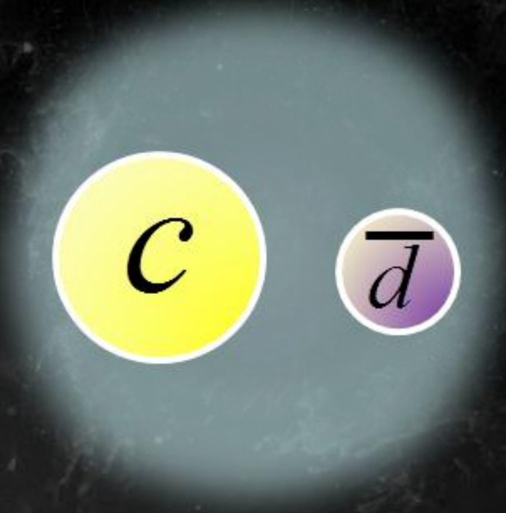

Medium modification of heavy meson spectra from QCD sum rules

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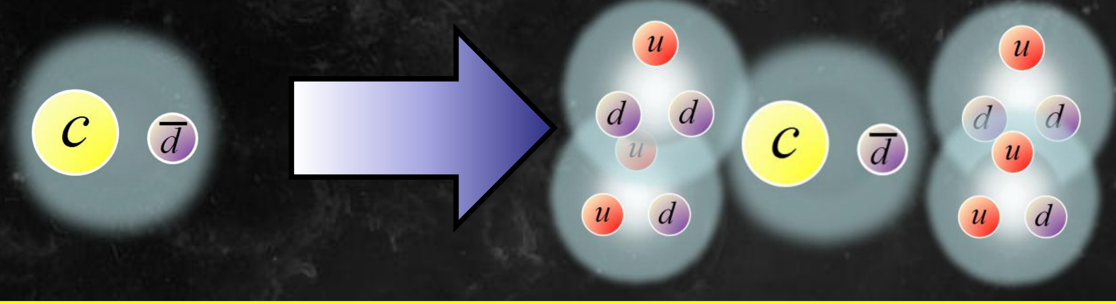
Philipp Gubler (*RIKEN*)
Makoto Oka (*TITech*)

Overview of Our Work

- Subject

D meson is modified in dense nuclear matter



- Purpose

To investigate D meson spectral function

- Method

QCD sum rules and **MEM**

Outline of Today's Talk

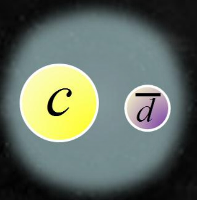
1. Introduction
   1-1. D meson in nuclear medium
   1-2. Previous works
2. Methods
   2-1. QCD sum rule
   2-2. D meson OPE
3. Results
   3-1. D meson spectral function in vacuum
   3-2. D meson spectral function in nuclear medium
   3-3. Relation between QCD vacuum condensates and hadron
4. Summary

1. Introduction

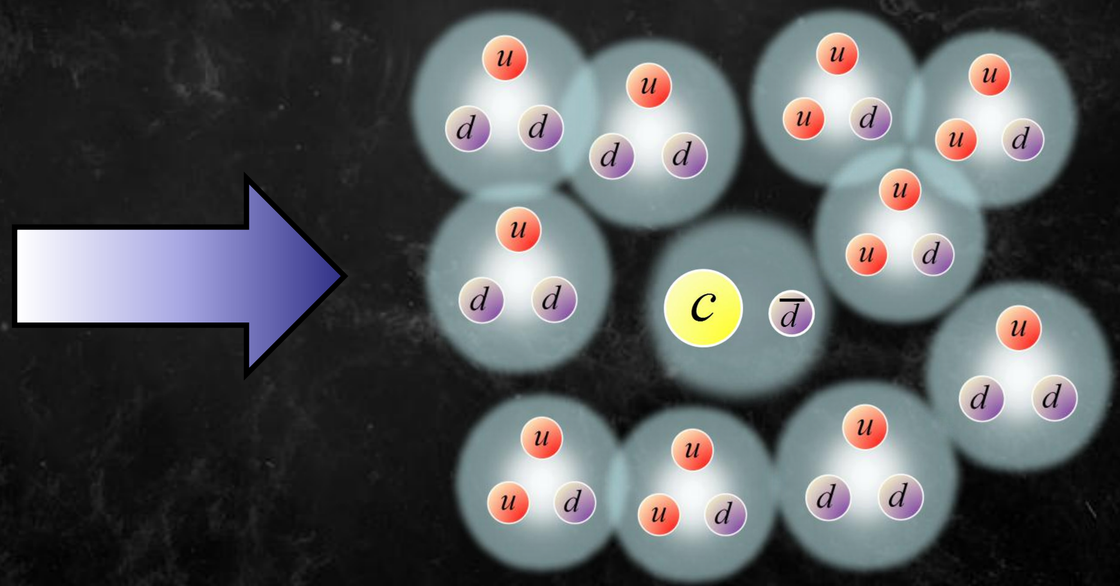
D meson in nuclear medium

If a D meson is put into nuclear medium, what will happen ?

