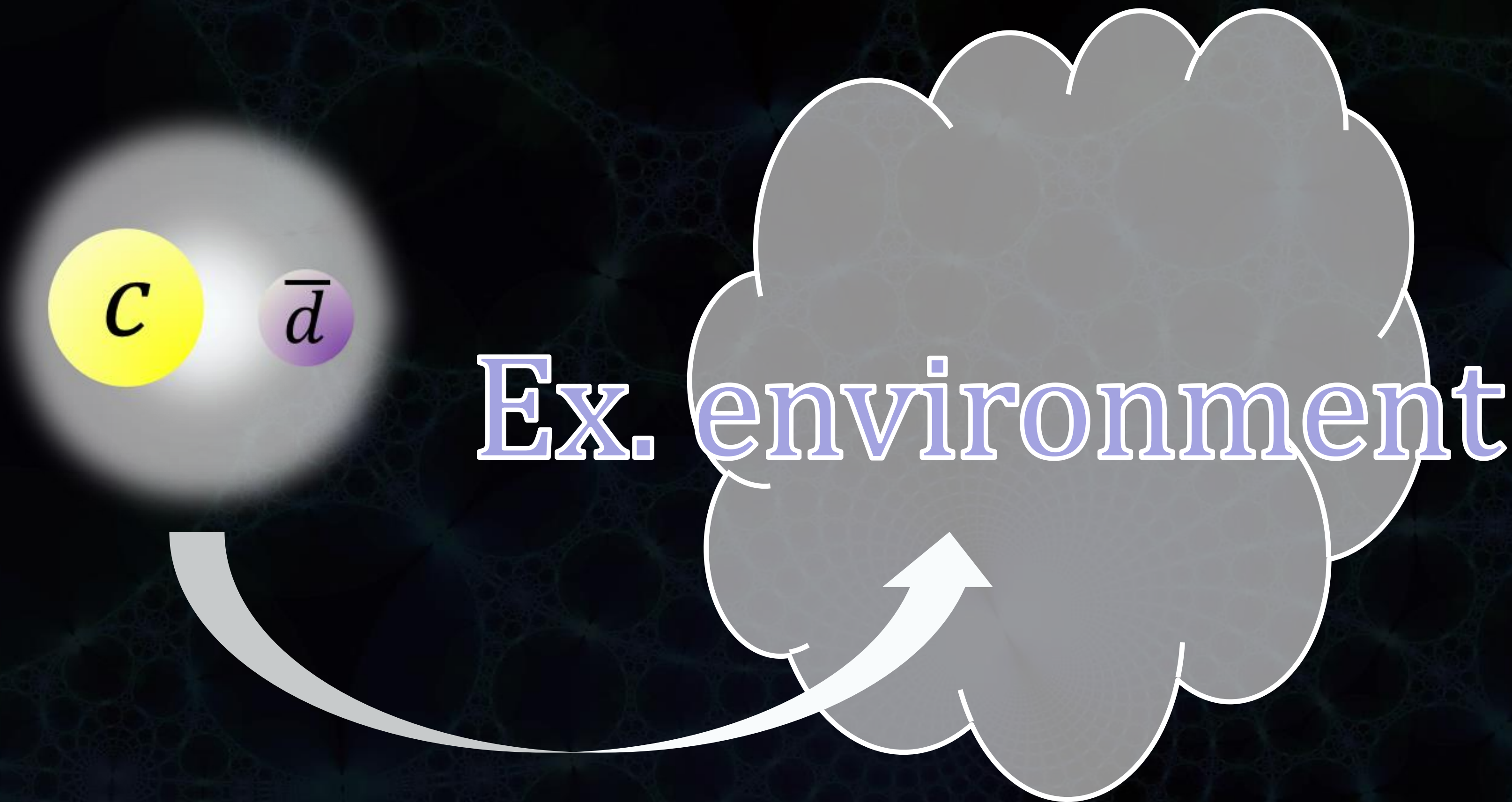
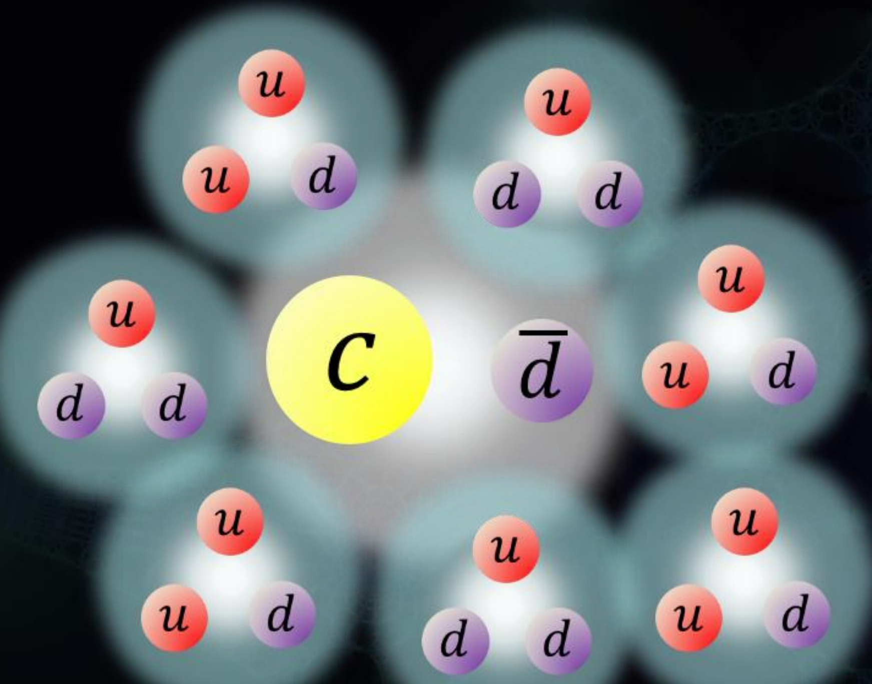
Recent progress of QCD sum rules for D meson in extreme environments

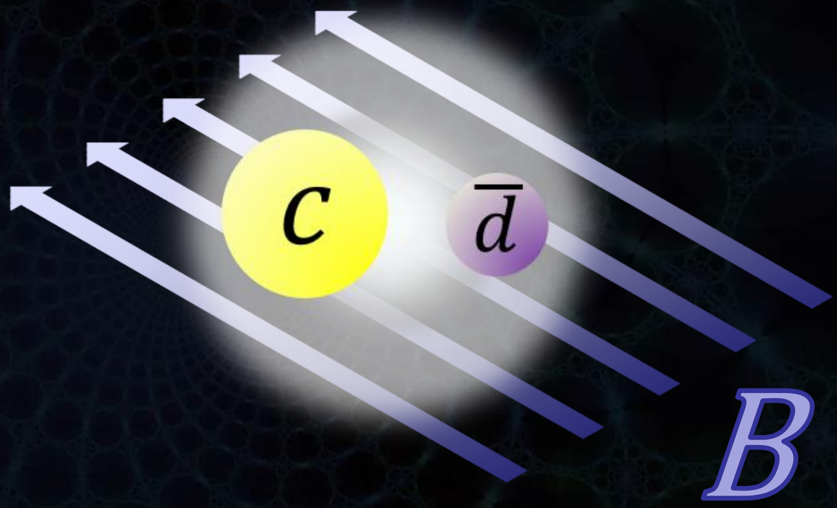


Kei Suzuki (Tokyo Institute of Tech.)

Outline of talk

1. Introduction
   - QCD sum rules in external field
2. D meson in nuclear medium from QCD sum rules
3. D meson in magnetic field from QCD sum rules





1. Introduction

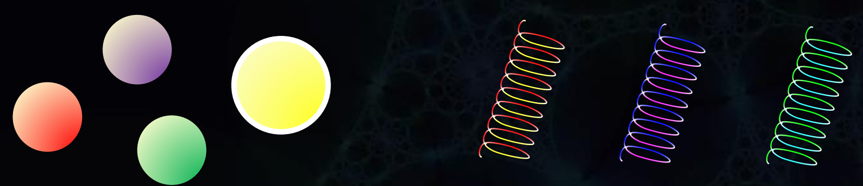
M.A. Shifman, A.I. Vainshtein, and V.I. Zakharov, Nucl. Phys. B**147**, 385 (1979); B**147**, 448 (1979)

QCD sum rule

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

$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\, \rho(s)\, ds$$

Quark and Gluon dynamics

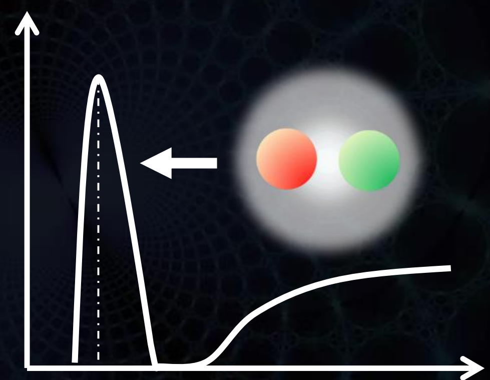


QCD vacuum condensates

$\langle \bar{q} q \rangle$ $\langle G_{\mu\nu} G^{\mu\nu} \rangle$

etc…

Hadron properties
(mass, width…)

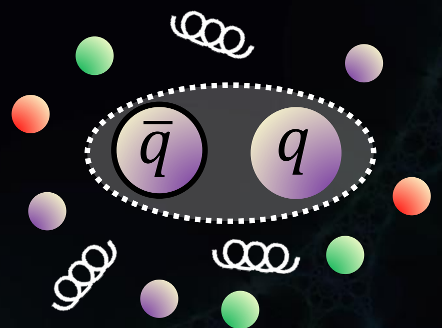


QCD sum rules in external field

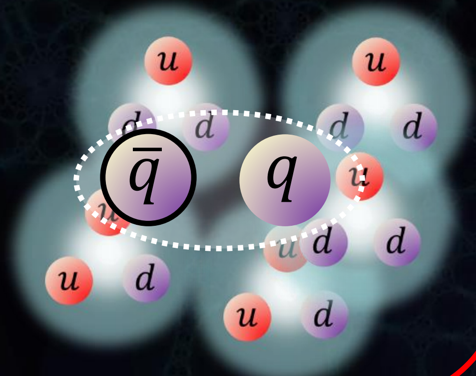
$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\, \rho(s)\, ds$$

Medium modification of OPE INPUT

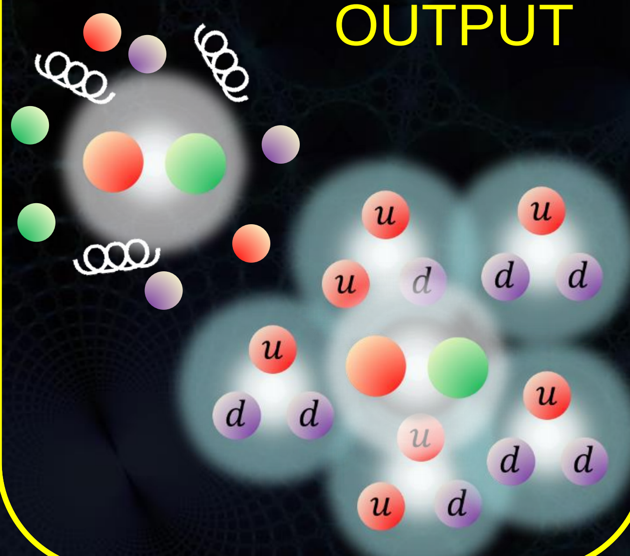
T- depend.
(ex. in hot π gas, QGP)



density depend.
(ex. in nuclear matter)

