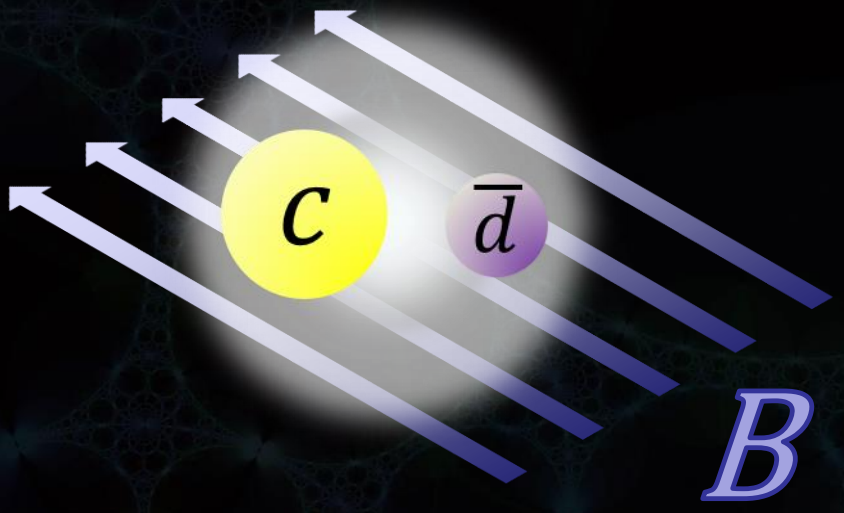


# D and D* meson mixing in magnetic field by QCD sum rules

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Philipp Gubler (RIKEN), Koichi Hattori (RIKEN BNL),
Su Houng Lee (Yonsei U.), Sho Ozaki (KEK)

# Outline of talk

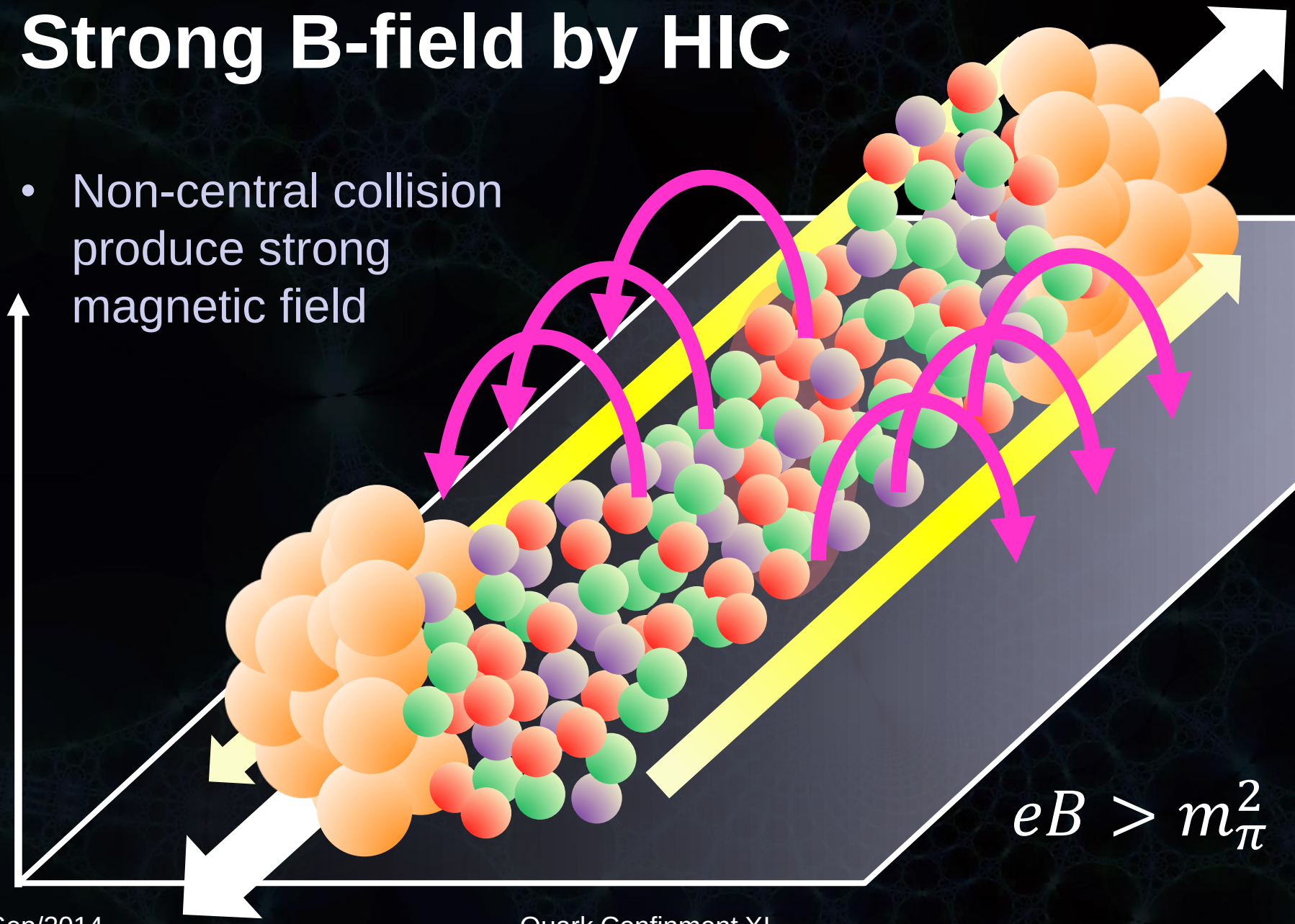
1. Introduction
   - D meson properties in magnetic field
2. QCD sum rule in magnetic field
   - D meson OPE in vacuum
   - D meson OPE in magnetic field
   - magnetic structure in spectral function
3. results