vacuum

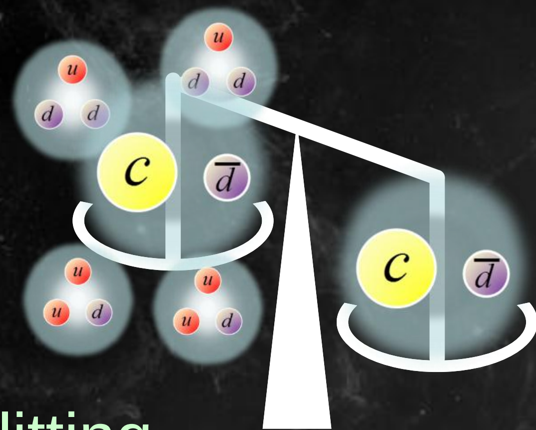


in nuclear medium

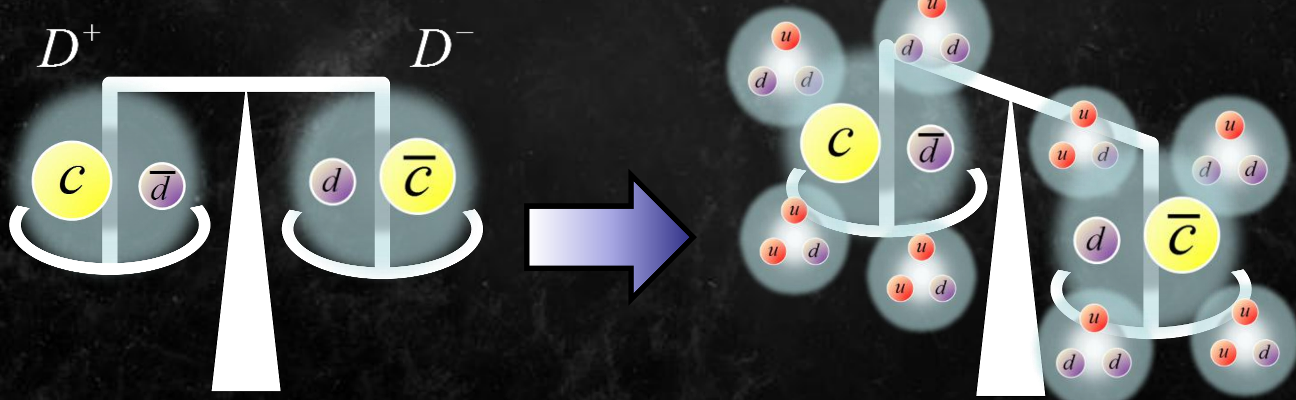


D meson properties in nuclear medium

- Mass shift (partial restoration of chiral symmetry etc.)



- D – $\bar{D}$ mass splitting



Mass:1.87GeV

different mass?

Previous work (from QCD sum rules)

There are many theoretical approachs

⇒ Talks by L.Tolos, S.Yasui

A. Hayashigaki, Phys.Lett. B487 (2000) 96

including condensates up to dim.4 $\langle \bar{q}q \rangle, \langle G^2 \rangle, \langle q^\dagger iD_0 q \rangle_N, \langle (u \cdot G)^2 - G^2/4 \rangle_N$

⇒mass shift : $(\Delta m_{D+} + \Delta m_{D-})/2 = -50$MeV at ρ_0

T. Hilger, R. Thomas, B. Kampfer, Phys. Rev. C79 (2009) 025202 $\langle \bar{q} g \sigma G q \rangle \ldots \quad \langle q^\dagger q \rangle_N \ldots$

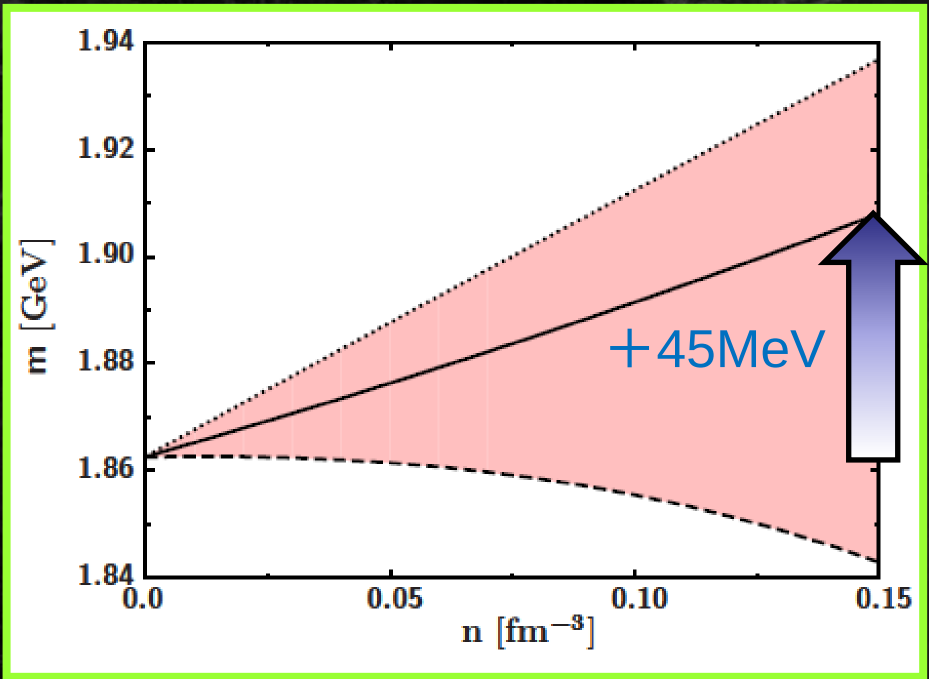
including condensates up to dim.5 and q_0-odd term

⇒mass shift : $+45$MeV and mass splitting : $(m_{D+} - m_{D-}) = -60$MeV at ρ_0

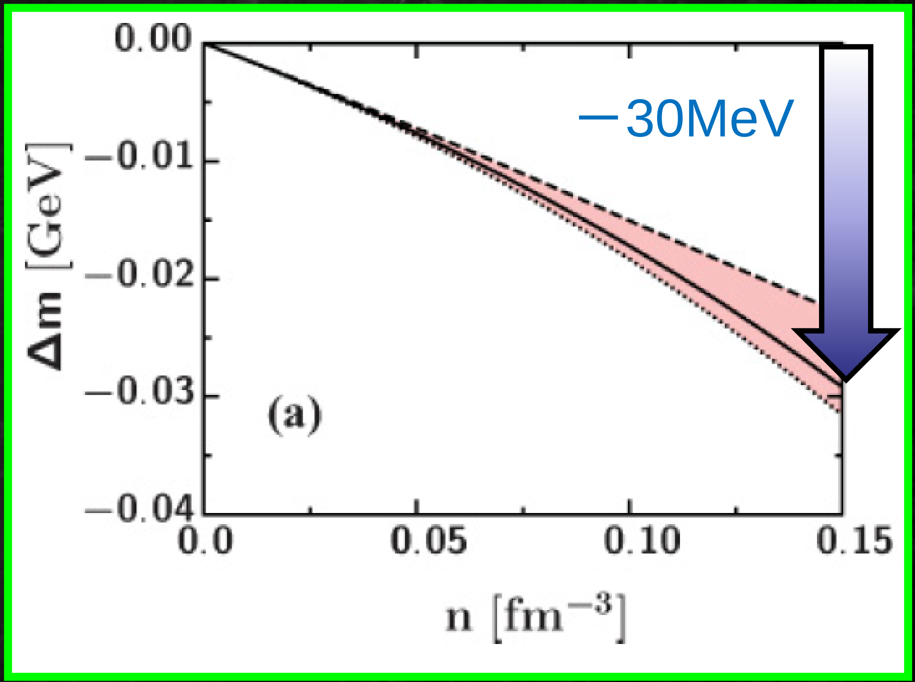
Previous work (from QCD sum rules)