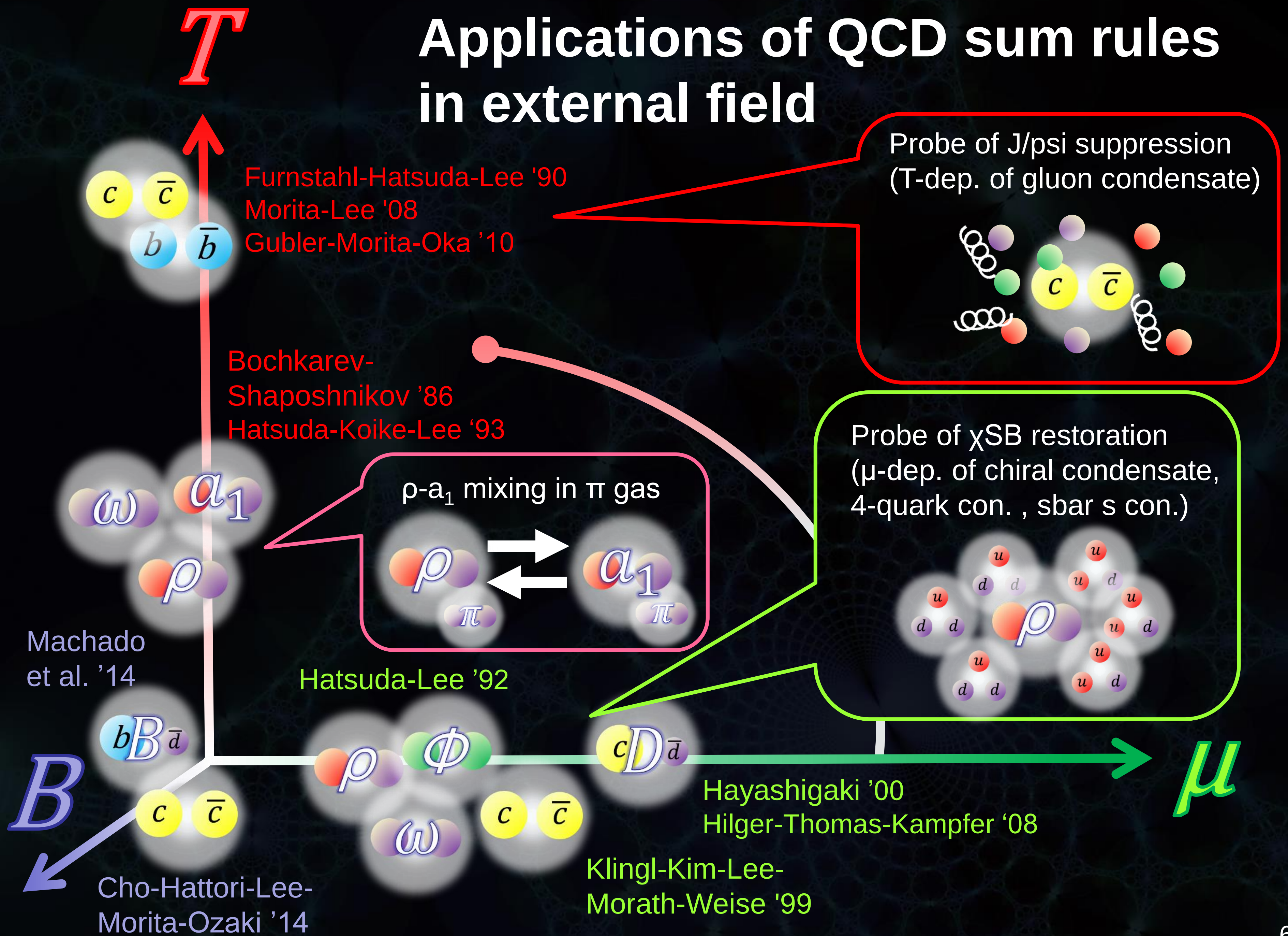


Hadron modification
OUTPUT

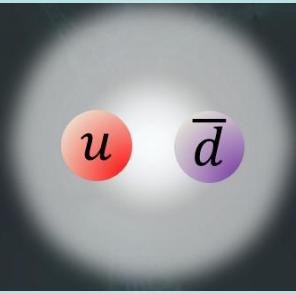
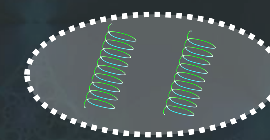
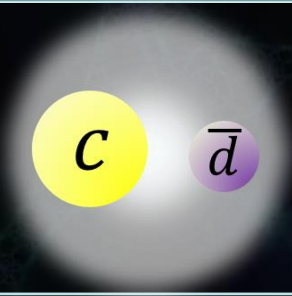
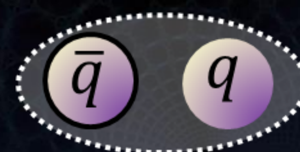
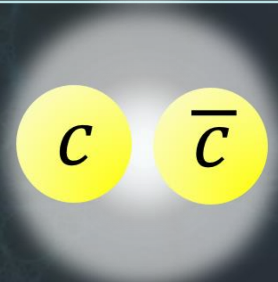
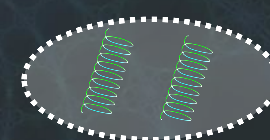


⇒QCD sum rule relates modification of OPE (or condensate) to modification of hadron state

Applications of QCD sum rules in external field



Difference of meson systems

Meson		Dominant contributions in vacuum
Light-Light (ρ, ω meson)		Probe of 4-quark and gluon condensates (2-quark condensate is suppressed as $m_q\langle\bar{q}q\rangle$)  
Light-Heavy (D, B meson)		Probe of 2-quark condensate as $m_c\langle\bar{q}q\rangle$  $\langle\bar{q}q\rangle$
Heavy-Heavy ($J/\psi, \Upsilon$)		Almost perturbative object (Probe of gluon condensate)  $\left\langle\frac{\alpha_s}{\pi}G^{\mu\nu}G_{\mu\nu}\right\rangle$

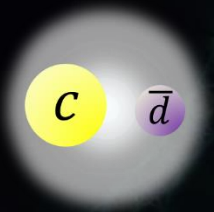
2. QCD sum rule in nuclear medium

Collaboration with
Philipp Gubler (ECT*) and Makoto Oka (TITech)