4. Summary

# 1. Introduction

# Strong B-field by HIC

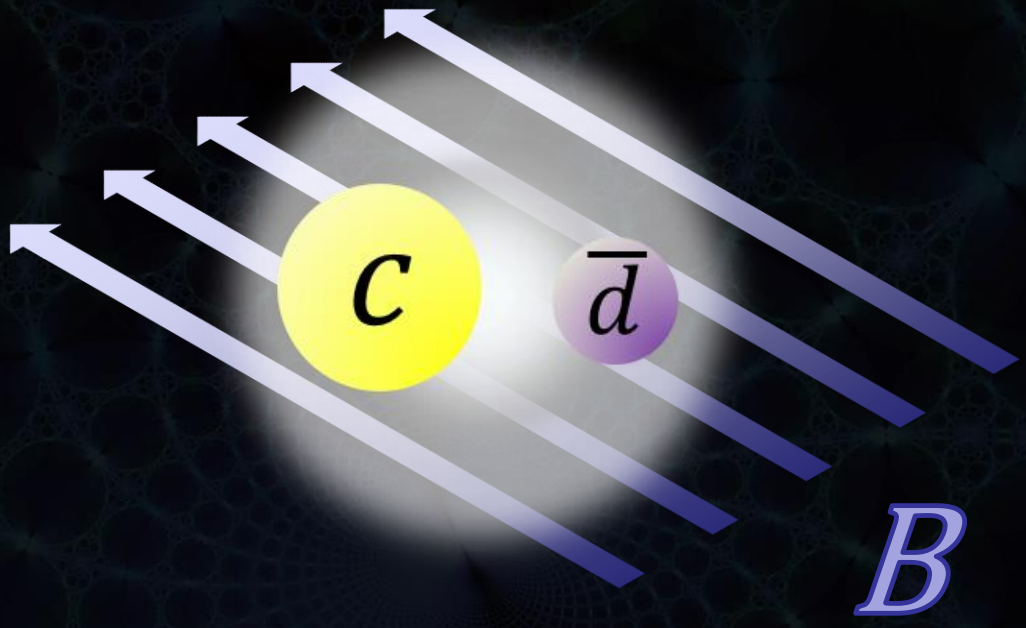
- Non-central collision produce strong magnetic field



$$eB > m_\pi^2$$

# Hadron properties in B-field

- What's happen hadrons in magnetic field?

