{D}$ meson ?**



- **Chiral partner structure**

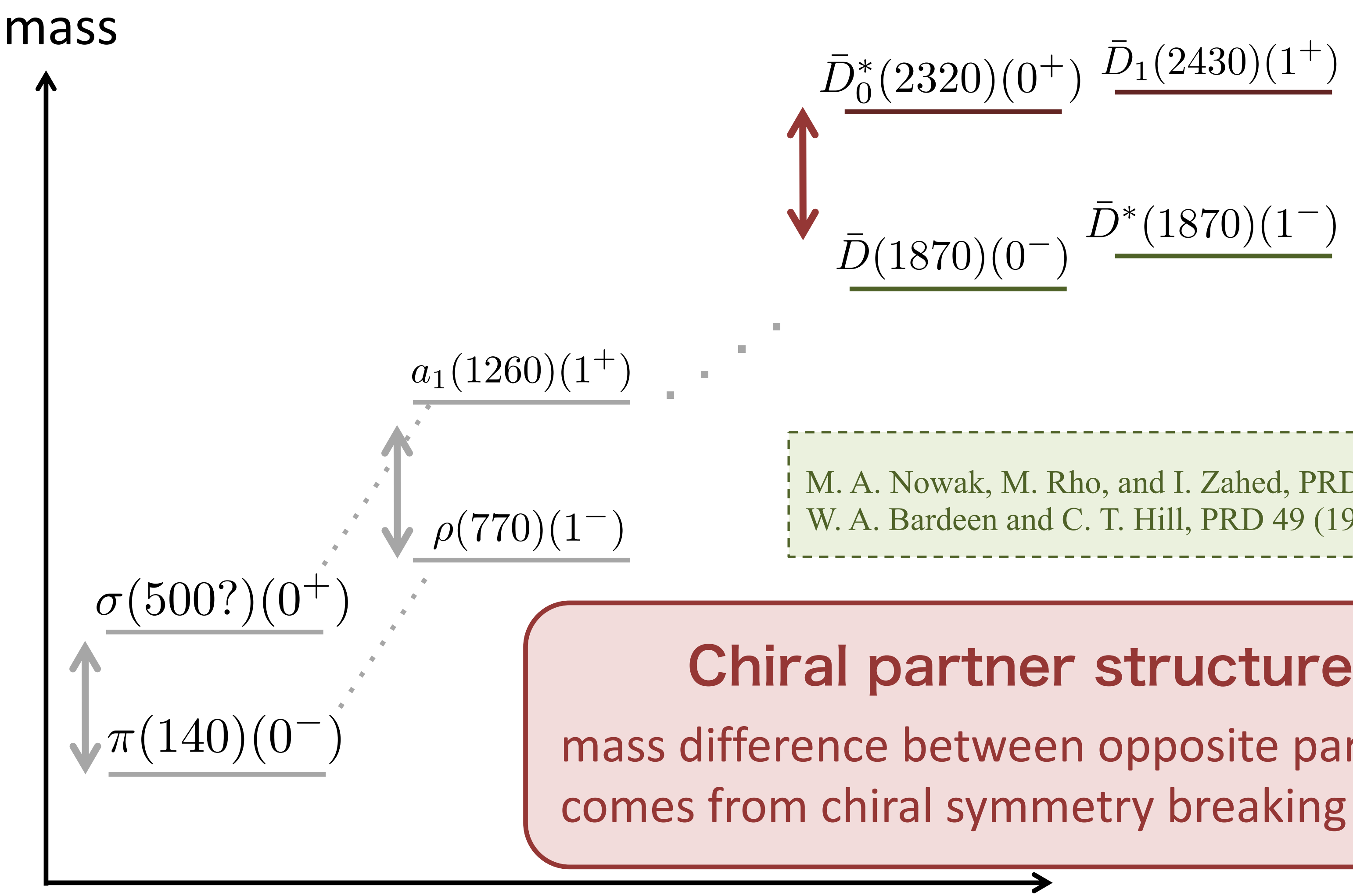


Chiral partner structure

mass difference between opposite parity state comes from chiral symmetry breaking

1. Introduction

- **Chiral partner structure**



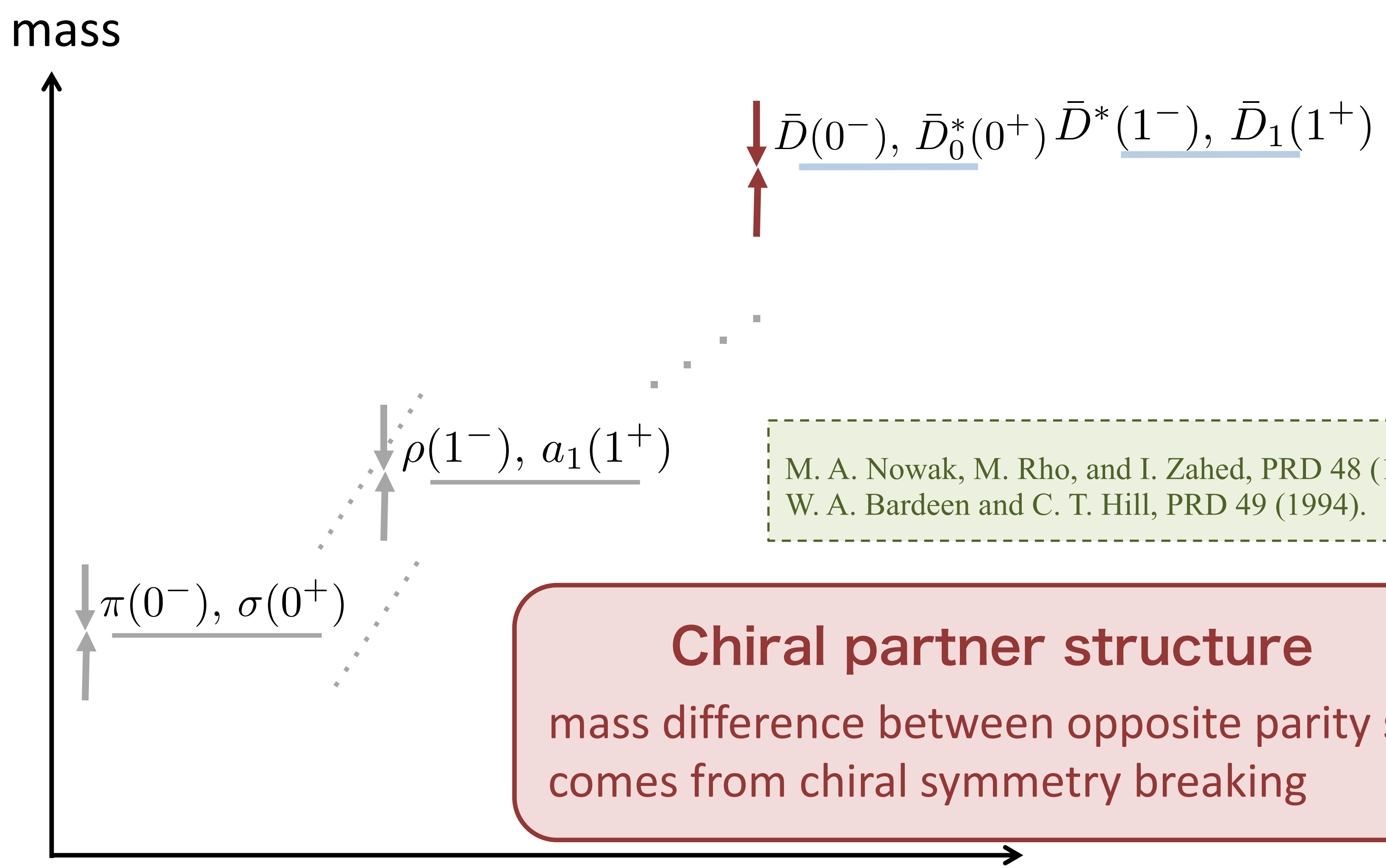
M. A. Nowak, M. Rho, and I. Zahed, PRD 48 (1993)
W. A. Bardeen and C. T. Hill, PRD 49 (1994).