T. Hilger, R. Thomas, B. Kampfer, Phys. Rev. C79 (2009) 025202

Mass shift $(\Delta m_{D+} + \Delta m_{D-})/2$



mass splitting $(m_{D+} - m_{D-})/2$



- These results depend on phenomenological parameter

⇒We need parameter independent analysis (=MEM)

2. Methods

Theoretical strategy for hadron in nuclear medium

We study density dependence of <u>spectral function</u>

Meson correlation function

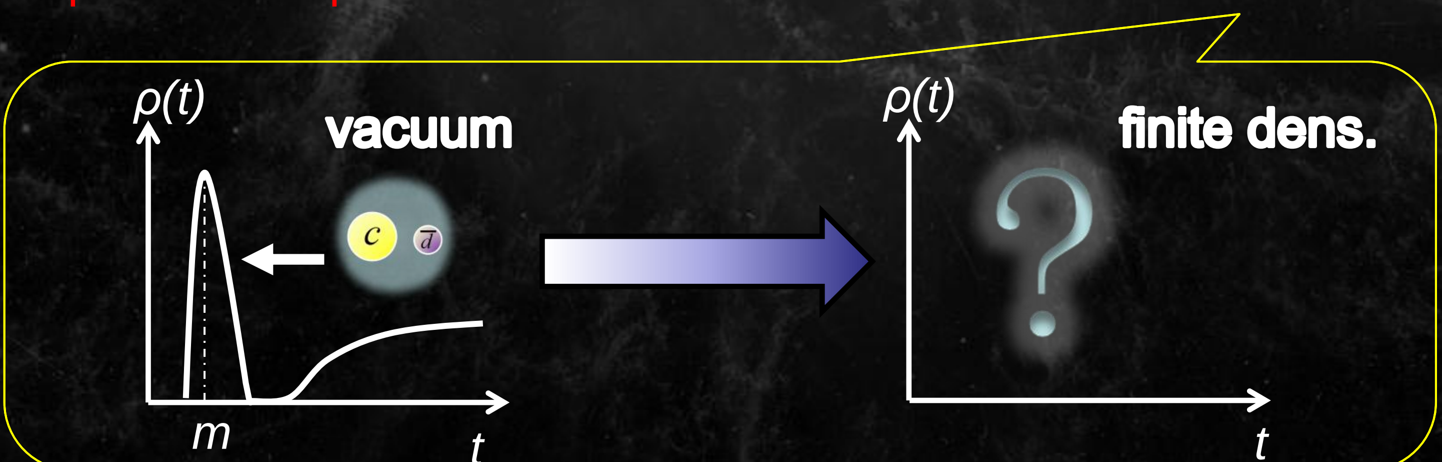
Non-perturbative QCD approach

<u>QCD sum rule</u> etc.

Spectral function of hadron state

D-dependence input

D-dependence output



QCD sum rule

- QCD sum rule

M.A. Shifman, A.I. Vainshtein, and V.I. Zakharov, Nucl. Phys. B**147**, 385 (1979); B**147**, 448 (1979)

Relation between operator product expansion (OPE) of correlation function and spectral function of hadron

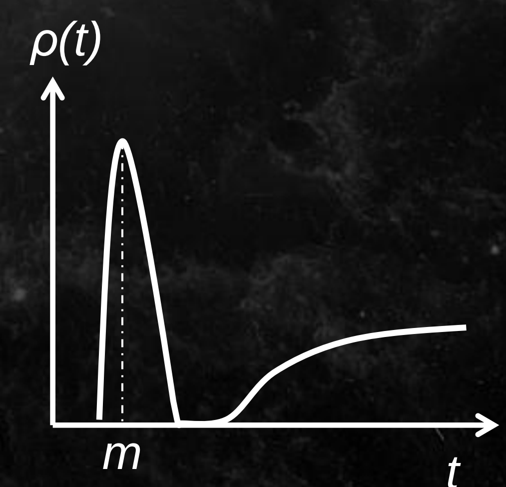
$$\boxed{\Pi_{\mathrm{OPE}}(q^2)} = \int_0^\infty \frac{\boxed{\rho(t)}}{t-q^2}dt$$