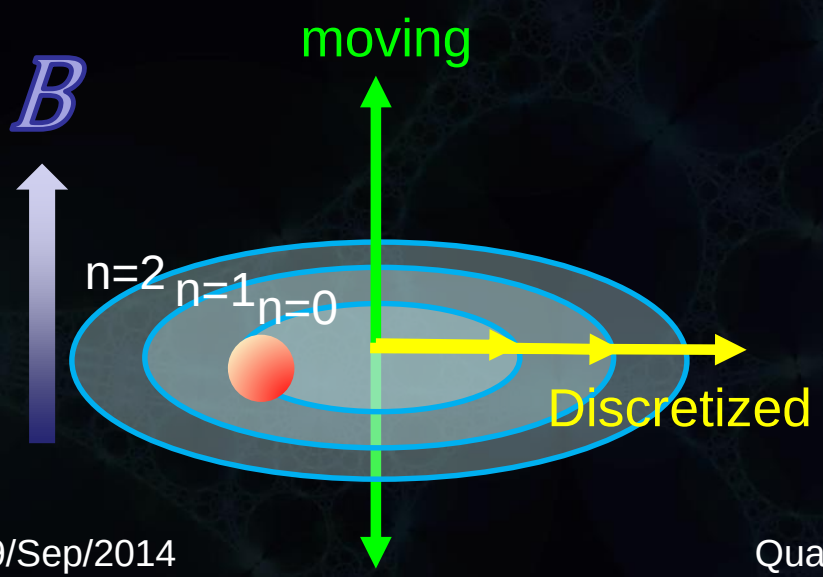



1. Landau Level (LL)
2. Spin mixing
3. Magnetic catalysis
4. Magnetic induced condensate …

# Landau Level

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

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





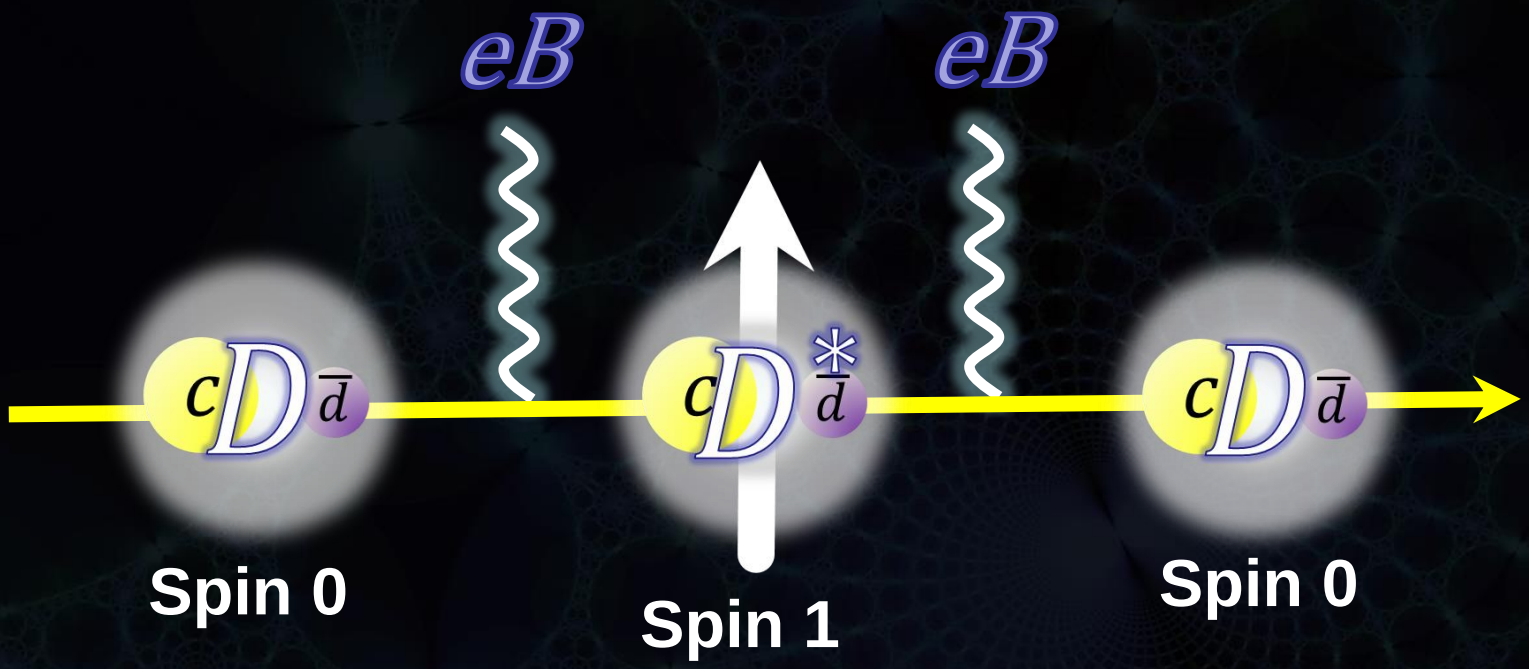
⇒Energy of charged hadron is enhanced


⇒Neutral particle do not change?