Chiral partner structure

mass difference between opposite parity state comes from chiral symmetry breaking

1. Introduction

- **At chiral restored point**



M. A. Nowak, M. Rho, and I. Zahed, PRD 48 (1993)
W. A. Bardeen and C. T. Hill, PRD 49 (1994).

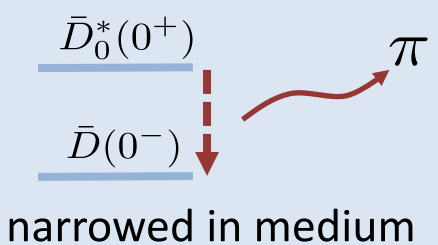
Chiral partner structure

mass difference between opposite parity state comes from chiral symmetry breaking

1. Introduction

- **What should we calculate ?**
  - It is worth calculating **spectral function** for $\bar{D}_0^*(0^+)$ meson because . . .

(I) The shape of spectral function reflects imaginary part for decay of $\bar{D}_0^* \to \bar{D}\pi$



(II) The spectral function is directly reflected into a double differential cross section $\frac{\partial^2\sigma}{\partial\Omega_D dE_D}$ (I will talk later in detail)

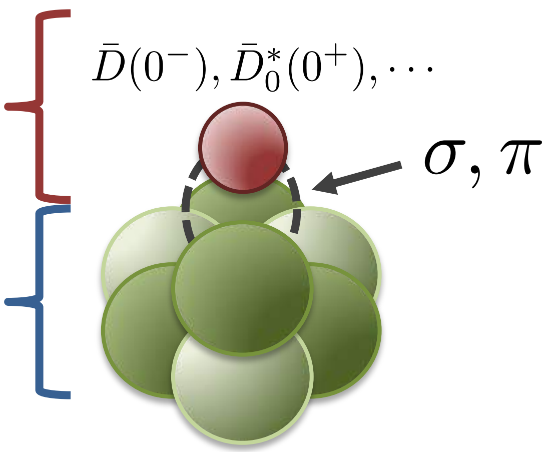
Contents

2. Model

- **Calculation method**
  - Medium effects to $\bar{D}$ mesons are mediated by σ, π meson exchanges

Effective Lagrangian based on chiral partner structure of $\bar{D}$ mesons

D. Suenaga and M. Harada PRD93 (2016)
D. Suenaga, M. Harada and S. Yasui PRC96 (2017)



Nuclear matter is constructed by parity doublet model with one loops

Y. Motohiro, Y. Kim, M. Harada,PRC92(2015)
D. Suenaga, PRC97 (2018)

2. Model

- **Symmetry of heavy-light mesons**
  - Lagrangian for $\bar{D}$ mesons should be invariant under the . . .

(I) $SU(2)_L \times SU(2)_R$ chiral symmetry

(II) $SU(2)_S$ heavy quark spin symmetry (approximately)

(III) parity

2. Model

- **Heavy meson effective Lagrangian**
  - The Lagrangian in a relativistic form is

$$
\begin{aligned}
\mathcal{L} = & \partial_\mu \bar{D}_0^* \partial^\mu \bar{D}_0^{*\dagger} - \left(m^2 - m\delta_{\bar{D}_0^*}\right) \bar{D}_0^* \bar{D}_0^{*\dagger} - \partial_\mu \bar{D}_{1\nu} \partial^\mu \bar{D}_1^{\dagger\nu} + \partial_\mu \bar{D}_{1\nu} \partial^{\dagger\mu} D_1^\nu + \left(m^2 + m\delta_{\bar{D}_1}\right) \bar{D}_{1\mu} \bar{D}_1^{\dagger\mu} \\
& + \partial_\mu \bar{D} \partial^\mu \bar{D}^\dagger - \left(m^2 - m\delta_{\bar{D}}\right) \bar{D} \bar{D}^\dagger - \partial_\mu \bar{D}_\nu^* \partial^\mu \bar{D}^{*\dagger\nu} + \partial_\mu \bar{D}_\nu^* \partial^{\dagger\mu} D^{*\nu} + \left(m^2 + m\delta_{\bar{D}^*}\right) \bar{D}_\mu^* \bar{D}^{*\dagger\mu} \\
& - \frac{1}{2} \frac{m\Delta_m}{f_\pi} [\bar{D}_0^*(M + M^\dagger)\bar{D}_0^{*\dagger} - \bar{D}_{1\mu}(M + M^\dagger)\bar{D}_1^{\dagger\mu} - \bar{D}(M + M^\dagger)\bar{D}^\dagger + \bar{D}_\mu^*(M + M^\dagger)\bar{D}^{*\mu\dagger}] \\
& - \frac{1}{2} \frac{m\Delta_m}{f_\pi} [\bar{D}_0^*(M - M^\dagger)\bar{D}^\dagger - \bar{D}_{1\mu}(M - M^\dagger)\bar{D}^{*\dagger\mu} - \bar{D}(M - M^\dagger)\bar{D}_0^{*\dagger} + \bar{D}_\mu^*(M - M^\dagger)\bar{D}_1^{\dagger\mu}] \\
& - \frac{g}{2} \frac{m}{f_\pi} [\bar{D}_1^\mu(\partial_\mu M^\dagger - \partial_\mu M)\bar{D}_0^{*\dagger} - \bar{D}_0^*(\partial_\mu M^\dagger - \partial_\mu M)\bar{D}_1^{\dagger\mu} - \frac{1}{m}\epsilon^{\mu\nu\rho\sigma}\bar{D}_{1\mu}(\partial_\nu M^\dagger - \partial_\nu M)i\partial_\sigma \bar{D}_{1\rho}^\dagger] \\
& + \frac{g}{2} \frac{m}{f_\pi} [\bar{D}^{*\mu}(\partial_\mu M^\dagger - \partial_\mu M)\bar{D}^\dagger - \bar{D}(\partial_\mu M^\dagger - \partial_\mu M)\bar{D}^{*\dagger\mu} - \frac{1}{m}\epsilon^{\mu\nu\rho\sigma}\bar{D}_\mu^*(\partial_\nu M^\dagger - \partial_\nu M)i\partial_\sigma \bar{D}_\rho^{*\dagger}] \\
& + \frac{g}{2} \frac{m}{f_\pi} [\bar{D}_1^\mu(\partial_\mu M^\dagger + \partial_\mu M)\bar{D}^\dagger + \bar{D}(\partial_\mu M^\dagger + \partial_\mu M)\bar{D}_1^{\dagger\mu}] \\
& - \frac{g}{2} \frac{m}{f_\pi} [\bar{D}_0^*(\partial_\mu M^\dagger + \partial_\mu M)\bar{D}^{*\dagger\mu} + \bar{D}^{*\mu}(\partial_\mu M^\dagger + \partial_\mu M)\bar{D}_0^{*\dagger}] \\
& - \frac{g}{2} \frac{1}{f_\pi} [\epsilon^{\mu\nu\rho\sigma}\bar{D}_{1\nu}(\partial_\rho M^\dagger + \partial_\rho M)i\partial_\sigma \bar{D}_\mu^{*\dagger} + \epsilon^{\mu\nu\rho\sigma}\bar{D}_\mu^*(\partial_\rho M^\dagger + \partial_\rho M)i\partial_\sigma \bar{D}_{1\nu}^\dagger] \,,
\end{aligned}
$$

$$M = \sigma + i\tau^a\pi^a$$

M. A. Nowak, M. Rho, and I. Zahed, PRD 48 (1993)
W. A. Bardeen and C. T. Hill, PRD 49 (1994).

2. Model

- **Heavy meson effective Lagrangian**
  - Under the spontaneous chiral symmetry breaking: $\sigma = \sigma_0$

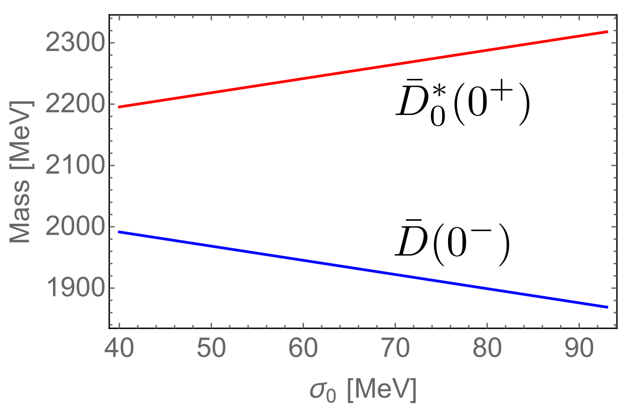
$$m_{\bar{D}_0^*} = m + \frac{\Delta_m}{2f_\pi}\sigma_0 - \frac{\delta_{\bar{D}_0^*}}{2} \qquad m_{\bar{D}_1} = m + \frac{\Delta_m}{2f_\pi}\sigma_0 + \frac{\delta_{\bar{D}_1}}{2}$$

$$m_{\bar{D}} = m - \frac{\Delta_m}{2f_\pi}\sigma_0 - \frac{\delta_{\bar{D}}}{2} \qquad m_{\bar{D}^*} = m - \frac{\Delta_m}{2f_\pi}\sigma_0 + \frac{\delta_{\bar{D}^*}}{2}$$