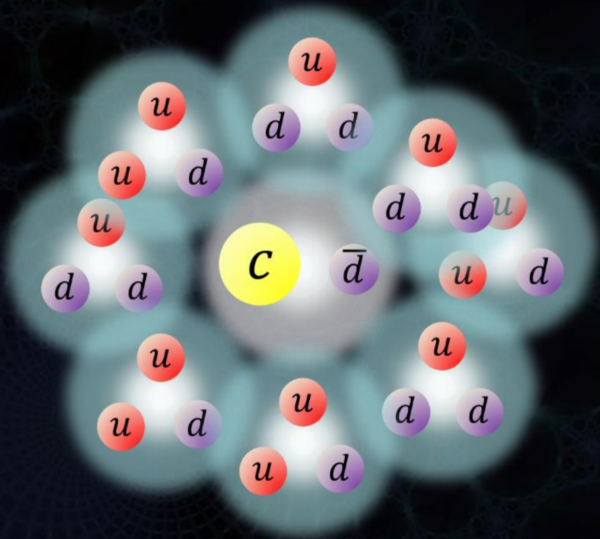
D meson in nuclear medium

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

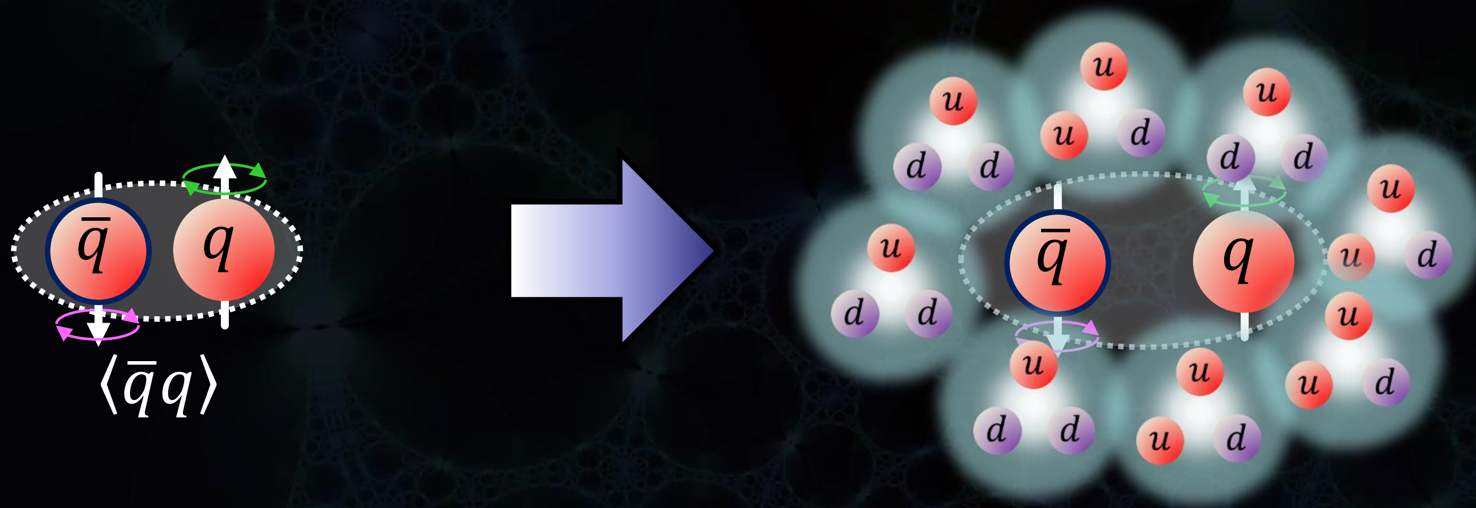
In vacuum



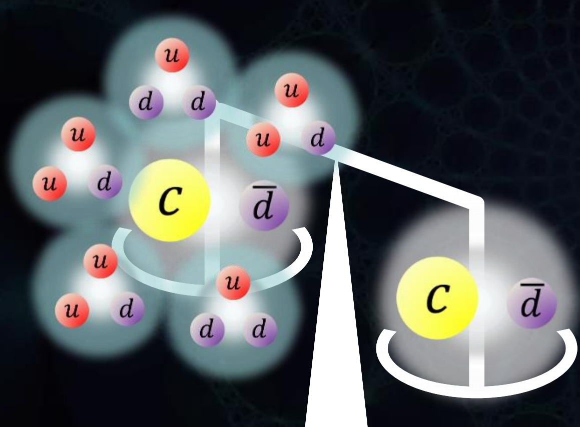
In nuclear medium



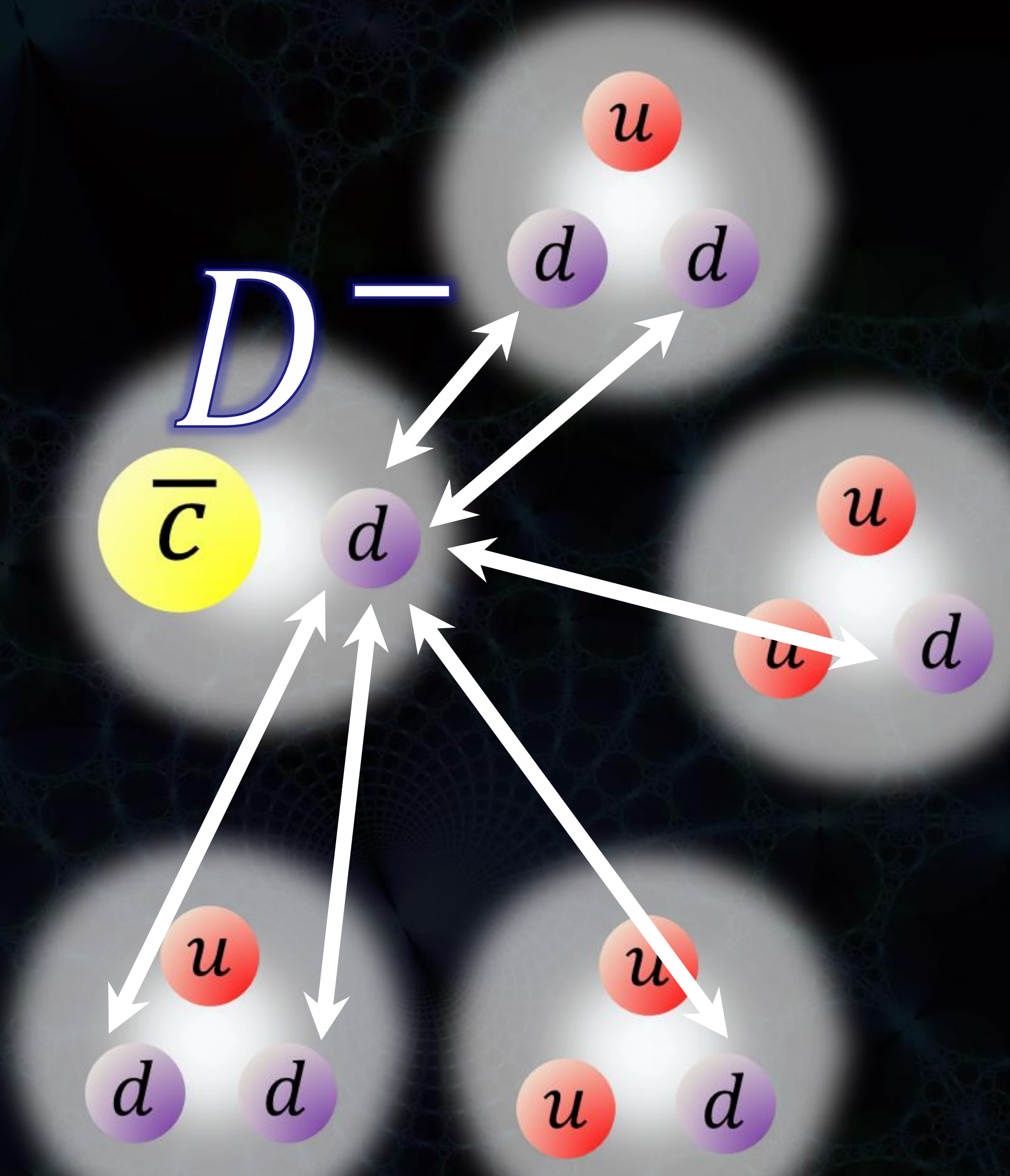
Chiral symmetry restoration in nuclear medium



- Hadron mass shift by chiral symmetry restoration



Pauli blocking

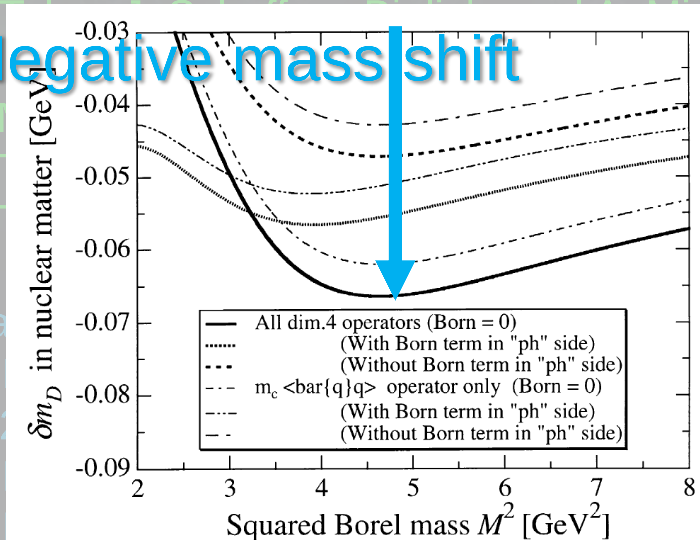


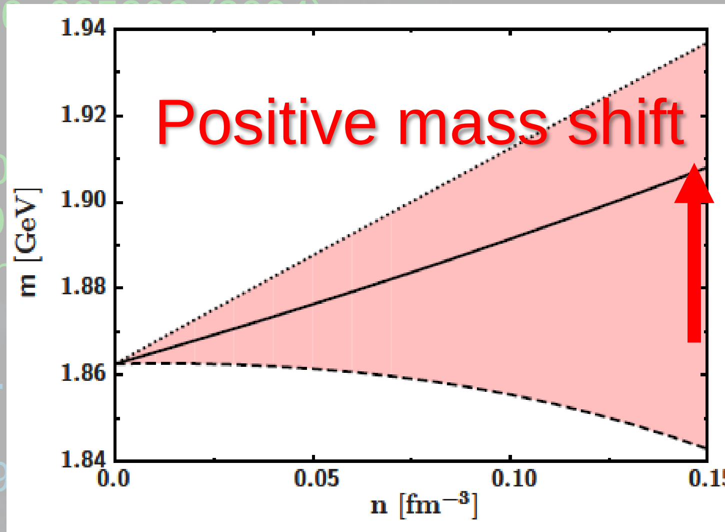
Only D⁻ feels <u>repulsive forces from Pauli effect</u>

⇒positive mass shift

Many previous works for D meson in medium

Coupled chanel approach





A. Kumar and A. Mishra, EPJ. A47, 164 (2011)

Pion exchange model

S. Yasui and K. Sudoh, PRC87, 015202 (2013)

QMC model

K. Tsushima, D.-H. Lu, A. W. Thomas, K. Saito, and R. Landau, PRC59, 2824 (1999)

A. Sibirtsev, K. Tsushima, and A. W. Thomas, EPJ. A6, 351 (1999)

QCD sum rules

P. Morath, W. Weise, and S.-H. Lee (1999)

A. Hayashigaki, PLB487, 96 (2000)

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

K. Azizi, N. Er, and H. Sundu, EPJ. C74, 3021 (2014)

QCD sum rules in nuclear matter

QCD sum rule

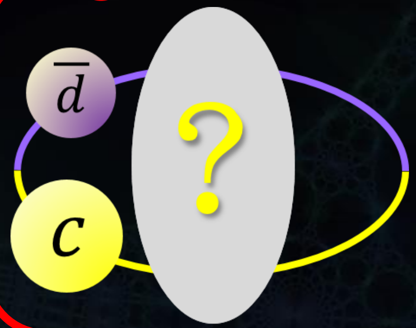
$$\Pi_{\mathrm{OPE}}(M) = \int_0^\infty K(s,M)\,\rho(t)\,ds$$

② Kernel

Weight of spectral function

- Gaussian sum rule

① OPE



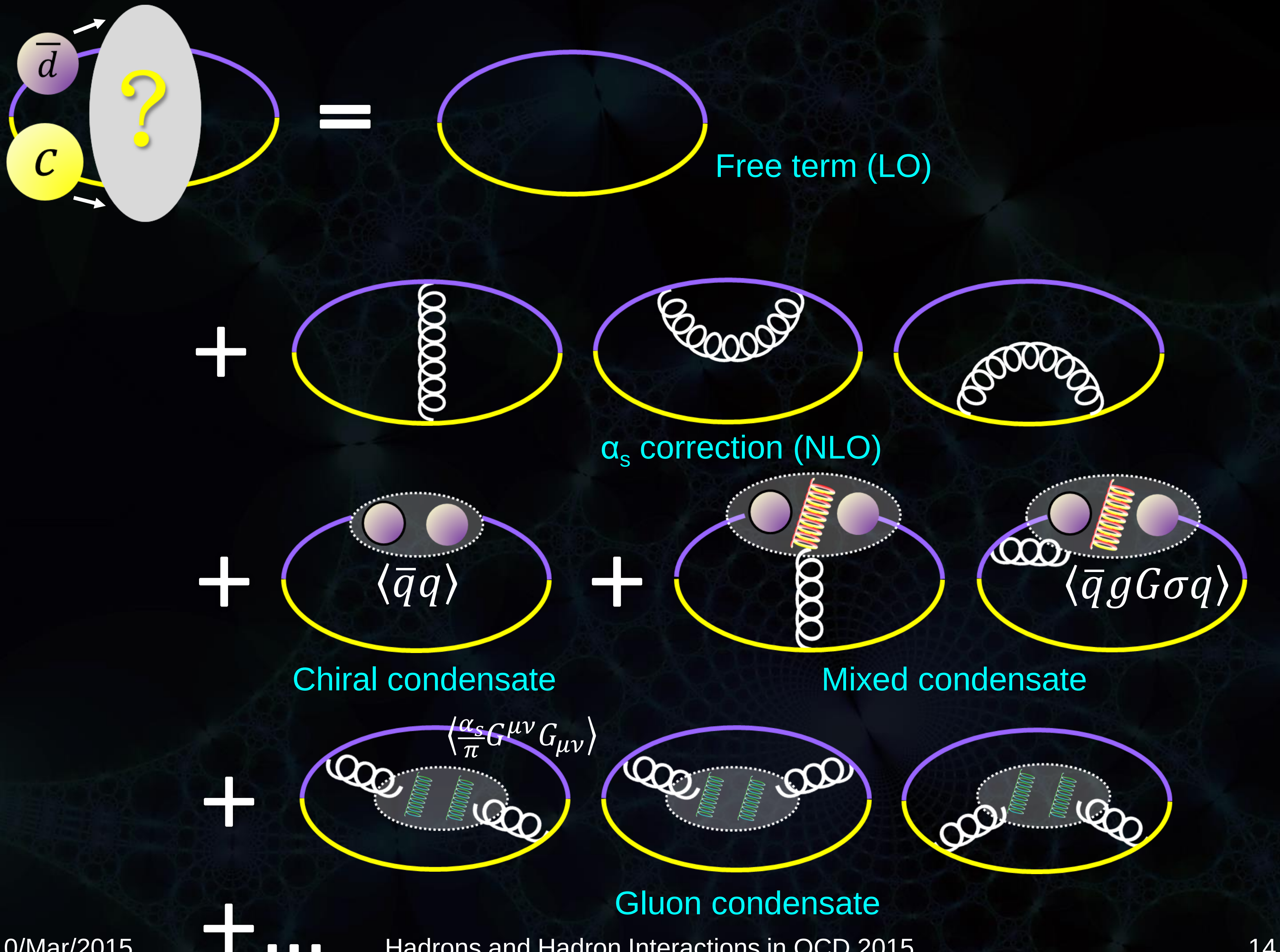
- dens.-dependence of condensates up to dim.5

③ Output spectral function

- maximum entropy method (MEM)

P. Gubler and M. Oka, PTP124 (2010) 995

cf.) A. Hayashigaki, PLB487 (2000) 96
T. Hilger, R. Thomas, B. Kampfer, PRC79 (2009) 025202


$\bar{d}$
c
?
=
Free term (LO)
+
α_s correction (NLO)
+
$\langle \bar{q}q \rangle$
+
$\langle \bar{q}gG\sigma q \rangle$
Chiral condensate
Mixed condensate
$\langle \frac{\alpha_s}{\pi} G^{\mu\nu} G_{\mu\nu} \rangle$
+
Gluon condensate
+ ...