J. Alford and M. Strickland, PRD88 (2013) 105017
S. Cho, K. Hattori, S. H. Lee, K. Morita, S. Ozaki, [arXiv:1406.4586]

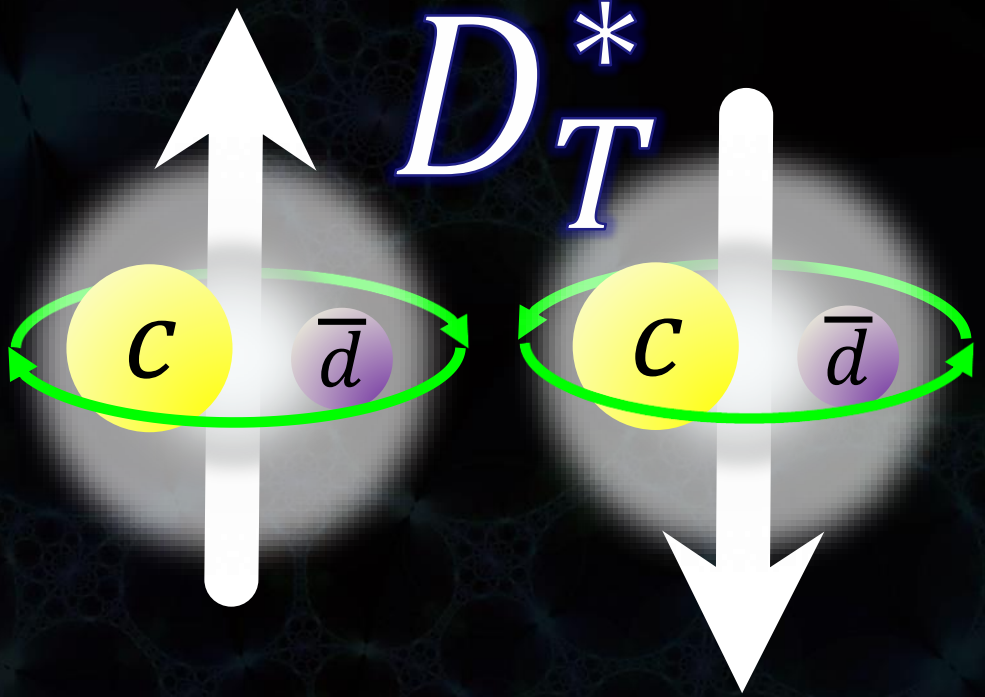
# Spin mixing

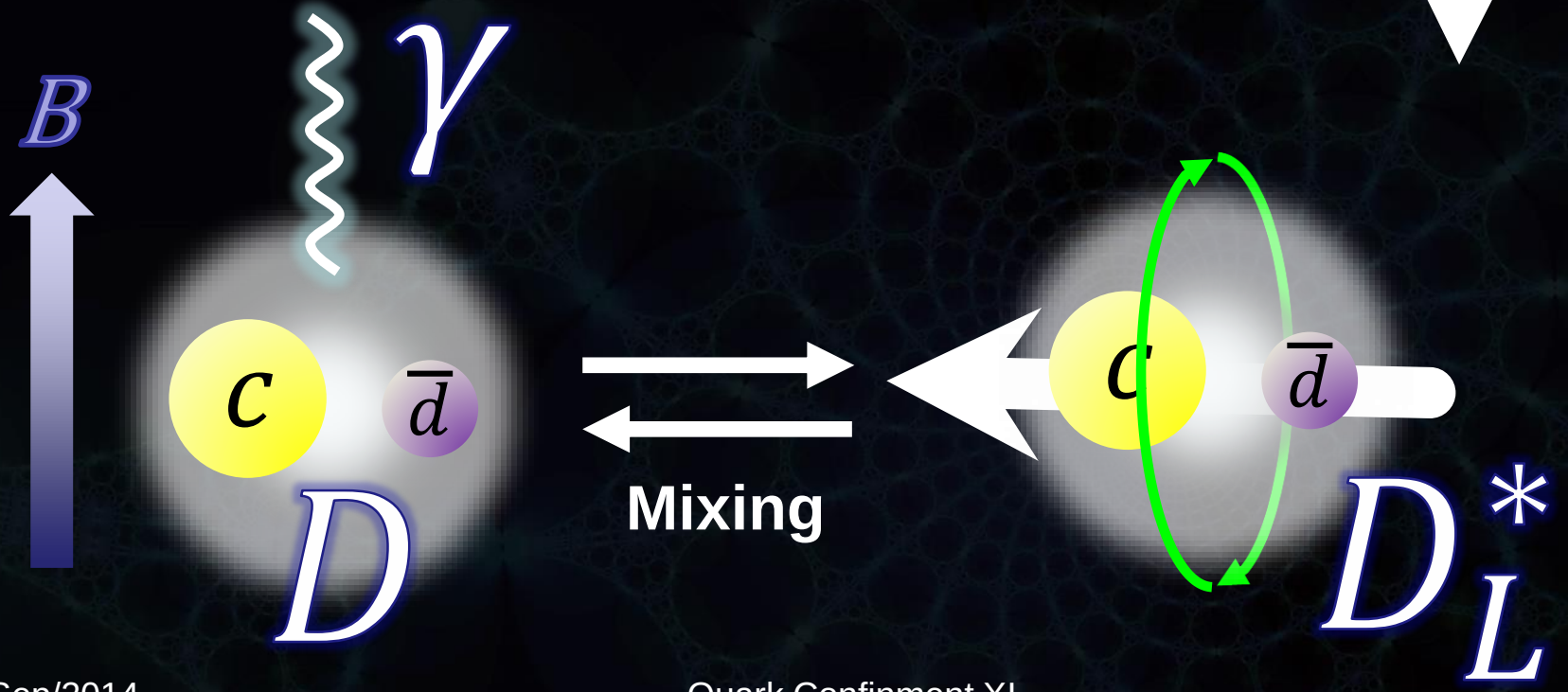
- Mixing of pseudoscalar and vector particle