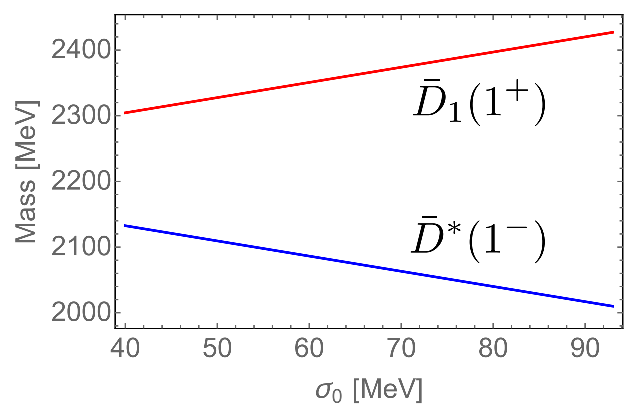
$m \cong$ (average mass of chiral partners)

$\Delta_m \cong$ (mass difference of chiral partners)

($\delta_{\bar{D}}, \delta_{\bar{D}^*}, \delta_{\bar{D}_0^*}, \delta_{\bar{D}_1}$ are added by the small violation of HQSS)



Chiral restoring



Chiral restoring

2. Model

- **Parity doublet model**
  - Let us introduce two types of fermions: $N_1\,(\mathrm{naive})$ and $N_2\,(\mathrm{mirror})$

$$N_{1L} \to g_L N_{1L}\ , \quad N_{1R} \to g_R N_{1R}$$
$$N_{2L} \to g_R N_{2L}\ , \quad N_{2R} \to g_L N_{2R}$$

under $SU(2)_L \times SU(2)_R$

C. E. DeTar and T. Kunihiro (1989)
D. Jido, M. Oka, and A. Hosaka (2001)

  - Chiral invariant Lagrangian is given by

$$\begin{aligned}
\mathcal{L}_N \;=\;& \bar{N}_{1R}\Big(i\partial\!\!\!/ + (\mu_B + \frac{\mu_I}{2}\tau^3)\gamma_0 - g_\omega \omega\!\!\!/ - g_\rho \rho\!\!\!/\Big) N_{1R} + \bar{N}_{1L}\Big(i\partial\!\!\!/ + (\mu_B + \frac{\mu_I}{2}\tau^3)\gamma_0 - g_\omega \omega\!\!\!/ - g_\rho \rho\!\!\!/\Big) N_{1L} \\
& + \bar{N}_{2R}\Big(i\partial\!\!\!/ + (\mu_B + \frac{\mu_I}{2}\tau^3)\gamma_0 - g_\omega \omega\!\!\!/ - g_\rho \rho\!\!\!/\Big) N_{2R} + \bar{N}_{2L}\Big(i\partial\!\!\!/ + (\mu_B + \frac{\mu_I}{2}\tau^3)\gamma_0 - g_\omega \omega\!\!\!/ - g_\rho \rho\!\!\!/\Big) N_{2L} \\
& - m_0 \left[\bar{N}_{1L} N_{2R} - \bar{N}_{1R} N_{2L} - \bar{N}_{2L} N_{1R} + \bar{N}_{2R} N_{1L}\right] \\
& - g_1 \left[\bar{N}_{1R} M^\dagger N_{1L} + \bar{N}_{1L} M N_{1R}\right] - g_2 \left[\bar{N}_{2R} M N_{2L} + \bar{N}_{2L} M^\dagger N_{2R}\right]
\end{aligned}$$

$$\begin{aligned}
\mathcal{L}_M \;=\;& \frac{1}{4}\mathrm{tr}[\partial_\mu M \partial^\mu M^\dagger] + \frac{\bar{\mu}^2}{4}\mathrm{tr}[MM^\dagger] - \frac{\lambda}{16}(\mathrm{tr}[MM^\dagger])^2 + \frac{\lambda_6}{48}(\mathrm{tr}[MM^\dagger])^3 + \frac{1}{4}\bar{m}\epsilon\mathrm{tr}[M + M^\dagger] \\
& - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\mu - \frac{1}{2}\mathrm{Tr}[\rho_{\mu\nu}\rho^{\mu\nu}] + \frac{m_\rho^2}{2}\rho_\mu\rho^\mu
\end{aligned}$$

$$M = \sigma + i\tau^a\pi^a$$

2. Model

- **Parity doublet model**
  - Mean field approximation: $\sigma \to \sigma_0 \ , \ \omega_\mu \to \omega_0 \delta_{\mu 0} \ , \ \rho^a_\mu \to \rho_0 \delta_{\mu 0} \delta^{a3}$
  - Diagonalize the mass matrix

$$\begin{pmatrix} N(939) \\ N^*(1535) \end{pmatrix} = \begin{pmatrix} \cos\theta & \gamma_5 \sin\theta \\ -\gamma_5 \sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} N_1 \\ N_2 \end{pmatrix} \Rightarrow \begin{aligned} m_{N(939)} &= \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\sigma_0^2 + 4m_0^2} - (g_2 - g_1)\sigma_0\right] \\ m_{N^*(1535)} &= \frac{1}{2}\left[\sqrt{(g_1+g_2)^2\sigma_0^2 + 4m_0^2} + (g_2 - g_1)\sigma_0\right] \end{aligned}$$

  - It is possible to treat $N(939)$ and $N^*(1535)$ simultaneously
  - $m_{N(939)} = m_{N^*(1535)} = m_0 \ (\sigma_0 \to 0)$ at the chiral restored point

  - Suggestion from lattice QCD

G. Aarts, et al, Phys.Rev. D92 (2015) no.1, 014503

2. Model

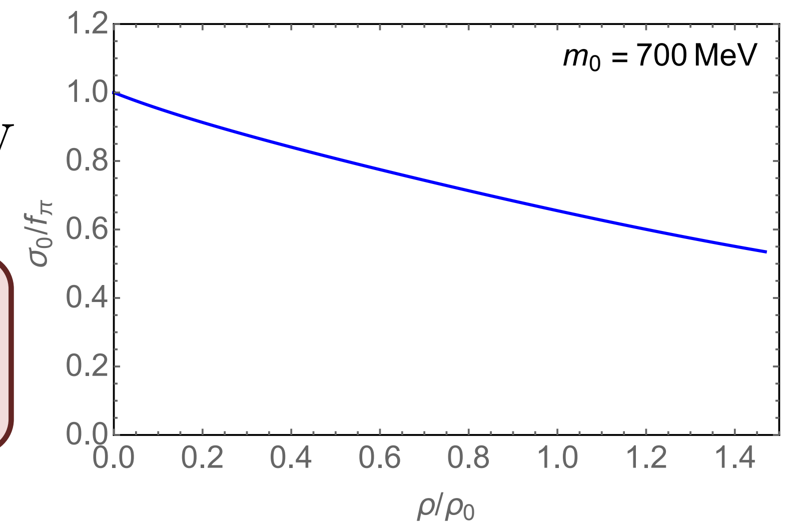
- **Parity doublet model**

  – Nuclear matter is constructed by fermion one loop with the following input parameters

m_+	m_-	m_ω	m_ρ	f_π	m_π	$\rho_0(\mu_B^*)$ (fm^{-3})	$E/A(\mu_B^*) - m_+$ (MeV)	K (MeV)	E_{sym} (MeV)
939	1535	783	776	93	140	0.16	−16	240	31

input in vacuum (first six columns) — input in nuclear matter (last four columns)