D meson OPE in nuclear matter

- All of the condensates have density dependence

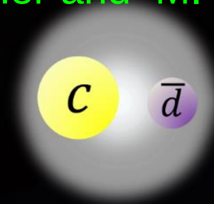
$\langle \bar{d}d \rangle_n = \langle \bar{d}d \rangle_{vac} + \frac{\sigma_N}{2m_q} n$	$\left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle_n = \left\langle \frac{\alpha_s}{\pi} G^2 \right\rangle_{vac} - \frac{8M_N^0}{9} n$	$\langle \bar{d} g\sigma G d \rangle_n = \lambda^2 \langle \bar{d}d \rangle_n$

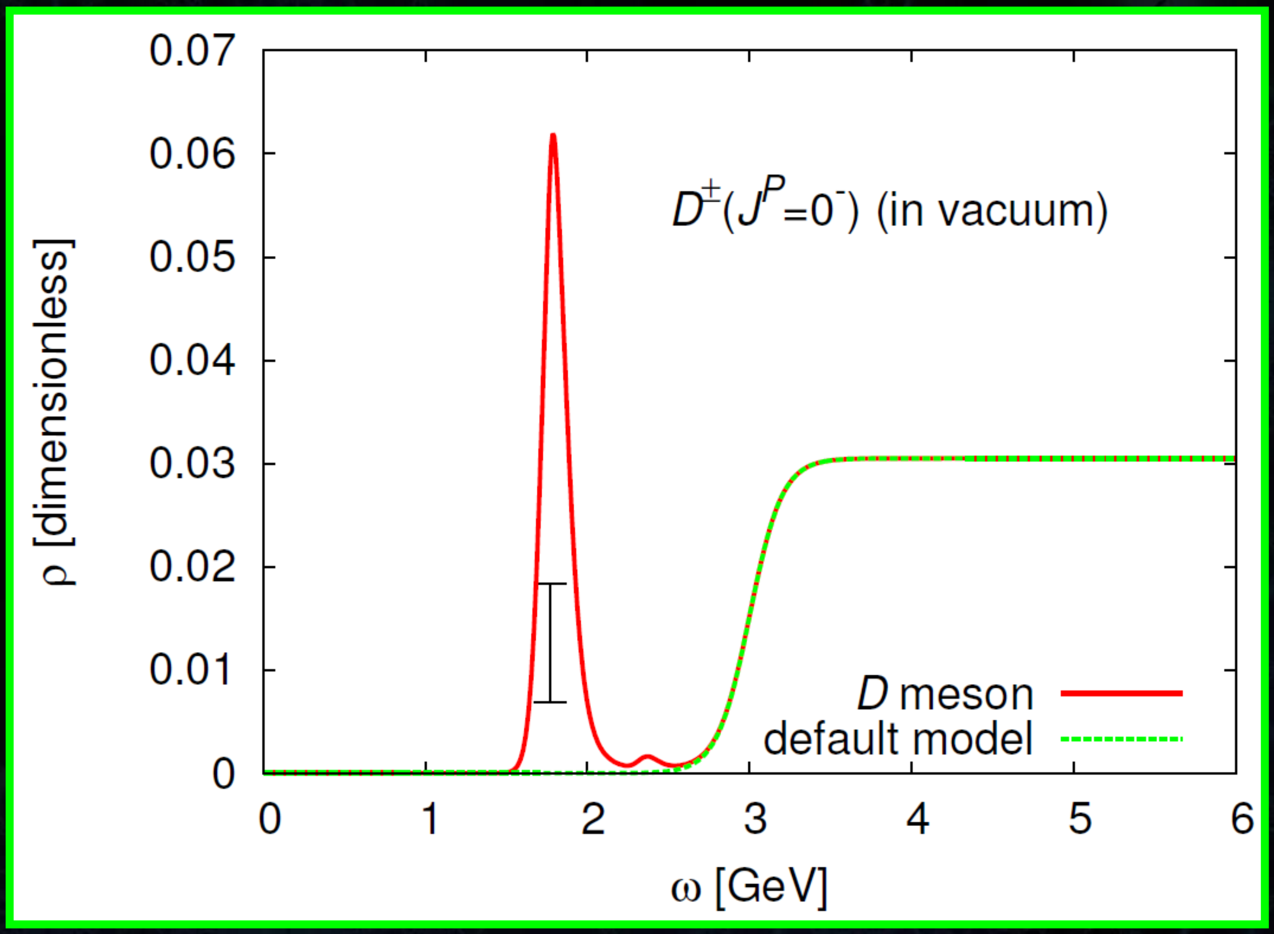
- New (Lorentz variant) condensates appear

$\langle d^\dagger d \rangle_n = \frac{3}{2} n$	$\left\langle \frac{\alpha_s}{\pi} \left(\frac{(vG)^2}{v^2} - \frac{G^2}{4} \right) \right\rangle_n = -\frac{3}{4} M_N A_2^g(\mu^2) n$
$\langle d^\dagger i D_0 d \rangle_n = \frac{3}{8} M_N A_2^q(\mu^2) n$	$\left[\langle \bar{d} D_0^2 d \rangle_n - \frac{1}{8} \langle \bar{d} g\sigma G d \rangle_n \right] = \frac{\lambda^2 \sigma_N}{2m_q} n$
$\langle d^\dagger g\sigma G d \rangle_n = (-0.33\mathrm{GeV}^2) n$	$\langle d^\dagger D_0^2 d \rangle_n = -\frac{1}{4} M_N^2 A_3^q(\mu^2) n + \frac{1}{12} \langle d^\dagger g\sigma G d \rangle_n$

KS, P. Gubler and M. Oka

D meson spectral function (in vacuum)

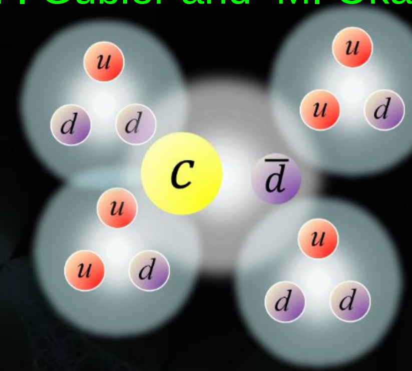




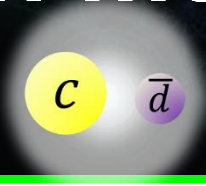
Mass : 1.78GeV Exp. : 1.87GeV

KS, P. Gubler and M. Oka

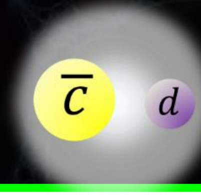
D meson spectral function (in medium)