transformation

$$\boxed{\Pi_{\mathrm{OPE}}(M^2)} = \int_0^\infty K(t, M^2)\boxed{\rho(t)}dt$$

Input OPE

Output spectral function → One hadron state



Setup in QCD sum rules

QCD sum rule

$$\Pi_{\mathrm{OPE}}(s,\tau) = \int_0^\infty K(t,s,\tau)\,\rho(t)\,dt$$

Gaussian sum rule

$$\frac{1}{\sqrt{4\pi\tau}} \exp\left[\frac{-(t-s^2)^2}{4\tau}\right]$$

D meson OPE

$$\begin{aligned}
G^{\mathrm{even}}(\hat{s},\tau) = {} & \frac{1}{\sqrt{4\pi\tau}}\frac{1}{\pi}\int_{m_h^2}^{\infty} ds e^{-\frac{(s-\hat{s})^2}{4\tau}} \mathrm{Im}\Pi^{\mathrm{pert}}(s) \\
& + \frac{1}{\sqrt{4\pi\tau}} e^{-\frac{(m_h^2-\hat{s})^2}{4\tau}} \Bigg[-m_h\langle\bar{q}q\rangle + \frac{1}{12}\langle\frac{\alpha}{\pi}G^2\rangle - \frac{1}{2}\left(\frac{3m_h^2-2\hat{s}}{4\tau} - \frac{2(m_h^2-\hat{s})^2 m_h^2}{(4\tau)^2}\right) m_h\langle\bar{q}g\sigma Gq\rangle \\
& \quad - \left\{ \left(\frac{7}{18}+\frac{1}{3}\ln\frac{\mu^2}{m_h^2}\right)\left(1-\frac{(m_h^2-\hat{s})m_h^2}{2\tau}\right) + \frac{m_h^4 - m_h^2\hat{s} - 2\tau}{3\tau} \right\} \langle\frac{\alpha_s}{\pi}\left(\frac{(vG)^2}{v^2}-\frac{G^2}{4}\right)\rangle \\
& \quad -2\left(1-\frac{(m_h^2-\hat{s})m_h^2}{2\tau}\right)\langle q^\dagger i\vec{D}_0 q\rangle \\
& \quad -4\left(\frac{3m_h^2-2\hat{s}}{4\tau} - \frac{2(m_h^2-\hat{s})^2 m_h^2}{(4\tau)^2}\right) m_h \left[\langle\bar{q}\vec{D}_0^2 q\rangle - \langle\frac{1}{8}\bar{q}g\sigma Gq\rangle\right]\Bigg]
\end{aligned}$$

$$\mathrm{Im}\Pi^{\mathrm{pert}}(s) = \frac{3}{8\pi}s\left(1-\frac{m_h^2}{s}\right)^2 \times \left(1+\frac{4}{3}\frac{\alpha_s}{\pi}R_0(m_h^2/s)\right)$$

$$R_0(m_h^2/s = x) = \frac{9}{4} + 2Li_2(x) + \ln x\ln(1-x) - \frac{3}{2}\ln\frac{1-x}{x} - \ln(1-x) + x\ln\frac{1-x}{x} - \frac{x}{1-x}\ln x$$

Output spectral function

- maximum entropy method (MEM)

P. Gubler and M. Oka, Prog. Theor. Phys. 124, 995 (2010)

D meson OPE in vacuum

$$\Pi_{\mathrm{OPE}}(M^2) = \text{perturbative term}$$
$$+ e^{-m_c^2/M^2}\left[-\boxed{m_c}\langle\bar{q}q\rangle + \frac{1}{2}\left(\frac{m_c^2}{2M^4} - \frac{1}{M^2}\right)\boxed{m_c}\langle \bar{q}g\sigma G q\rangle + \frac{1}{12}\left\langle \frac{\alpha_s}{\pi}G^2\right\rangle \right.$$
$$\left. - \frac{16\pi}{27}\frac{1}{M^2}\left(1+\frac{1}{2}\frac{m_c^2}{M^2} - \frac{1}{12}\frac{m_c^4}{M^4}\right)\alpha_s\langle\bar{q}q\rangle^2\right]$$

1. Chiral condensate
2. Mixed condensate
3. Gluon condensate
4. 4-quark condensate

Coefficients are proportional to <u>charm quark mass</u>
⇒These terms are <u>amplified</u>