  – Plot of σ_0 vs ρ with $m_0 = 700\,\mathrm{MeV}$



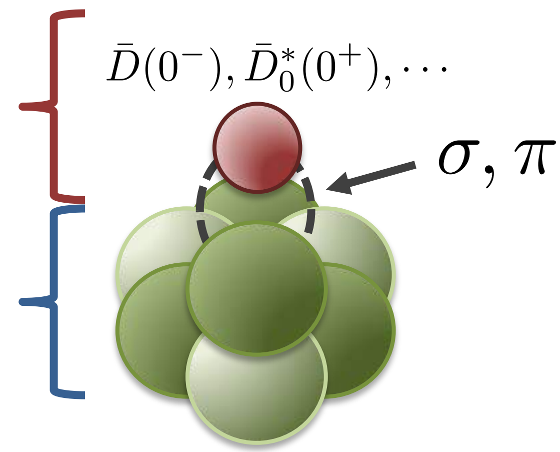
We find partial restoration of chiral symmetry in nuclear matter

2. Model

- **Calculation method**
  - Medium effects to $\bar{D}$ mesons are mediated by σ, π meson exchanges

Effective Lagrangian based on chiral partner structure of $\bar{D}$ mesons

Nuclear matter is constructed by parity doublet model with one loops

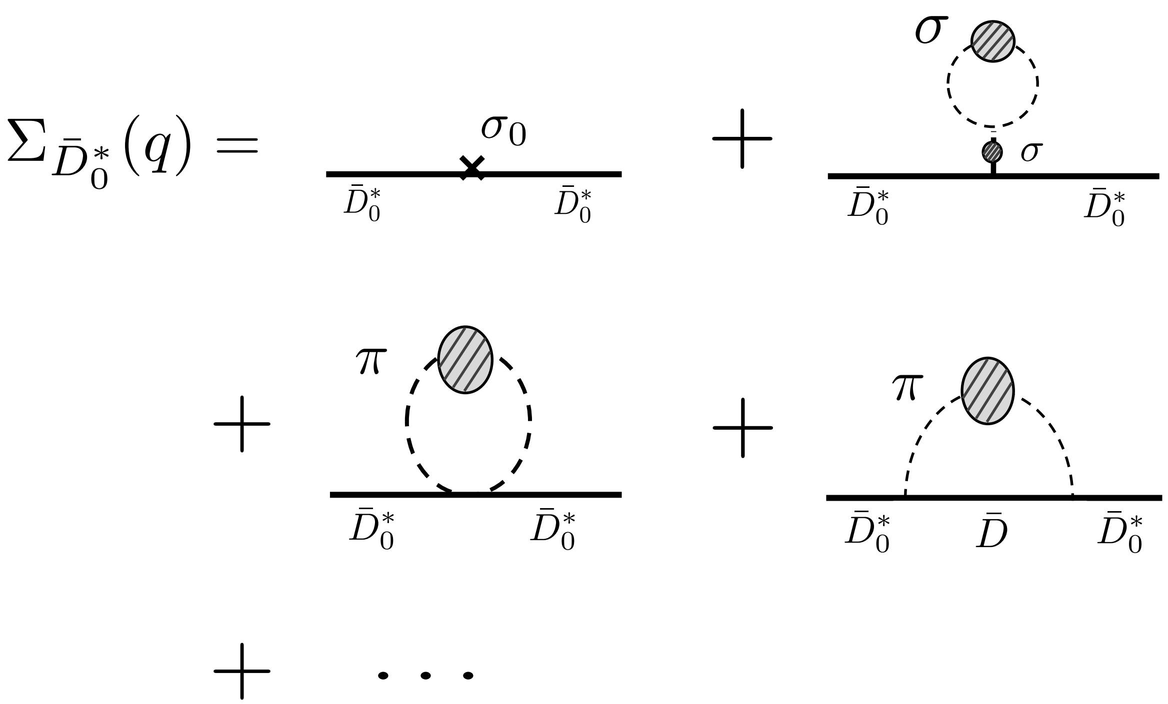


  - Mediating σ, π mesons must be calculated satisfying the **chiral Ward-Takahashi identity** to respect chiral symmetry

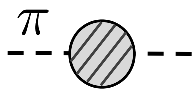
Contents

3. Results

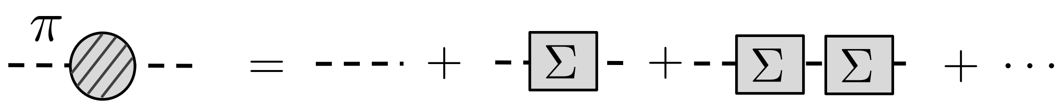
- **Self energy of $\bar{D}_0^*(0^+)$ meson**
  - We include not only mean field σ_0 but also σ, π exchanges