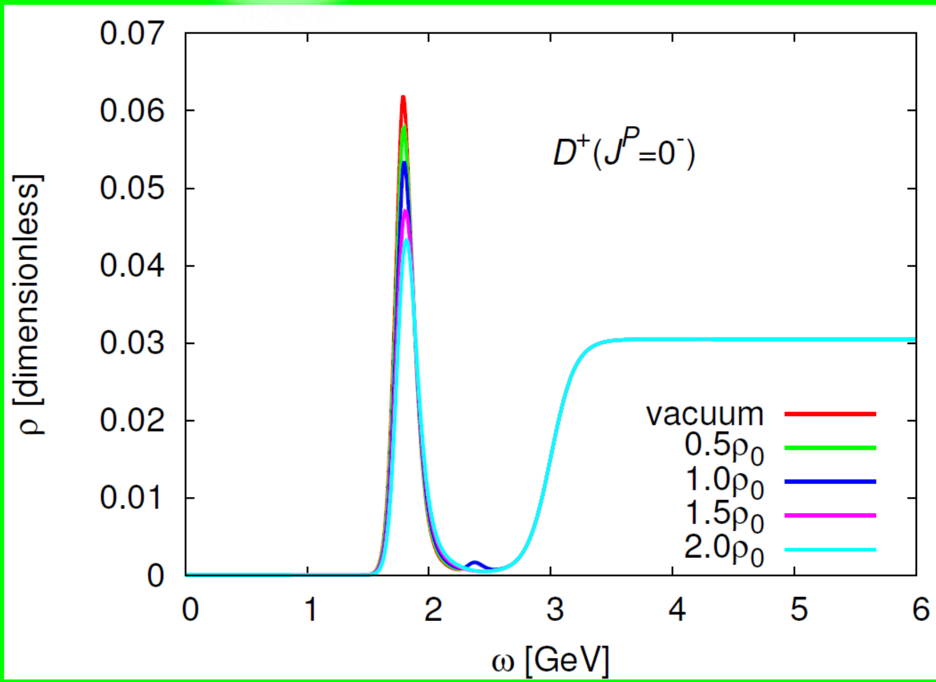


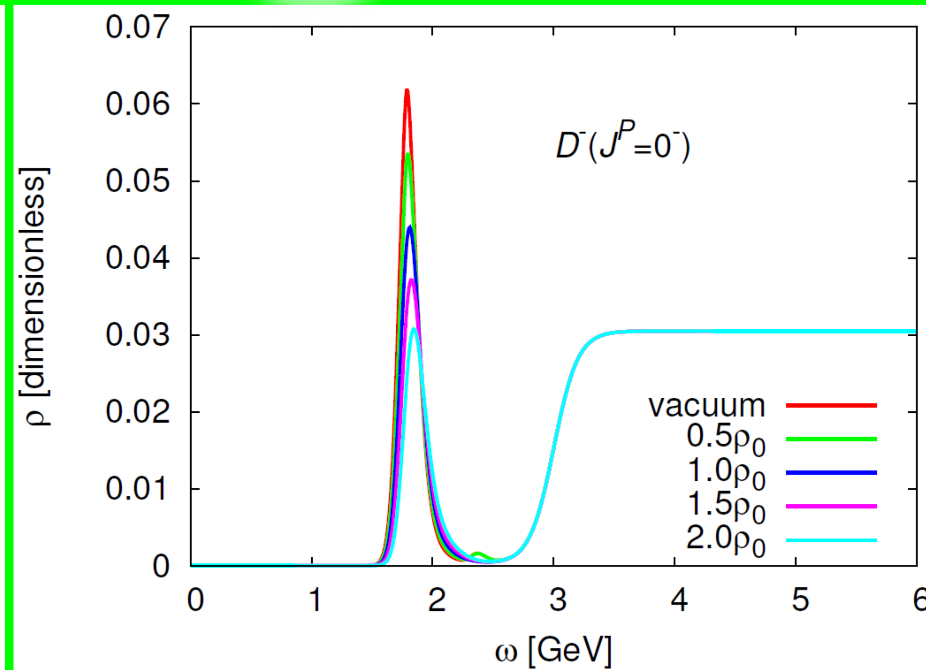
D$^+$



D$^-$



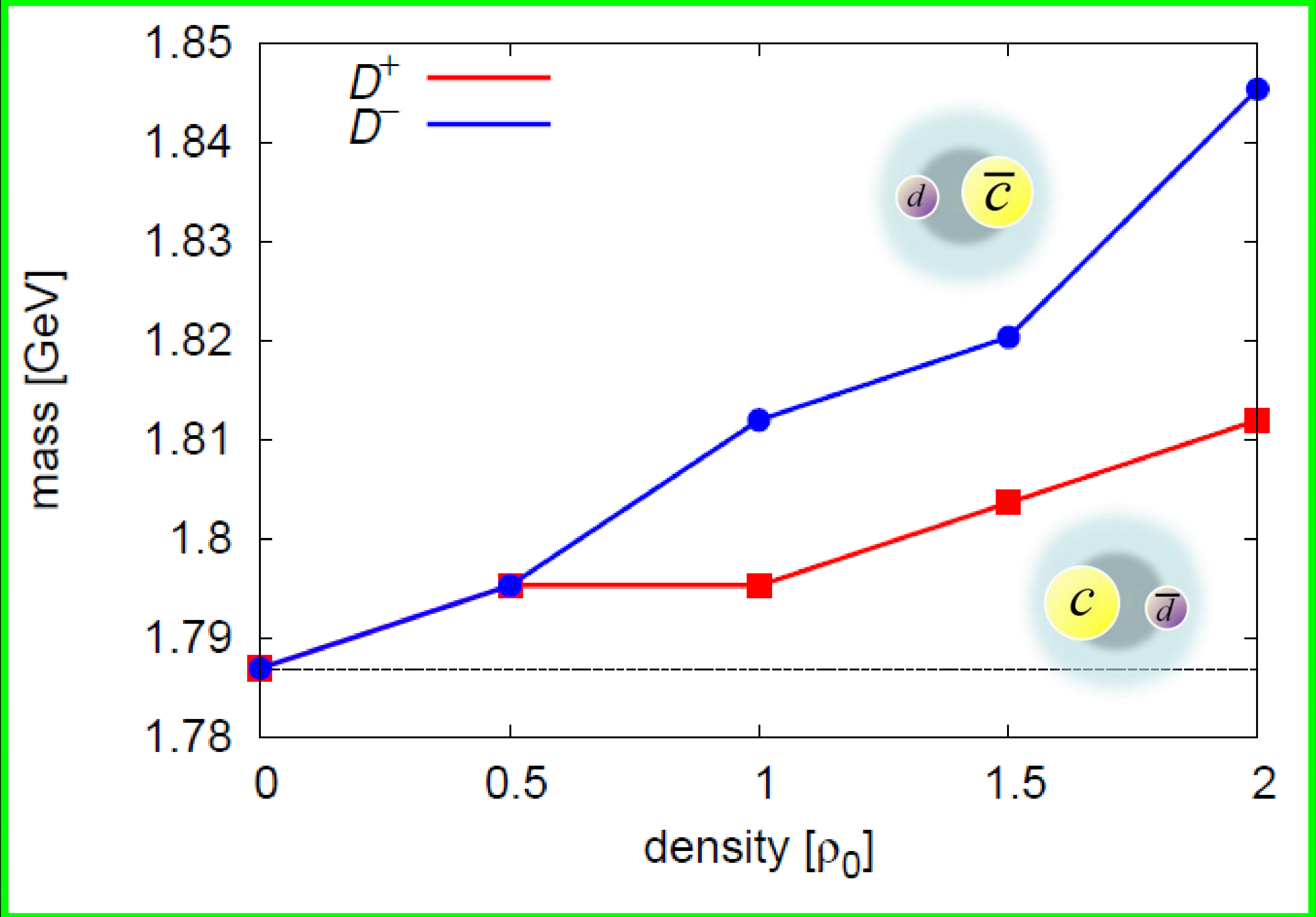




⇒Peak position in D$^\pm$ <u>shifts to higher energy side</u> with increasing density (D$^+$: ~10MeV D$^-$: ~30MeV at ρ_0)

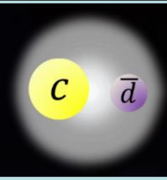
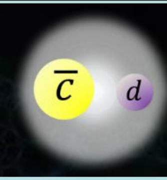
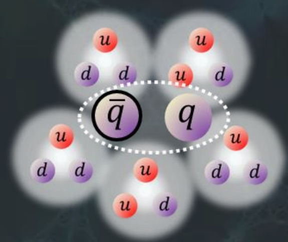
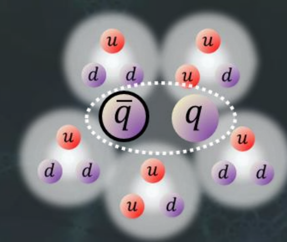
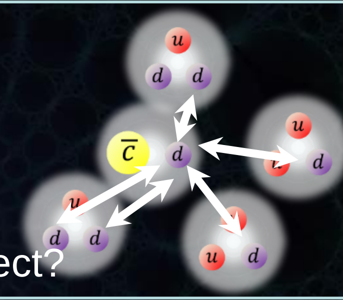
KS, P. Gubler and M. Oka

Comparison of D^{+}and D^{-}



⇒D^{+}-D^{-} mass splitting is about 20 MeV at ρ_0

Summary of D meson in nuclear medium

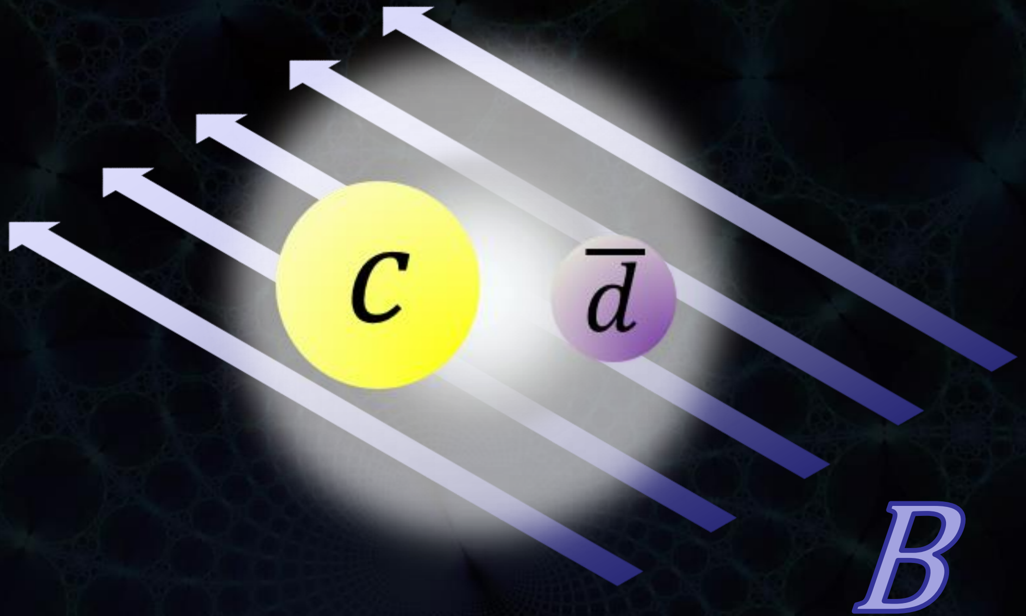
	D+	D-
	D+ 	D- 
Reduction of $\langle \bar{q}q \rangle$	Increase↑↑ 	Increase↑↑ 
Increase of q_0-odd condensate	Decrease↓	Increase↑  Pauli effect?
Our results	Increase↑	More increase↑↑

3. QCD sum rule in magnetic field

Collaboration with
Philipp Gubler (ECT*), Koichi Hattori (RIKEN BNL),
Su Houng Lee (Yonsei U.) and Sho Ozaki (KEK)

Hadron properties in B-field

- What's happen hadrons in magnetic field?

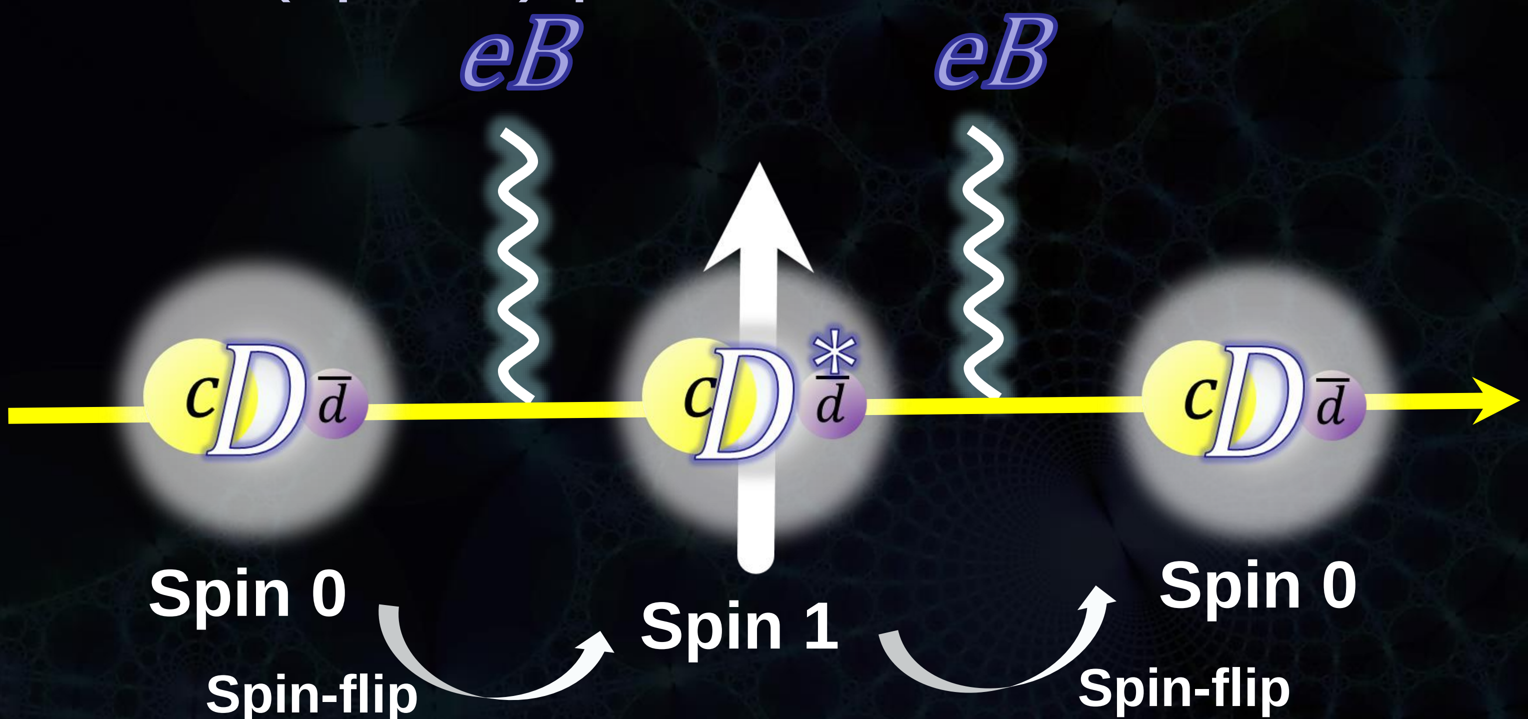


1. Spin mixing
2. Landau Level (LL)
3. Magnetic catalysis (B-dependence of $\langle \bar{q}q \rangle$)
4. Magnetic induced condensate ($\langle \bar{q}\sigma_{12}q \rangle$…)

C.S. Machado et al. PRD88 (2013), J. Alford and M. Strickland, PRD88 (2013), S. Cho et al. PRL113 (2014)

Spin mixing

- Mixing between pseudoscalar (spin 0) and vector (spin 1) particles

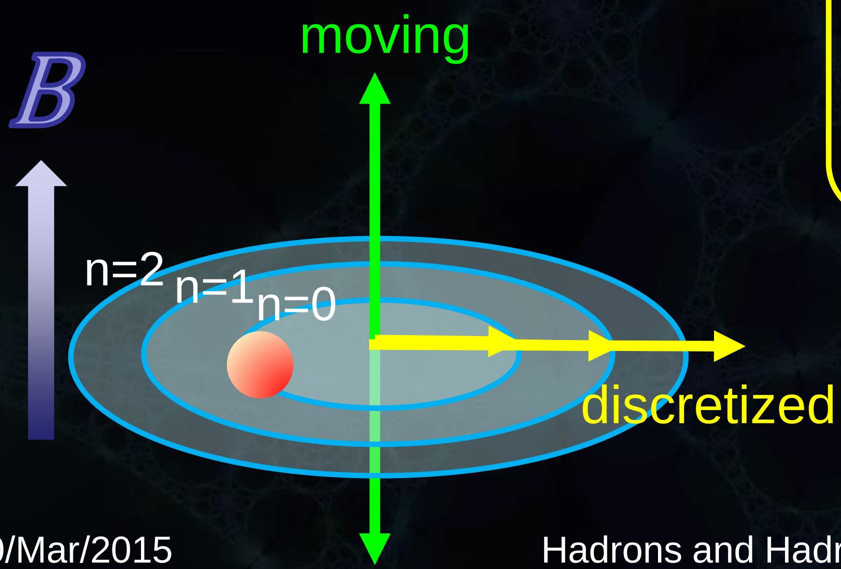


⇒Negative mass shift in D meson by level repulsion

Landau level

- Energy level of a charged particle is discretized by magnetic field

$$E_n = \sqrt{m^2 + p_z^2 + (2n+1)|qB| - g s_z qB}$$



Charged meson
⇒Mass increase

Neutral meson
⇒No change?