Other condensates are relatively suppressed

⇒We expect that chiral and mixed condensate are dominant

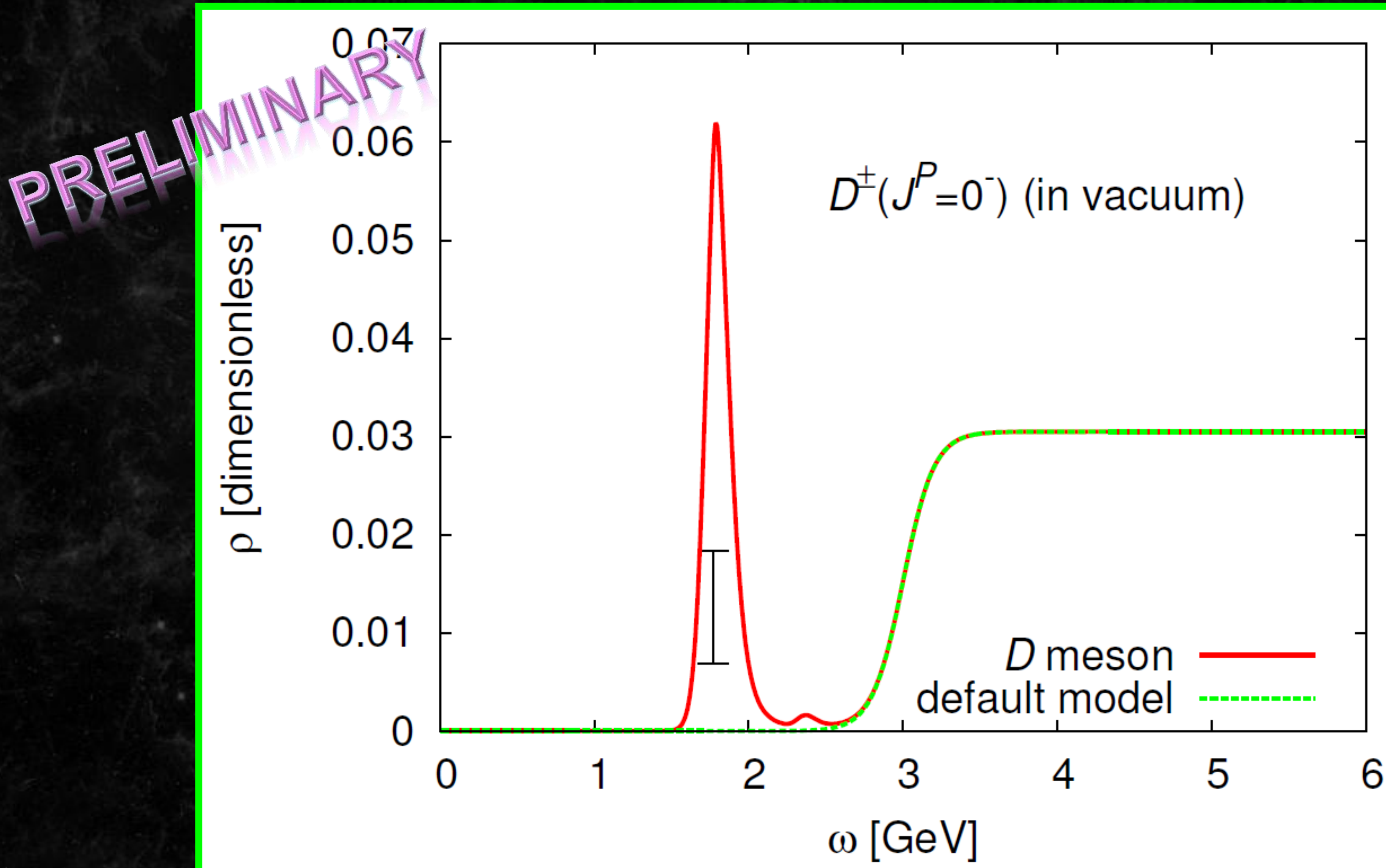
3. Results

3-1. D meson spectral function in vacuum

3-2. D meson spectral function in nuclear matter

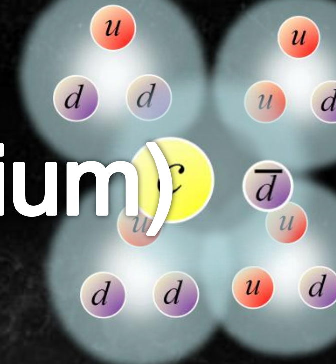
3-3. Relation between condensates and hadron

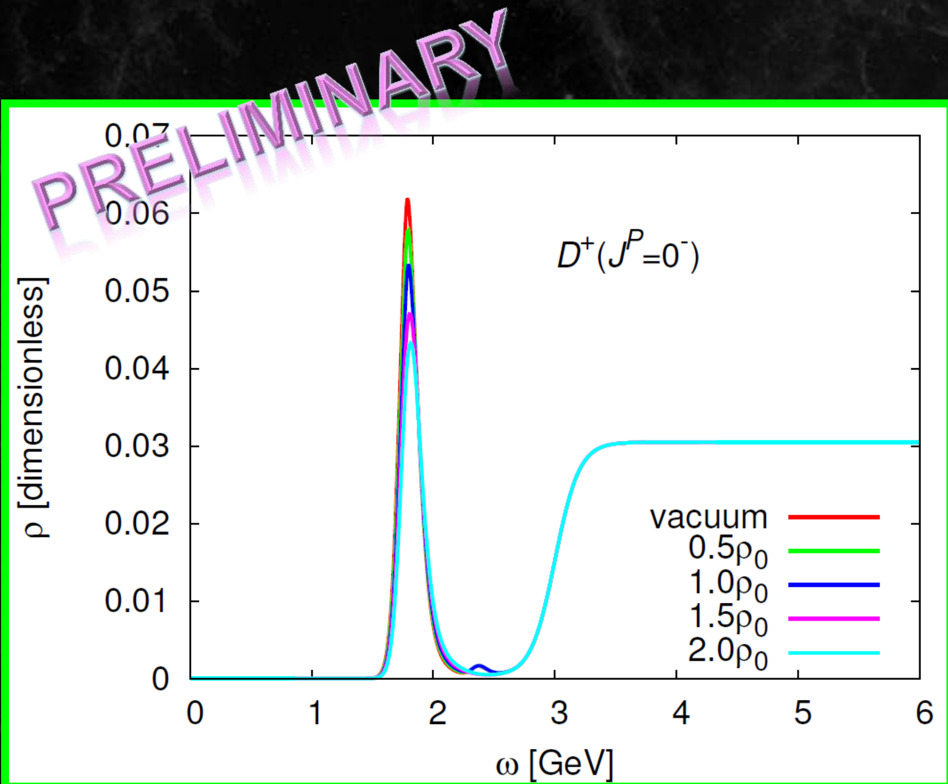
D meson spectral function (in vacuum)

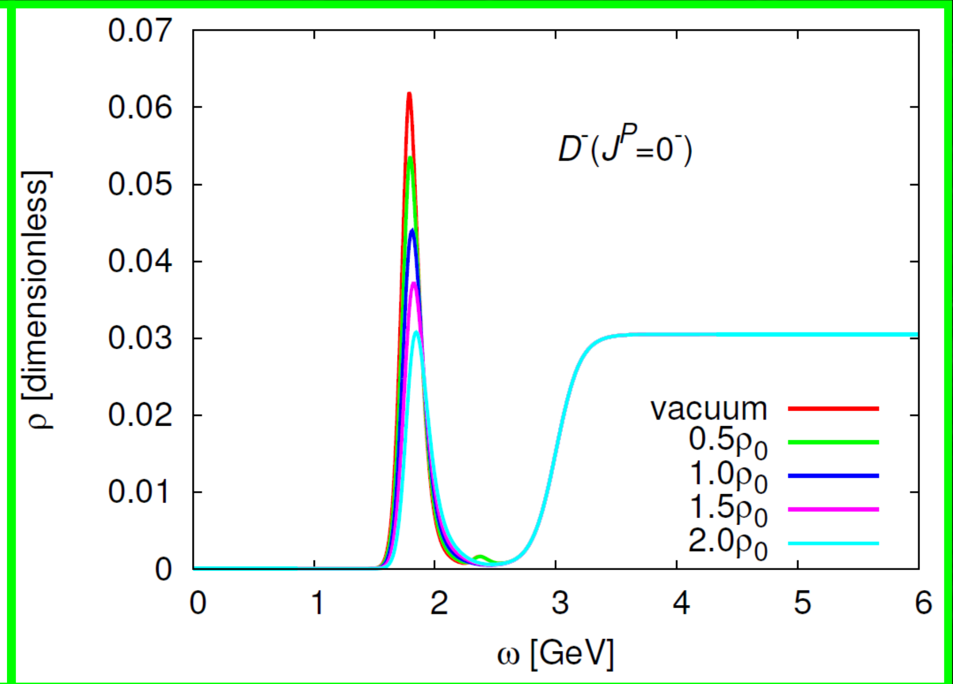


Mass : 1.78GeV Exp. : 1.87GeV

D meson spectral function (in medium)