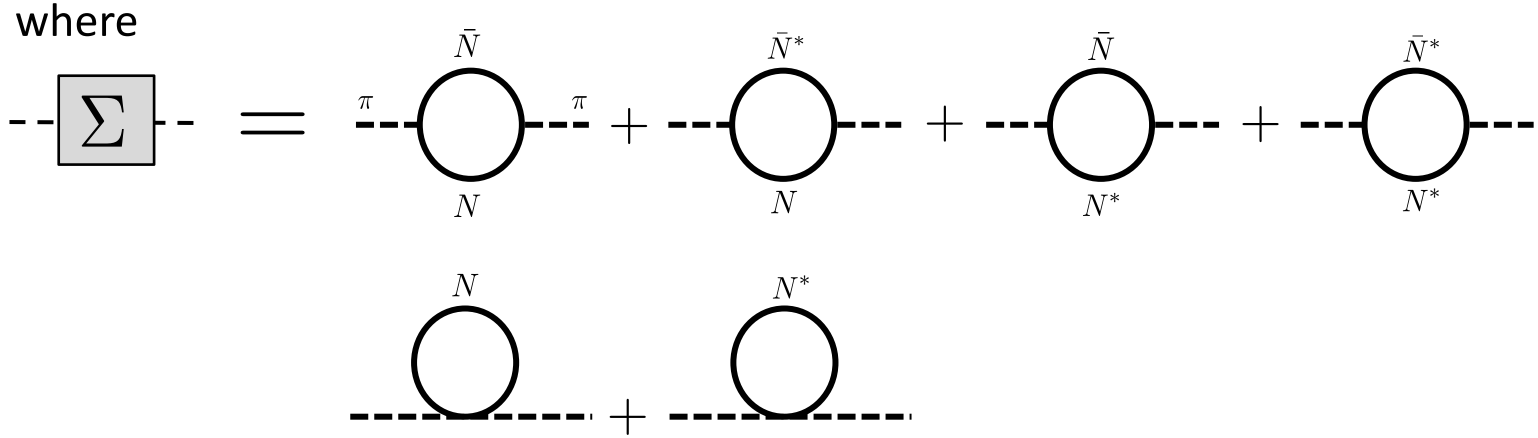
3. Results

- **Two point functions of σ, π mesons**
  - For example, 

 is



where

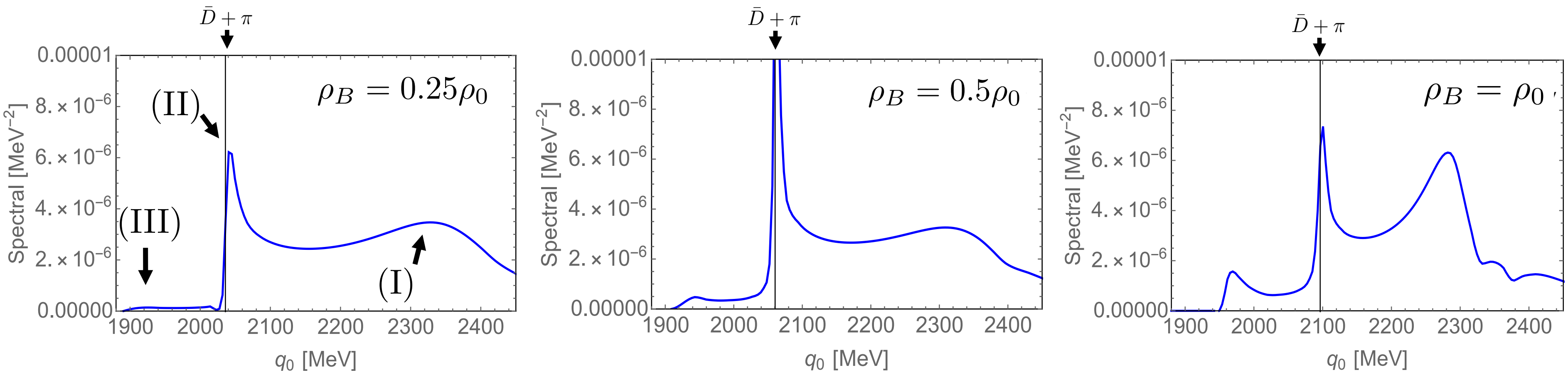


- Chiral Ward–Takahashi is satisfied

- **Spectral function for $\bar{D}_0^*(0^+)$**

D. Suenaga, arXiv:1805.01709

  - Spectral function at several densities with $m_0 = 700\ \mathrm{MeV}$



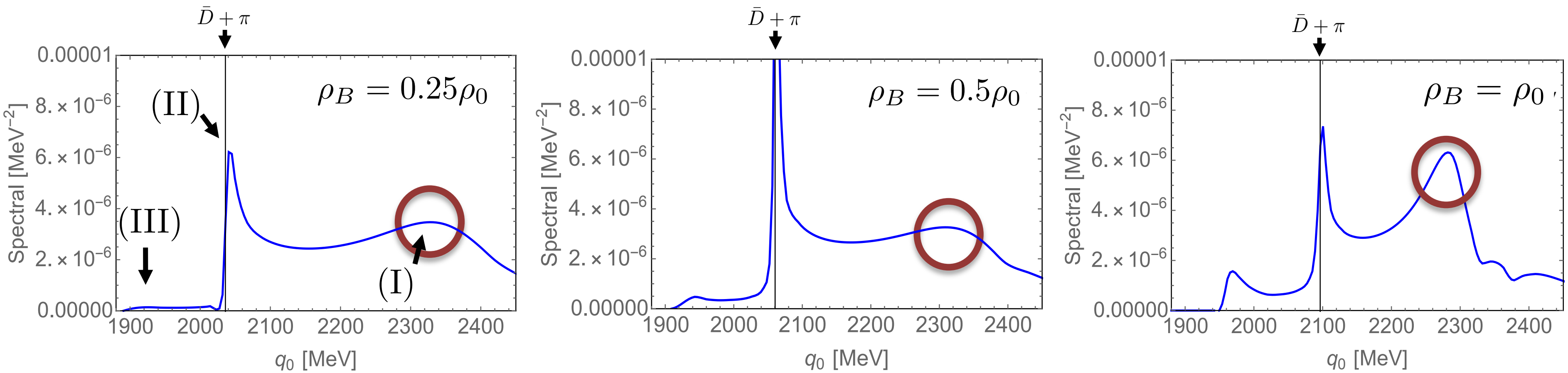
- We obtain three kinds of peaks:
  - (I) $\bar{D}_0^*(0^+)$ resonance
  - (II) threshold enhancement
  - (III) Landau damping

3. Results

- **Spectral function for $\bar{D}_0^*(0^+)$**

D. Suenaga, arXiv:1805.01709

– Spectral function at several densities with $m_0 = 700\ \mathrm{MeV}$



– The first peak from right corresponds to a resonance of $\bar{D}_0^*(0^+)$

– At $\rho_B = 0.25\rho_0 \to 0.5\rho_0$, this peak gets melted by collisional broadening

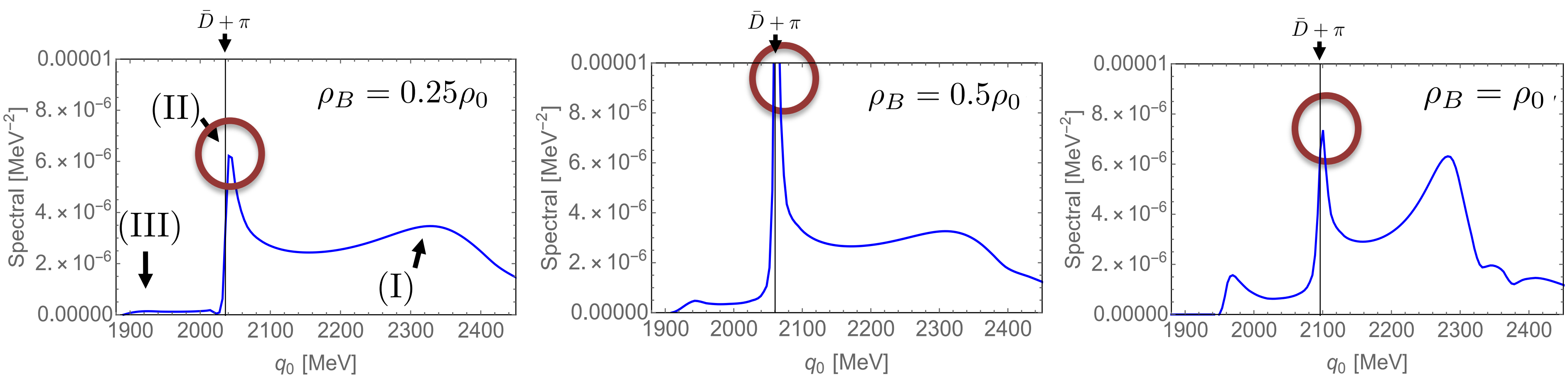
– At $\rho_B = 0.5\rho_0 \to 1.0\rho_0$, this peak grows by narrowing of $\bar{D}_0^* \to \bar{D} + \pi$ decay

3. Results

- Spectral function for $\bar{D}_0^*(0^+)$

D. Suenaga, arXiv:1805.01709

  - Spectral function at several densities with $m_0 = 700$ MeV

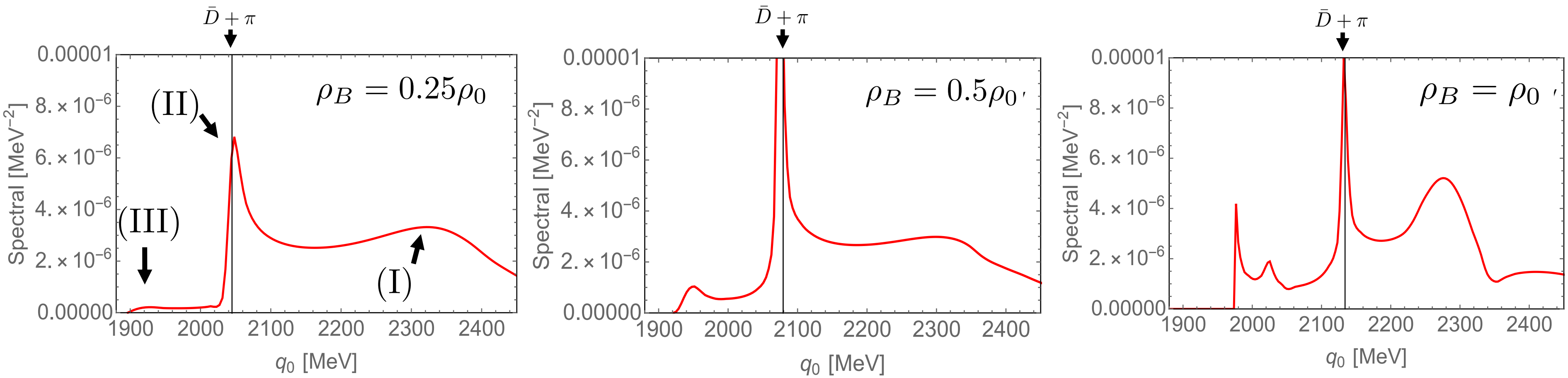


- The second peak corresponds to a threshold enhancement
- Its peak position reflects mass of $\bar{D}(0^-)$ and remarkably enhanced
- This peak can be an appropriate probe to study partial restoration of chiral symmetry in nuclear matter

- **Spectral function for $\bar{D}_0^*(0^+)$**

D. Suenaga, arXiv:1805.01709

  - Spectral function at several densities with $m_0 = 500\,\mathrm{MeV}$



- The results with $m_0 = 500\,\mathrm{MeV}$ show qualitatively the same tendency