QCD sum rules in magnetic field

QCD sum rule

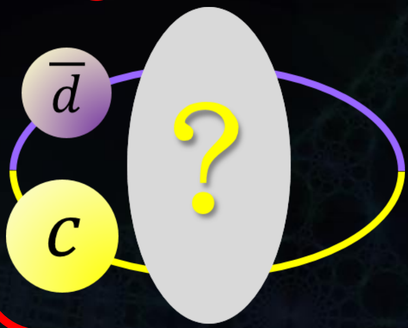
$$\Pi_{\mathrm{OPE}}(M) = \int_0^\infty K(s, M)\,\rho(t)\,ds$$

② Kernel

Weight of spectral function

- Borel sum rule

① OPE



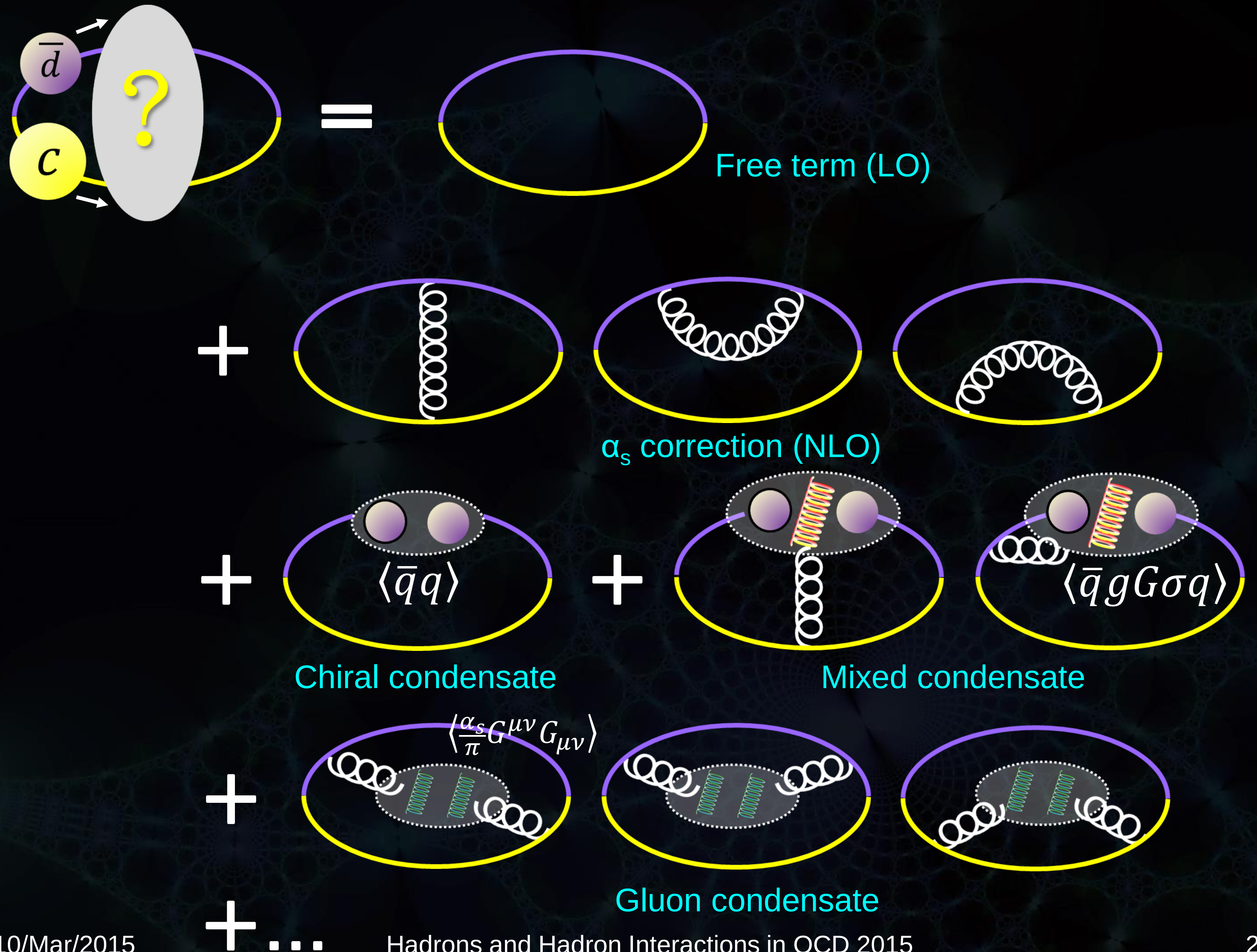
- B-dependence of OPE

(B-dependence of propagator and condensate)

③ Output spectral function

- Ansatz of functional form (pole + continuum)
- New structure formed by B-field

cf.) C. S. Machado et al. PRD89 (2014) [arXiv:1307.1797]
S. Cho, et al. PRL113 (2014) [arXiv:1406.4586]

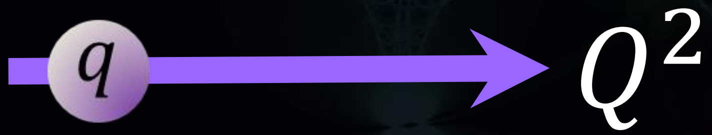


$\bar{d}$
c
?
=
Free term (LO)
+
α_s correction (NLO)
+
$\langle \bar{q}q \rangle$
+
$\langle \bar{q}gG\sigma q \rangle$
Chiral condensate
Mixed condensate
$\langle \frac{\alpha_s}{\pi} G^{\mu\nu} G_{\mu\nu} \rangle$
+
Gluon condensate
+ ...

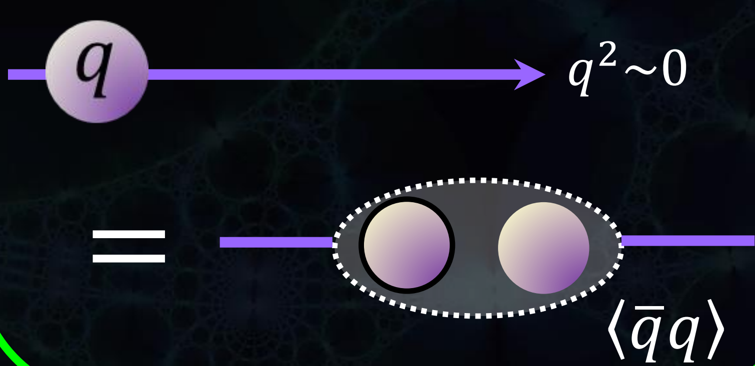
Concept of OPE (separation of scale)

Vacuum

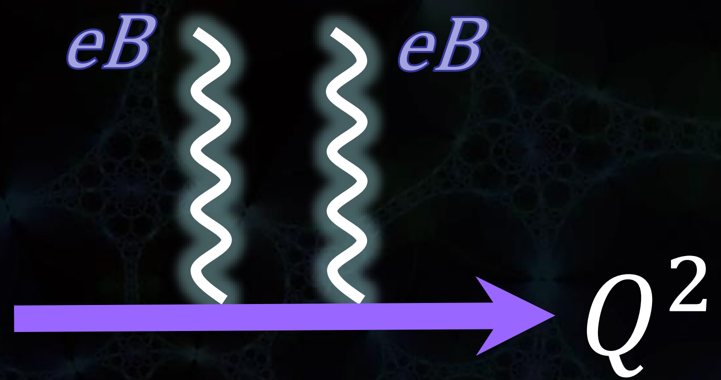
- Large momentum



- Small momentum

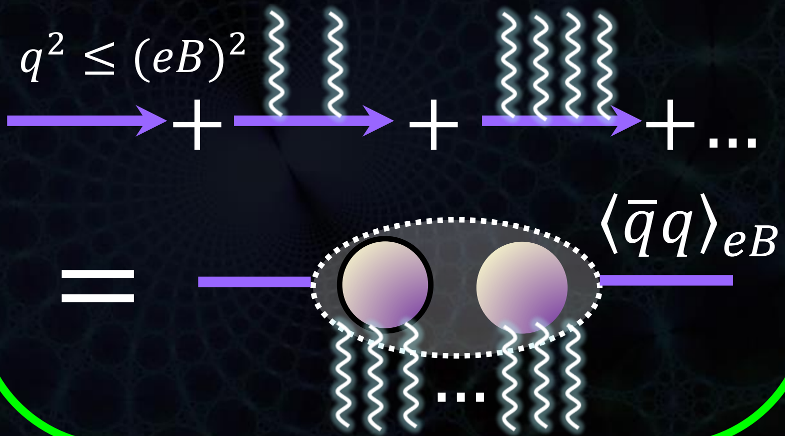


Magnetic field



Expansion w.r.t. weak field

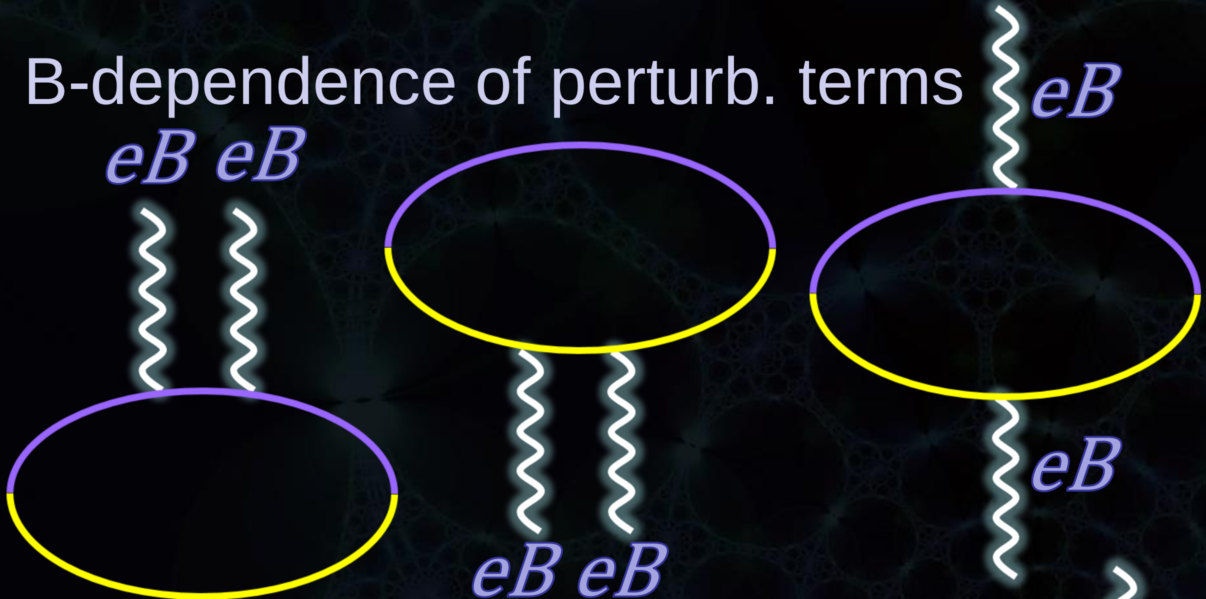
$Q^2 \gg (eB)^2 \Rightarrow$ up to 2nd order