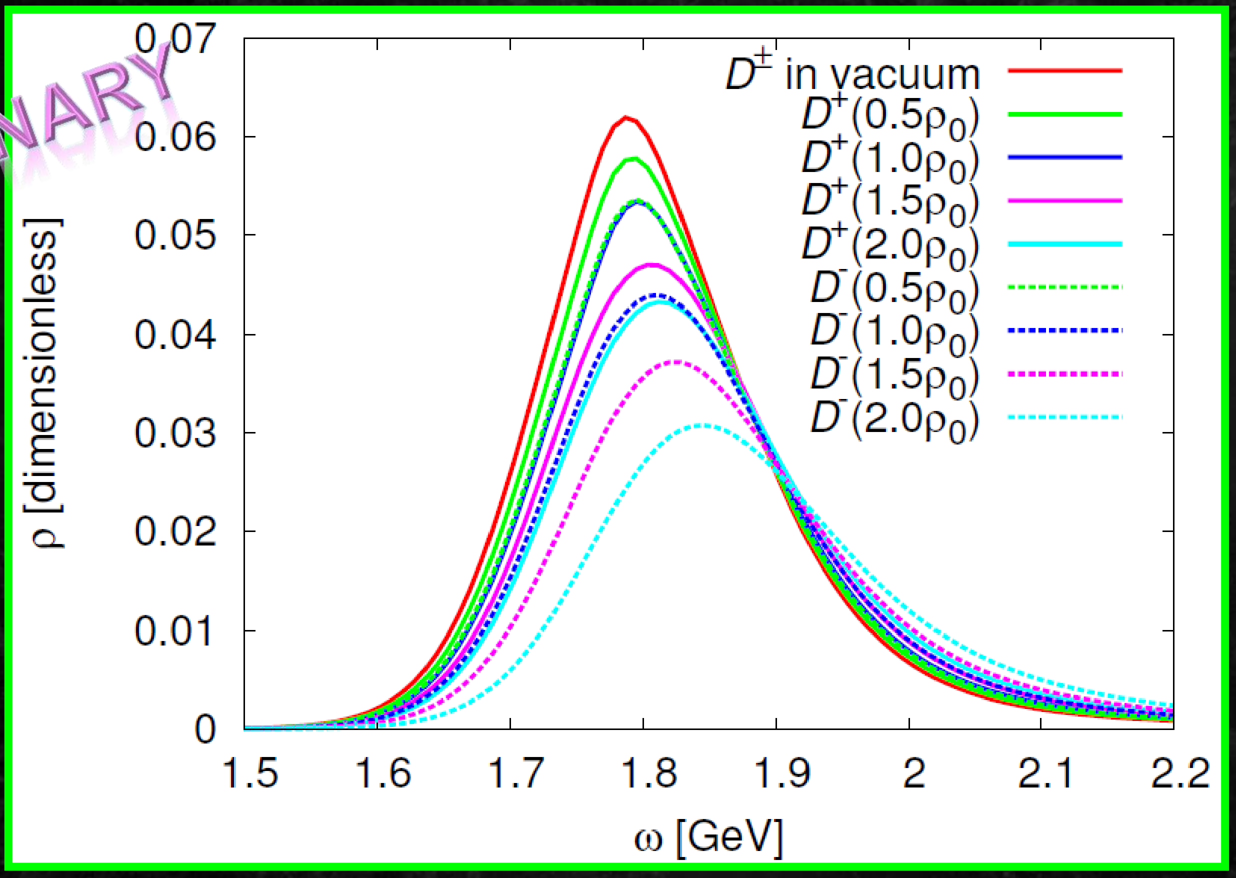






⇒Peak position in $D^\pm$ shifts to higher energy side with increasing density (D^+: ~10MeV D^-: ~30MeV at ρ_0)