- **The origin of threshold enhancement**
  - Consider the self-energy of $\bar{D}_0^*$ meson in a simplified model: mean field level with a constant Landau damping

$$\Sigma^{(1)}_{\bar{D}_0^*}(s) = \frac{s - m^{\mathrm{vac}2}_{\bar{D}_0^*}}{\pi} \mathrm{P}\int_0^\infty ds' \frac{\mathrm{Im}\Sigma_{\bar{D}_0^*}(s')}{(s'-s)(s'-m^{\mathrm{vac}2}_{\bar{D}_0^*})} + i\mathrm{Im}\Sigma_{\bar{D}_0^*}(s)$$

with
$$\mathrm{Im}\Sigma_{\bar{D}_0^*}(s) = \begin{cases} -c & \text{for} \quad m^2_{\bar{D}} < s < (m_{\bar{D}}+m_\pi)^2 \\ -\frac{3}{16\pi}\left(\frac{m\Delta_m}{f_\pi}\right)^2 F^2(|\vec{q}|;\Lambda)\sqrt{\left(1-\frac{(m_{\bar{D}}+m_\pi)^2}{s}\right)\left(1-\frac{(m_{\bar{D}}-m_\pi)^2}{s}\right)} & \text{for} \quad (m_{\bar{D}}+m_\pi)^2 < s \end{cases}$$

Landau damping

Opening of $\bar{D}_0^* \to \bar{D}\pi$ decay

  - The self-energy in the second Riemann sheet $\Sigma^{(2)}_{\bar{D}_0^*}(s)$ is obtained as

$$\Sigma^{(2)}_{\bar{D}_0^*}(s) = \Sigma^{(1)}_{\bar{D}_0^*}(s) - \frac{3g^2}{8\pi}F^2(|\vec{q}|,\Lambda)\sqrt{\left(\frac{(m_{\bar{D}}+m_\pi)^2}{s}-1\right)\left(1-\frac{(m_{\bar{D}}-m_\pi)^2}{s}\right)}$$

3. Results

- **The origin of threshold enhancement**
  - Let us search for the pole of $\bar{D}_0^*$ propagator in the first and second Riemann sheet
  - If the pole is found in the first Riemann sheet ⇨ $\bar{D}\pi$ bound state
  - If the pole is found in the second Riemann sheet ⇨ $\bar{D}\pi$ virtual state
  - The chiral restoration effect is included to the following mass formulae ($\sigma_0 = f_\pi$ in the vacuum)

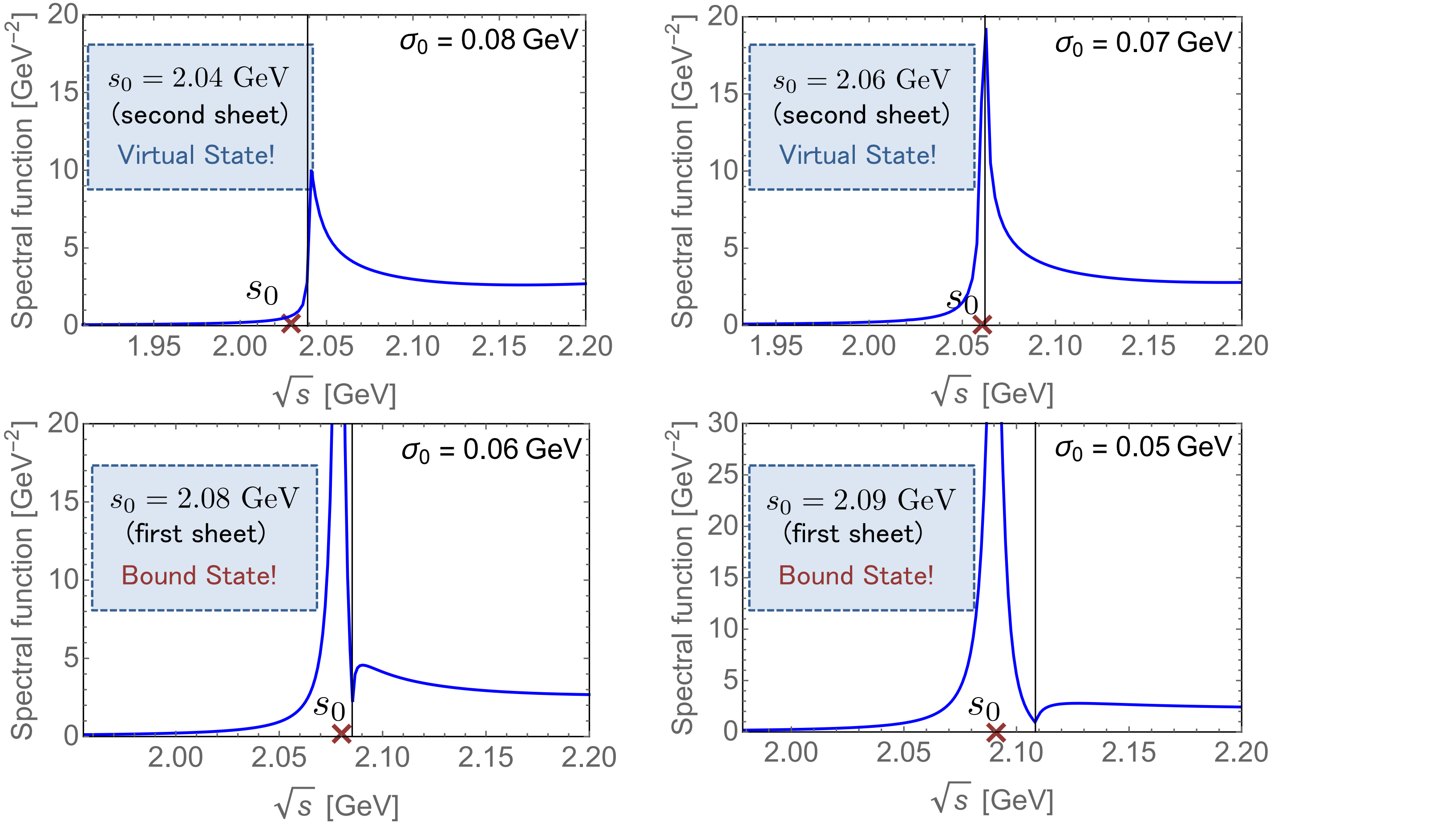
$$m_{\bar{D}} = m - \frac{\Delta_m}{2f_\pi}\sigma_0 - \delta_{\bar{D}}$$