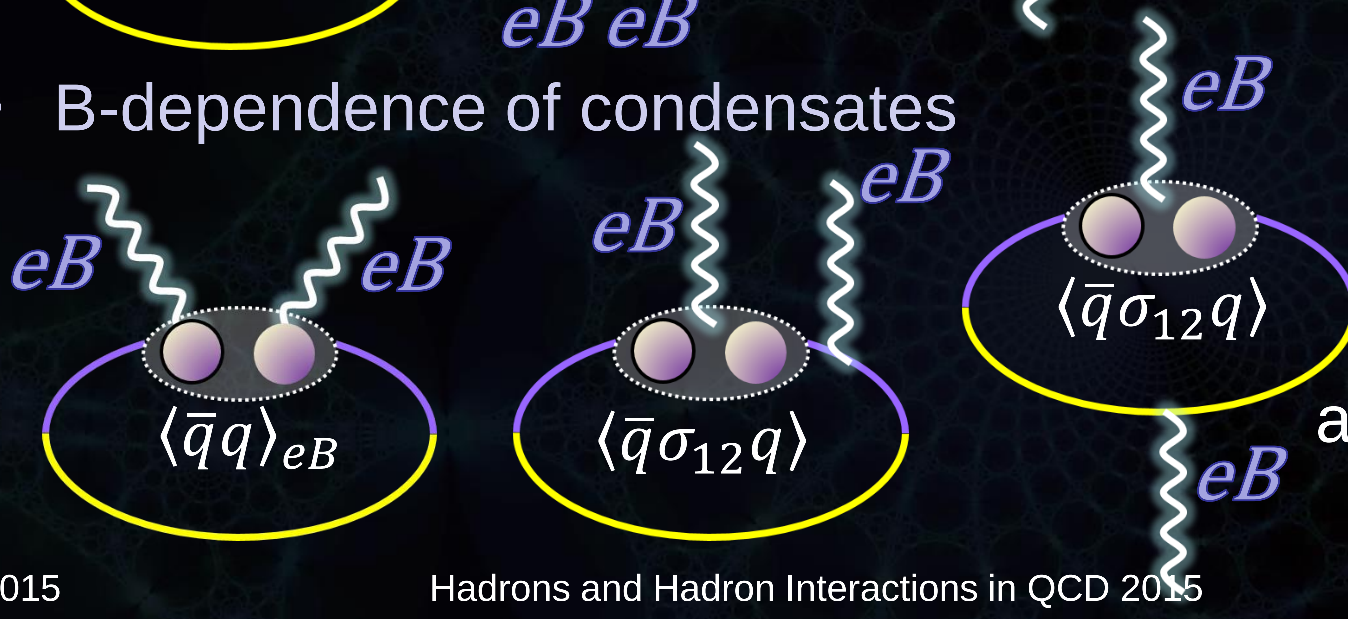
cf.) C. S. Machado et al. PRD89 (2014) [arXiv:1305.3308]

OPE in magnetic field

- B-dependence of perturb. terms



- B-dependence of condensates



and $\langle \bar{q} \gamma^{\mu} D^{\nu} q \rangle$

B-dependence of condensates

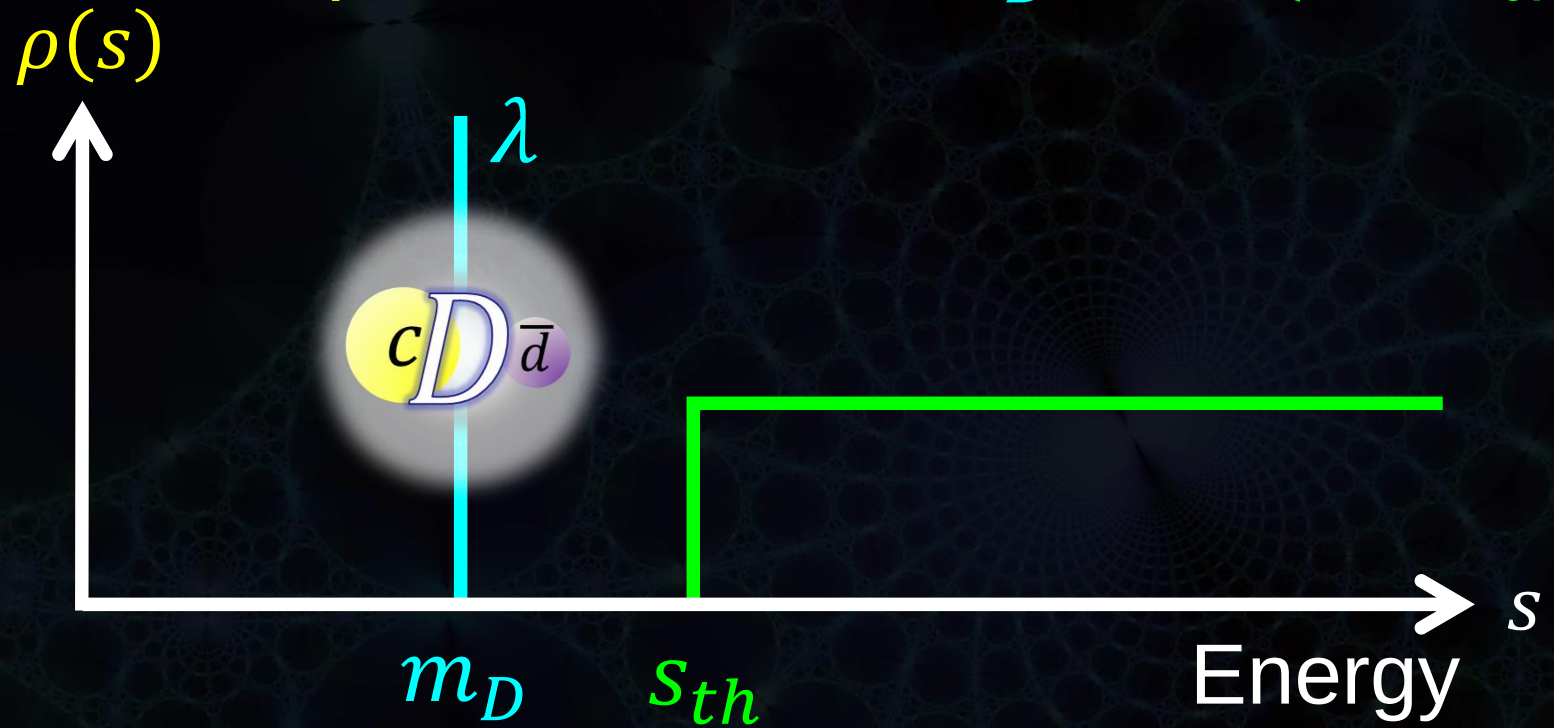
Condensates	Input
$\langle \bar{q}q \rangle_{eB}$	From ChPT and lattice QCD (including $\langle \bar{u}u \rangle$ and $\langle \bar{d}d \rangle$ splitting) T.D. Cohen et al. PRC76 (2007), G.S. Bali et al., PRD86 (2012) 071502
$\langle \bar{q}\sigma_{12}q \rangle$	From lattice QCD (including $\langle \bar{u}\sigma_{12}u \rangle$ and $\langle \bar{d}\sigma_{12}d \rangle$ splitting) G.S. Bali et al., PRD86 (2012) 094512
$\langle \bar{q}\gamma^{\mu} D^{\nu} q \rangle$	Estimation from constituent quark propagator
$\langle G_{\mu\nu} G^{\mu\nu} \rangle_{eB}$	No (Small B-dependence is evaluated by lattice QCD)
$g\langle \bar{q} G_{\mu\nu} \sigma^{\mu\nu} q \rangle_{eB}$	No (Unknown B-dep.)

Phenomenological side (in vacuum)

$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\, \rho(s)\, ds$$

- We assume D meson pole + continuum as a spectral function

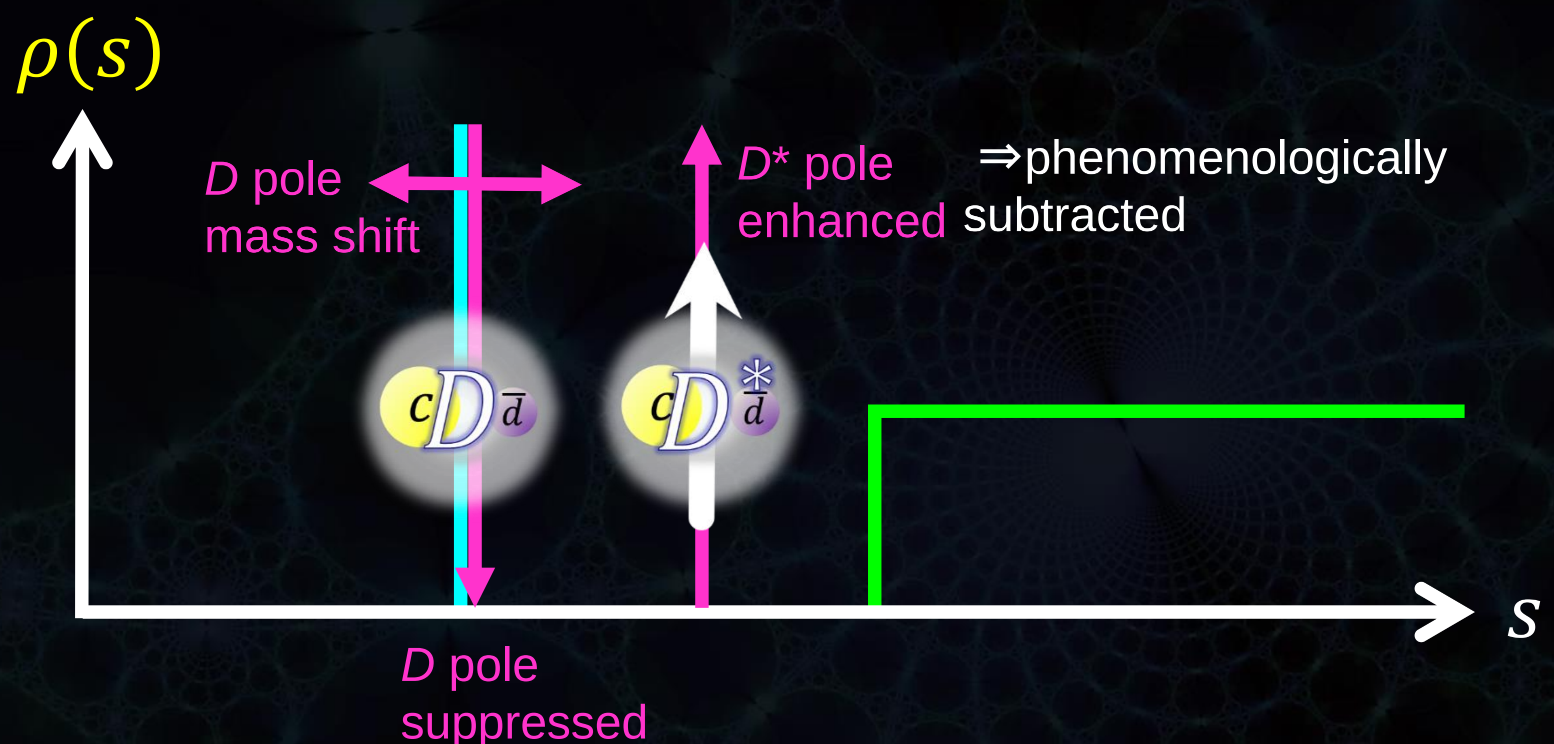
$$\rho(s) = \lambda\delta(s - m_D^2) + \theta(s - s_{th})$$



Expected spectral function (in B-field)