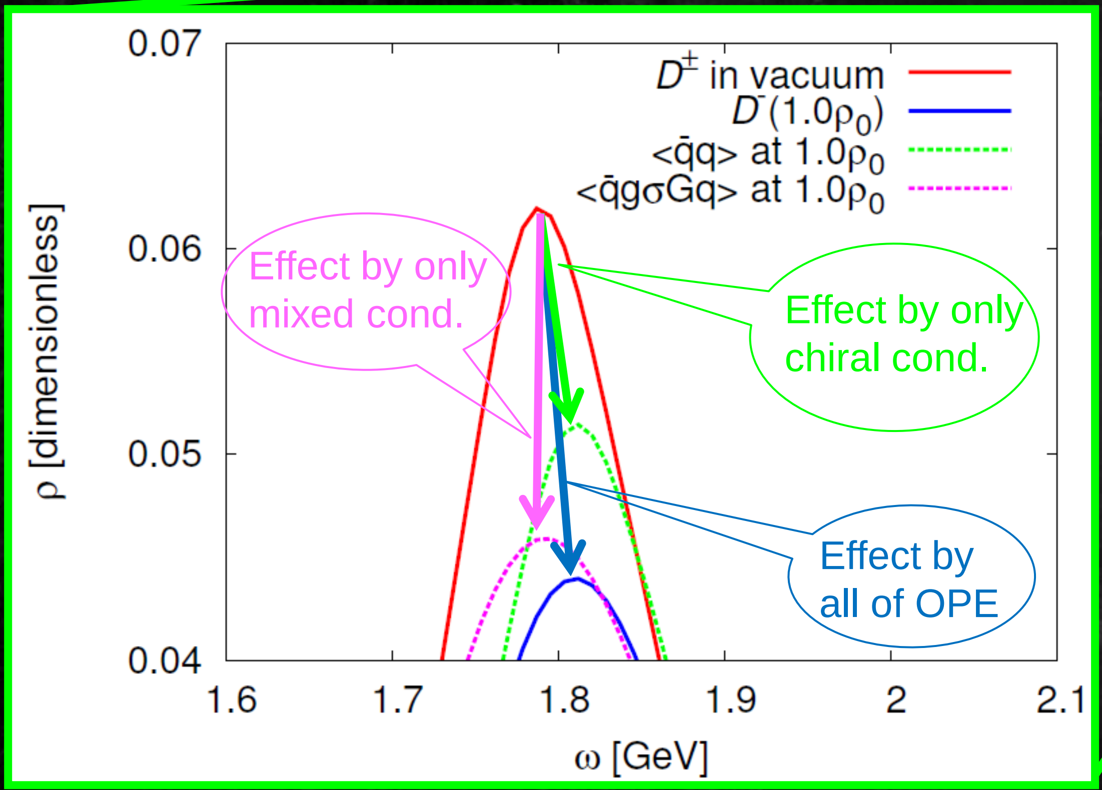
Comparison of D^+ and D^-

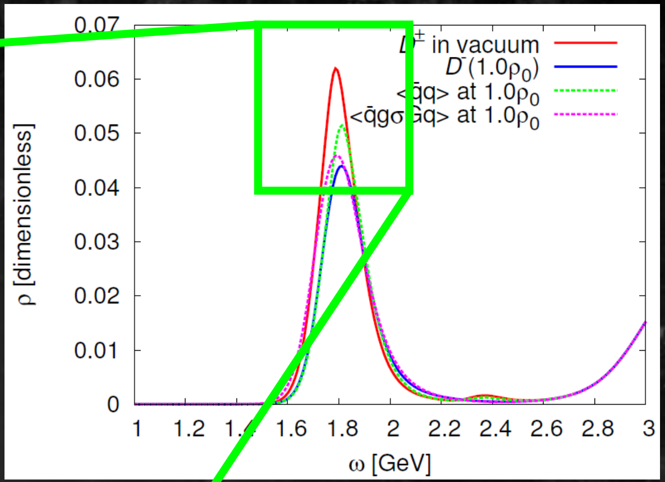


D^- is changed more rapidly than D^+

$\Rightarrow D^+$-D^- mass splitting is about 20 MeV at ρ_0

Contribution of vacuum condensates





⇒Most dominant contribution of mass shift to higher energy is <u>D-dependence of chiral condensate</u>

Summary

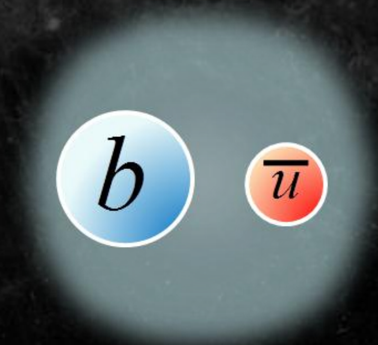
- We extracted D meson spectral functions in nuclear medium from QCD sum rules and MEM
- We obtained mass shift and D-$\bar{D}$ mass splitting

D^+ mass shift	D^- mass shift	D^+-D^- splitting
~+10MeV	~+30MeV	~20MeV

- Mass shift comes from density dependence of chiral condensate

Outlook

- B meson, D_s meson, D^* meson…



Backup

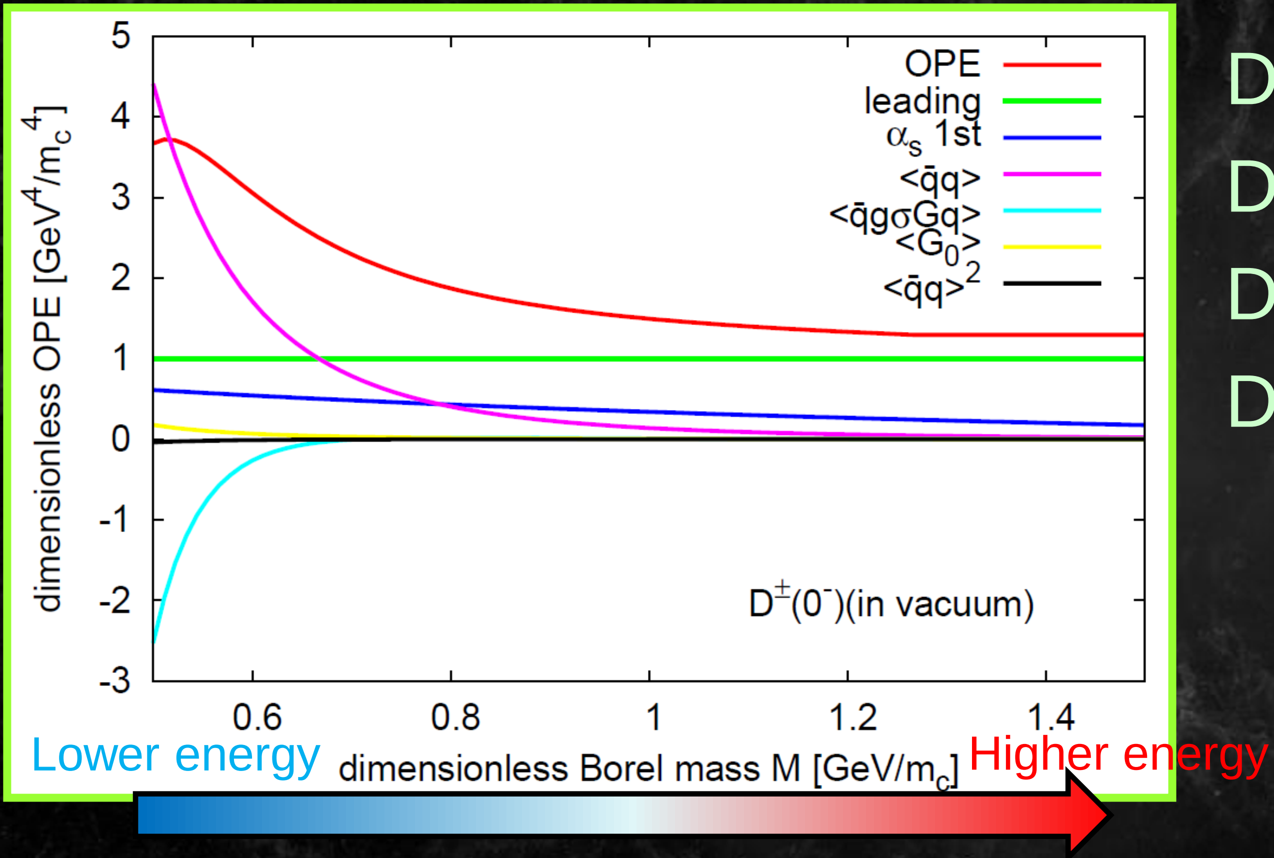
D meson OPE in nuclear medium

- New (Lorentz variant) condensates appear
- All of the condensates have density dependence