$$m_{\bar{D}_0^*} = m + \frac{\Delta_m}{2f_\pi}\sigma_0 - \delta_{\bar{D}_0^*}$$

$\delta_{\bar{D}}, \delta_{\bar{D}_0^*}$ are added by the violation of HQSS

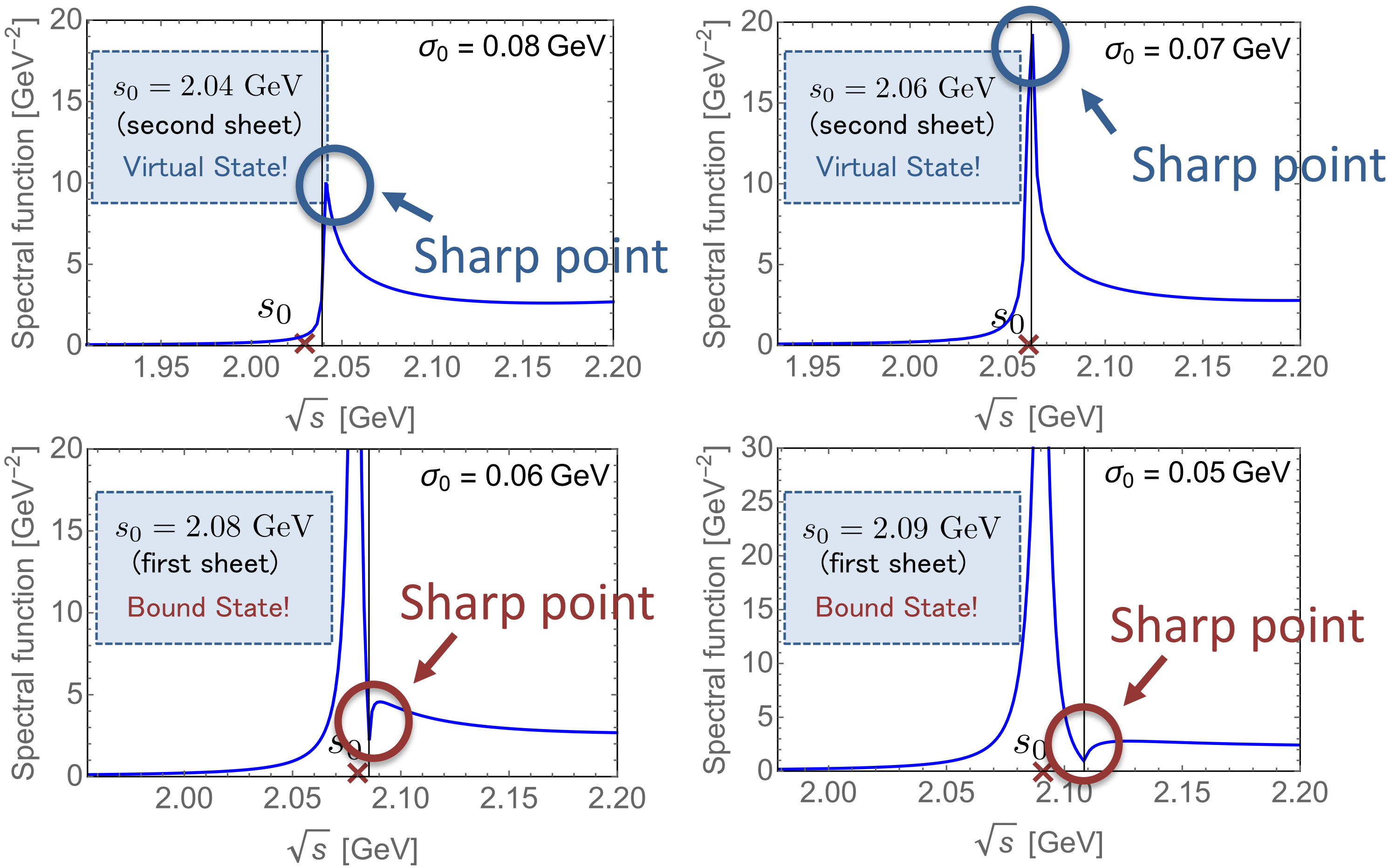
3. Results

- **The origin of threshold enhancement**
  - Spectral function with several choices of σ_0



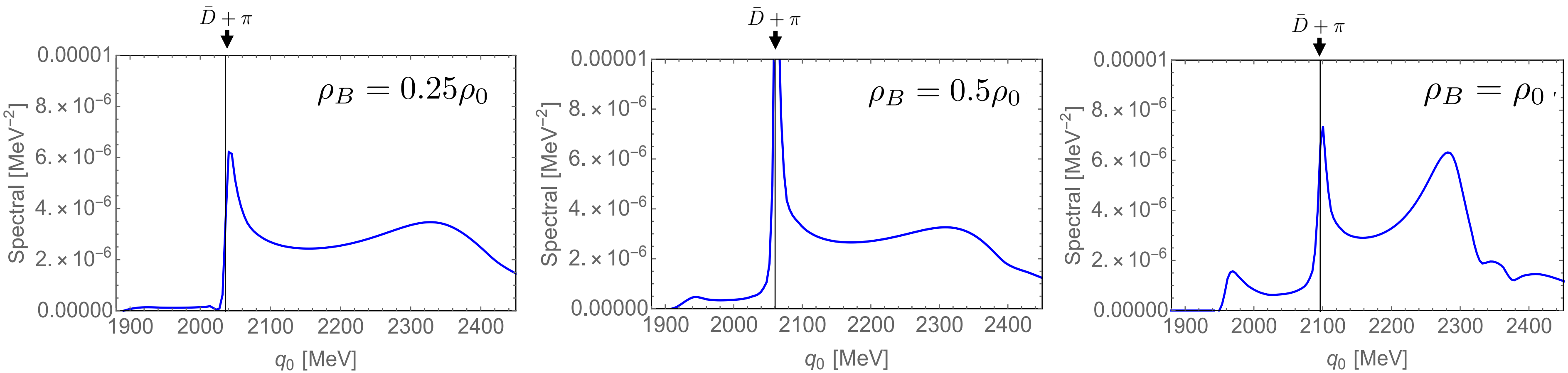
3. Results

- **The origin of threshold enhancement**
  - Spectral function with several choices of σ_0



3. Results

- **Go back to the results**
  - Spectral function at several densities with $m_0 = 700\ \mathrm{MeV}$



- The sharp point at the threshold is upward-convex

⇩

- There may be virtual state (no bound state) just below the threshold (this is true for $m_0 = 500\,\mathrm{MeV}$ as well)

Contents

4. Conclusions

- **Conclusions**
  - We study spectral function for $\bar{D}_0^*(0^+)$ in nuclear matter paying special attention to the partial restoration of chiral symmetry
  - Chiral partner structure for $\bar{D}$ mesons and parity doublet model for constructing nuclear matter are employed
  - In the spectral function for $\bar{D}_0^*(0^+)$, a revival of the resonance of $\bar{D}_0^*(0^+)$ at higher density is found due to the narrowing of $\bar{D}_0^* \to \bar{D} + \pi$ decay width by partial restoration of chiral symmetry
  - The threshold enhancement can be an appropriate probe to explore partial restoration of chiral symmetry at density
  - The threshold enhancement may be induced by a virtual state at and less than $\rho_B = \rho_0$

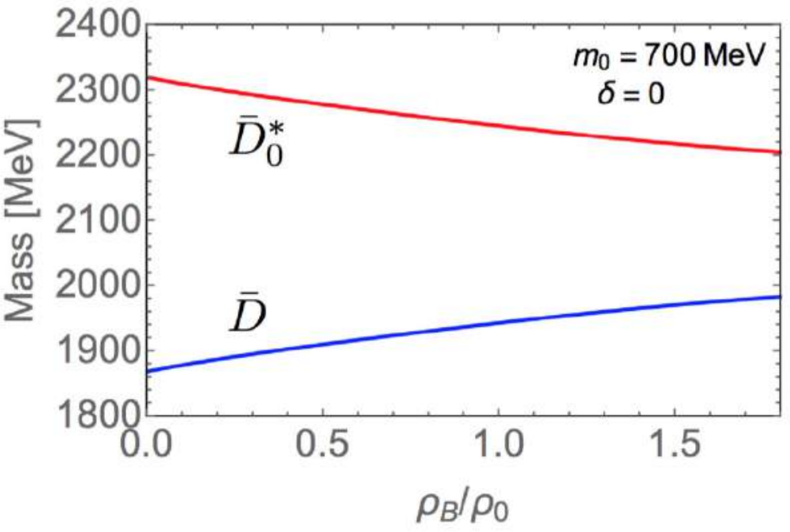
Thank you

HMET

- **Chiral partner structure**
  - Density dependence of $\bar{D}$ mesons

$$m_{\bar{D}_0^*} = m + \frac{\Delta_m}{2f_\pi}\sigma_0 - \frac{\delta_{\bar{D}_0^*}}{2}$$

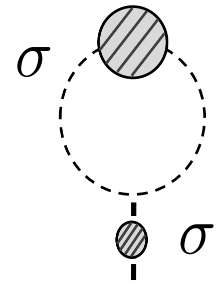
$$m_{\bar{D}} = m - \frac{\Delta_m}{2f_\pi}\sigma_0 - \frac{\delta_{\bar{D}}}{2}$$



Calculation method

- **One loop calculation**

  - For example, one-loop correction $\delta\sigma_0$ is calculated by



$$
\begin{aligned}
\delta\sigma_0 &= \frac{i}{-\tilde{m}_\sigma^2}\left(-i\lambda\sigma_0 + i\frac{10}{3}\lambda_6\sigma_0^3\right)\int\frac{d^4k}{(2\pi)^4}\left(F(k,\Lambda)\right)^2 \mathrm{Re}\left[G_\sigma(k) - G_\sigma^{\mathrm{vac}}(k)\right]\times 3 \\
&= -\frac{3}{2\tilde{m}_\sigma^{*2}}\left(\lambda\sigma_0 - \frac{10}{3}\lambda_6\sigma_0^3\right)\int\frac{d^4k}{(2\pi)^4}\left(F(k,\Lambda)\right)^2 \epsilon(k_0)\left\{\rho_\sigma(k) - \rho_\sigma^{\mathrm{vac}}(k)\right\} \\
&= -\frac{3}{4\pi^3\tilde{m}_\sigma^{*2}}\left(\lambda\sigma_0 - \frac{10}{3}\lambda_6\sigma_0^3\right)\int_0^\infty dk_0\int_0^\infty dk k^2\left(F(k,\Lambda)\right)^2\left\{\rho_\sigma(k) - \rho_\sigma^{\mathrm{vac}}(k)\right\}
\end{aligned}
$$