$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\, \rho(s)\, ds$$

- We assume D meson pole + continuum + magnetic structure as a spectral function



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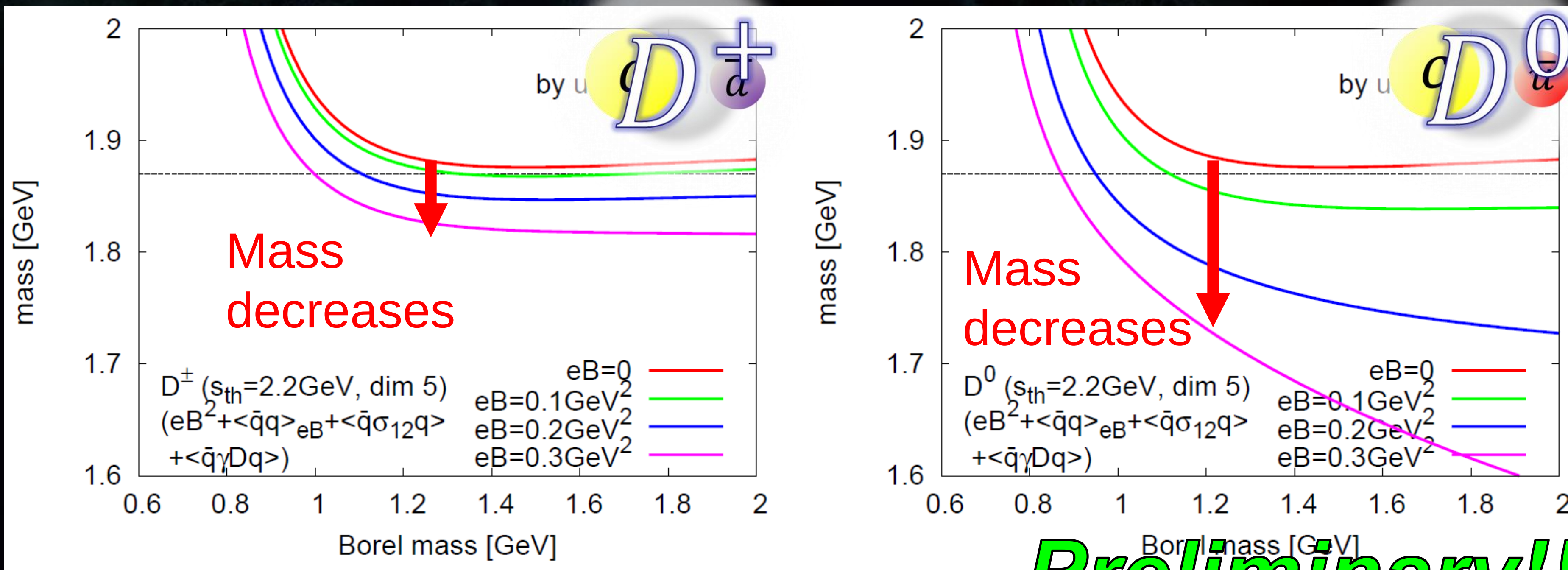
Results



	Charged D	Neutral D
Our results	Decrease↓	More decrease↓↓
Pictures	Mixing↓ (+hadron LL↑ + others?)	Mixing↓ (+others?)

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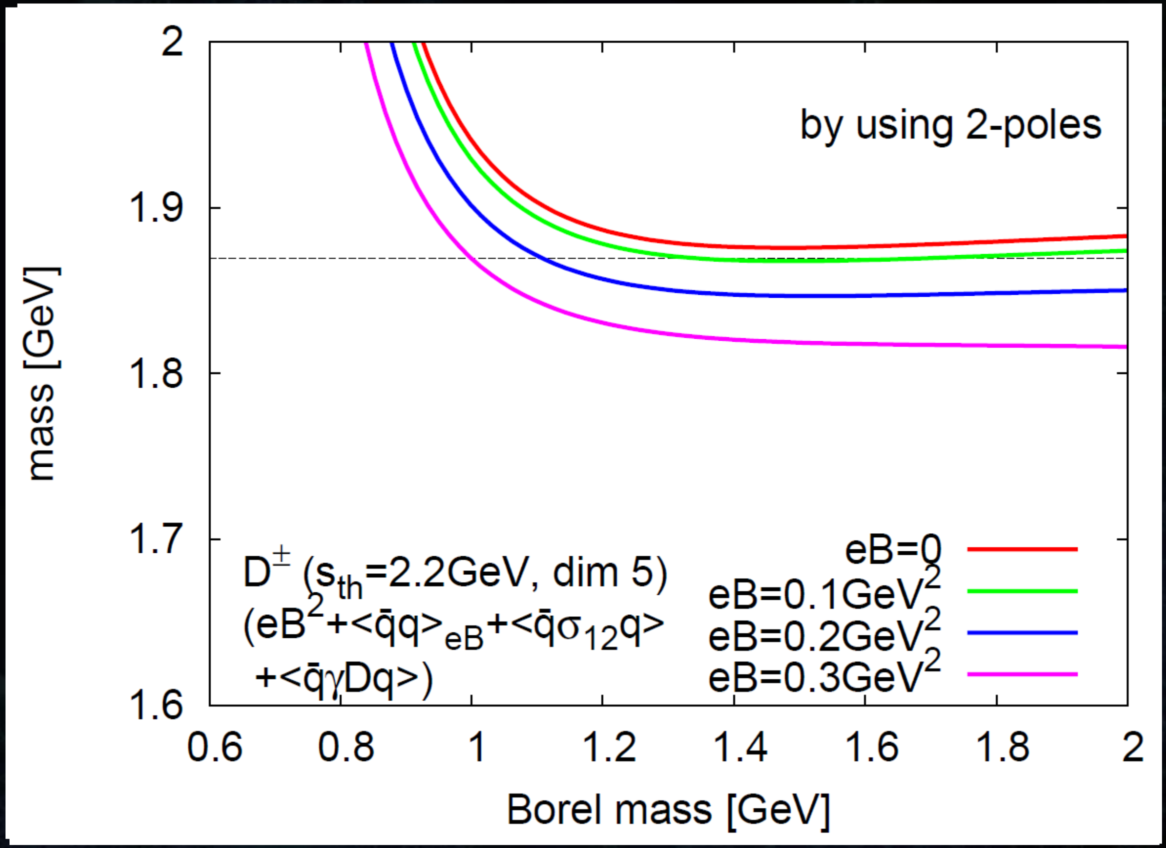
Results (condensate contribution)



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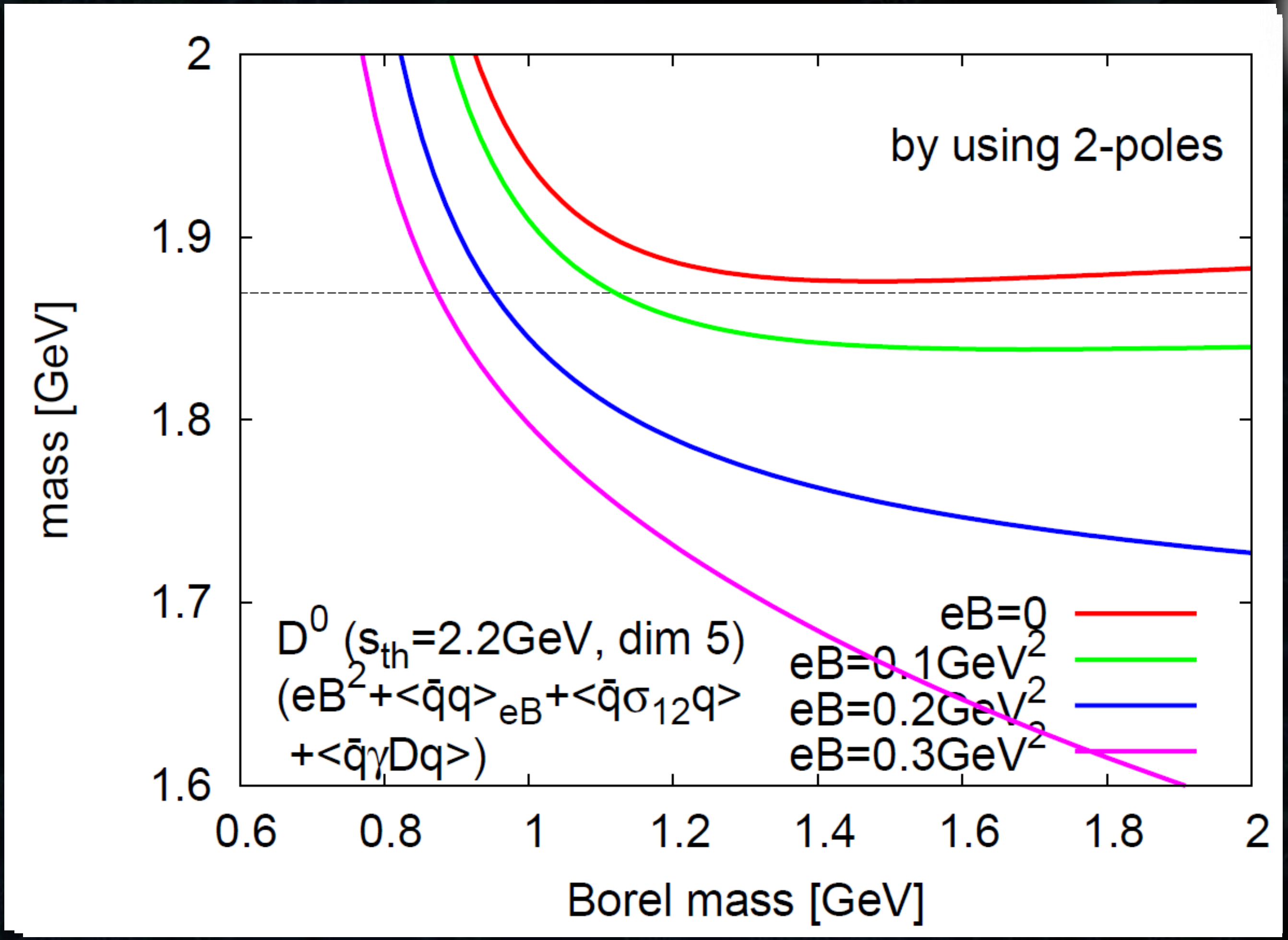
Results (condensate contribution)



Summary of D meson in magnetic field

- We investigated D meson spectral function in magnetic field by QCD sum rules

	Charged D	Neutral D
Our results	Decrease↓	More decrease↓↓
Pictures	Mixing↓ (+ hadron LL↑ + others?)	Mixing↓ (+ others?)

- Our results are consistent with spin mixing
- Hadron Landau level is included in charged one?
- Condensate contributions was estimated

Backup

D meson OPE (in vacuum)

$$\Pi_{\mathrm{OPE}}(M^2) = \text{perturbative term}$$

$$+e^{-m_c^2/M^2}\left[-m_c\langle\bar{q}q\rangle + \frac{1}{2}\left(\frac{m_c^2}{2M^4} - \frac{1}{M^2}\right)m_c\langle\bar{q}g\sigma Gq\rangle\right.$$

$$\left.+\frac{1}{12}\left\langle\frac{\alpha_s}{\pi}G^2\right\rangle - \frac{16\pi}{27}\frac{1}{M^2}\left(1 + \frac{1}{2}\frac{m_c^2}{M^2} - \frac{1}{12}\frac{m_c^4}{M^4}\right)\alpha_s\langle\bar{q}q\rangle^2\right]$$

1. Chiral condensate
2. Mixed condensate

Coefficients are proportional to charm quark mass
⇒These terms are enhanced

3. Gluon condensate
4. 4-quark condensate

Other condensates are relatively suppressed