$$
\begin{aligned}
\langle \bar{d}d \rangle &= \langle \bar{d}d \rangle_{vac} + \frac{\sigma_N}{2m_q} n \,, \\
\langle \frac{\alpha_s}{\pi} G^2 \rangle &= \langle \frac{\alpha_s}{\pi} G^2 \rangle_{vac} - \frac{8M_N^0}{9} n \,, \\
\langle \bar{d} g \sigma \mathscr{G} d \rangle &= \lambda^2 \langle \bar{d}d \rangle \,, \\
\langle d^\dagger d \rangle &= \frac{3}{2} n \,, \\
\langle \frac{\alpha_s}{\pi} \left(\frac{(vG)^2}{v^2} - \frac{G^2}{4} \right) \rangle &= -\frac{3}{4} M_N \alpha_s(\mu^2) A_2^g(\mu^2) n \,, \\
\langle d^\dagger i D_0 d \rangle &= \frac{3}{8} M_N A_2^q(\mu^2) n \,, \\
\left[\langle \bar{d} D_0^2 d \rangle - \frac{1}{8} \langle \bar{d} g \sigma \mathscr{G} d \rangle \right] &= \frac{\lambda^2 \sigma_N}{2m_q} n \,, \\
\langle d^\dagger g \sigma \mathscr{G} d \rangle &= (-0.33 \mathrm{GeV}^2) n \,, \\
\langle d^\dagger D_0^2 d \rangle &= -\frac{1}{4} M_N^2 A_3^q(\mu^2) n + \frac{1}{12} \langle d^\dagger g \sigma \mathscr{G} d \rangle \,.
\end{aligned}
$$

⇒QCD sum rules relate D-dependence of condensates to D-dependence of hadron

How to determine criterion of Borel window ?



Dim3: enhanced

Dim4: suppressed

Dim5: enhanced

Dim6: suppressed

- Dim 6 (4-quark) condensate is strongly suppressed

⇒Should we regard the highest term as 4-quark con.?

Separation of D$^+$ and D$^-$

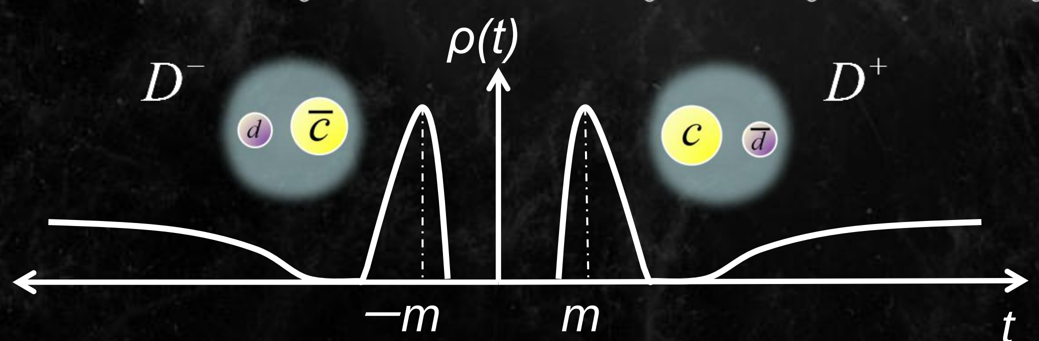
- In finite density, we have to construct <u>q_0 sum rule</u> instead of q_0^2

$$\Pi(q_0) = \Pi^{\text{even}}(q_0^2) + q_0 \Pi^{\text{odd}}(q_0^2)$$

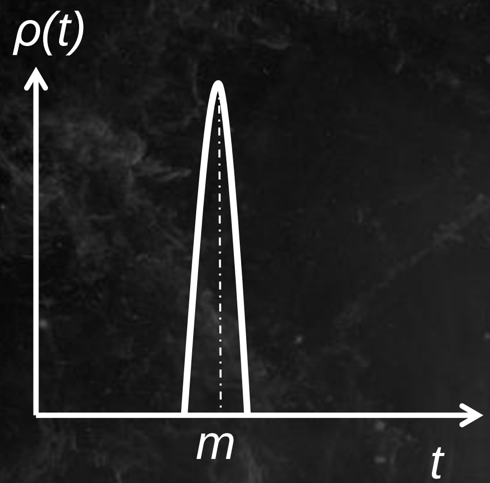
- Moreover, we <u>separate positive and negative energy</u> on q_0 axis

$$\Pi^+(q_0) = \Pi^{\text{even}}(q_0^2) + q_0 \Pi^{\text{odd}}(q_0^2)$$

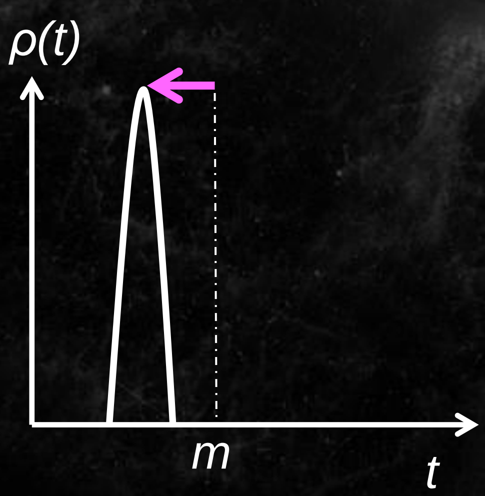
$$\Pi^-(-q_0) = \Pi^{\text{even}}(q_0^2) - q_0 \Pi^{\text{odd}}(q_0^2)$$



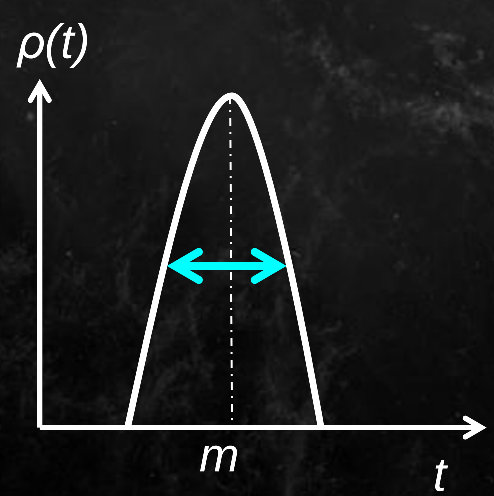
3 possibility of spectral modification



1. Mass shift



2. width broadening



3. residue reduction