$$
F(k,\Lambda) = \frac{\Lambda^2}{\vec{k}^2 + \Lambda^2}
$$

4. Conclusions

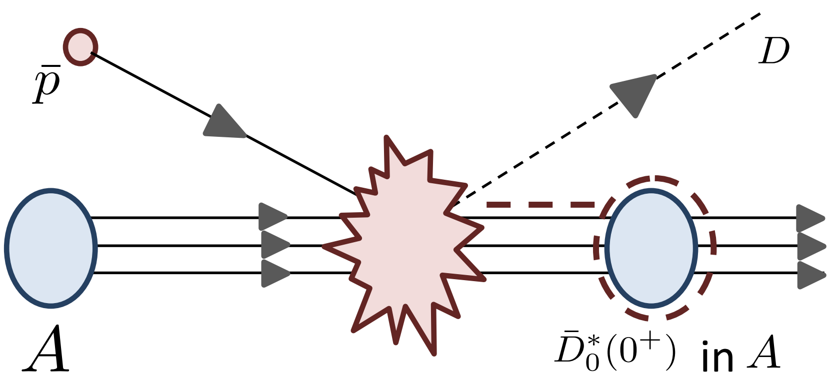
- **Future prospect**
  - (Density averaged) spectral function for $\bar{D}_0^*(0^+)$ meson ($\bar{\rho}(E_{\bar{D}_0^*})$) is reflected to a double cross section of e.g. $\bar{p} + A \to D + (\bar{D}_0^* \text{ in } A)$

$$\frac{d^2\sigma}{d\Omega_D dE_D} \propto \left(\frac{d\sigma}{d\Omega_D}\right)_0 \times \bar{\rho}(E_{\bar{D}_0^*})$$

elementally process

(spectral function)

O. Morimatsu and K. Yazaki, (1985)



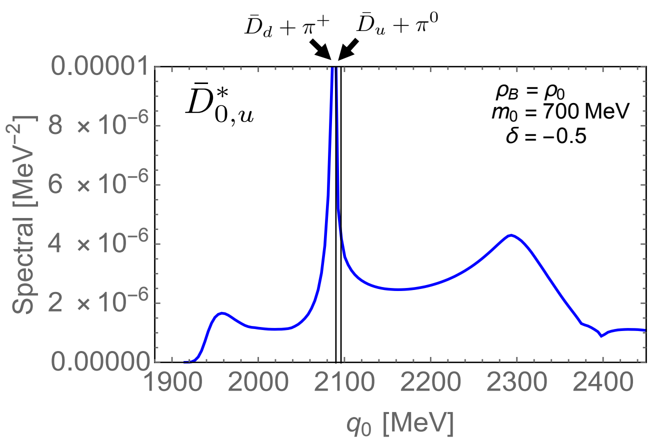
3. Results

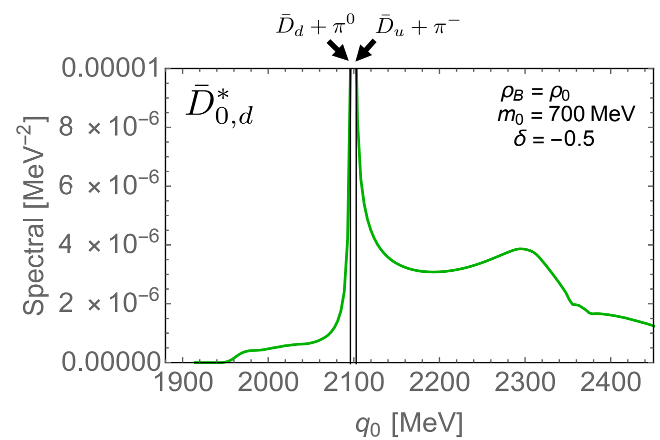
- **Spectral function for $\bar{D}_0^*(0^+)$**

D. Suenaga, arXiv:1805.01709

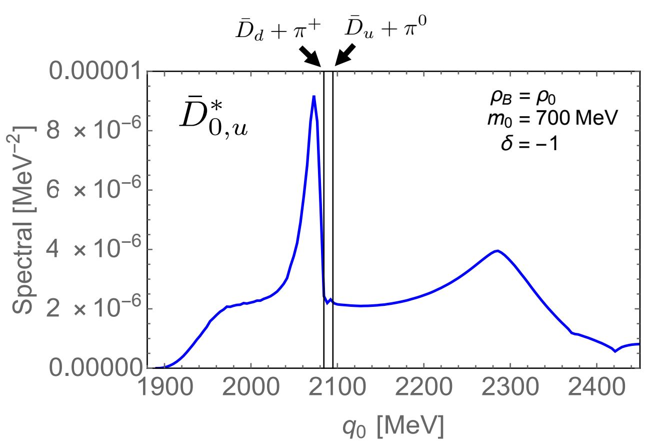
  – Spectral functions at neutron-rich matter with $m_0 = 700\,\mathrm{MeV}$

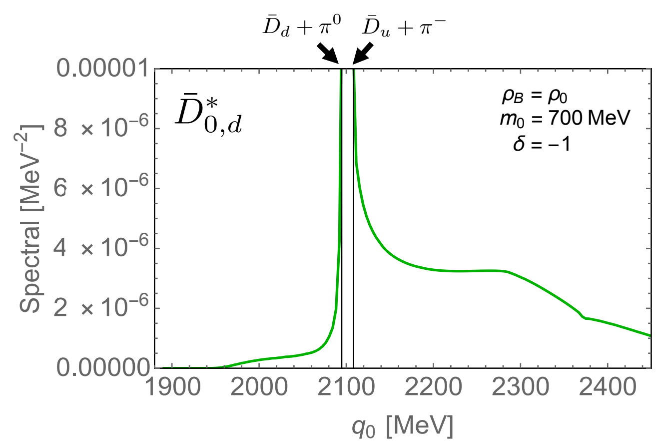
$$\rho_p = \frac{1}{4}\rho_0 \qquad \rho_n = \frac{3}{4}\rho_0$$





$$\rho_p = 0 \qquad \rho_n = \rho_0$$





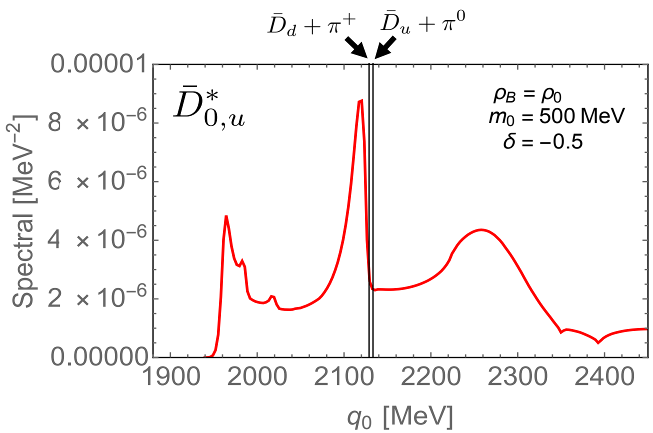
3. Results

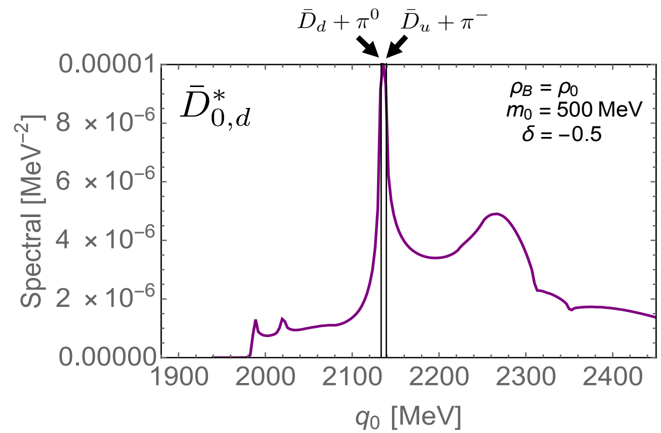
- **Spectral function for $\bar{D}_0^*(0^+)$**

D. Suenaga, arXiv:1805.01709

  - Spectral functions at neutron-rich matter with $m_0 = 500\,\mathrm{MeV}$

$$\rho_p = \frac{1}{4}\rho_0 \qquad \rho_n = \frac{3}{4}\rho_0$$





$$\rho_p = 0 \qquad \rho_n = \rho_0$$