# Spin mixing

- mixed with only longitudinal *D**



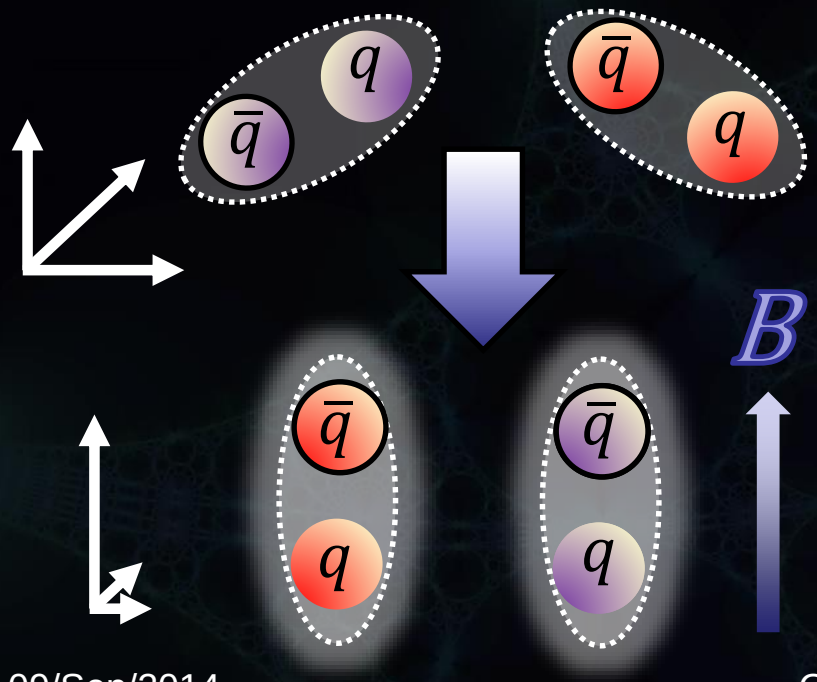



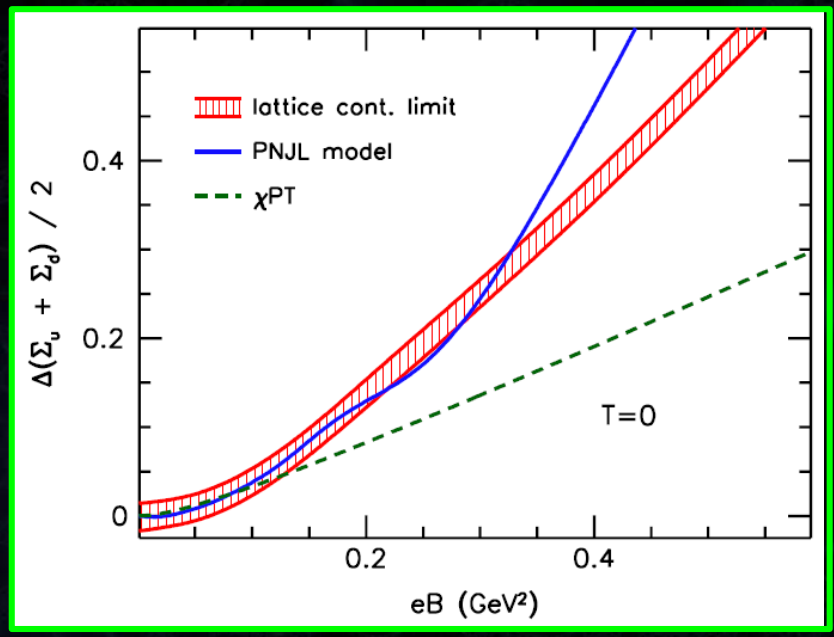
S.Klevansky and R. H. Lemmer PRD39 (1989) 3478

# Magnetic Catalysis

- Charged particle is trapped in 1+1 dimension by magnetic field

⇒chiral condensate is enhanced




G.S. Bali et al., PRD86 (2012) 071502

B. Ioffe and A. V. Smilga, NPB232 (1984) 109

# Magnetic induced condensate

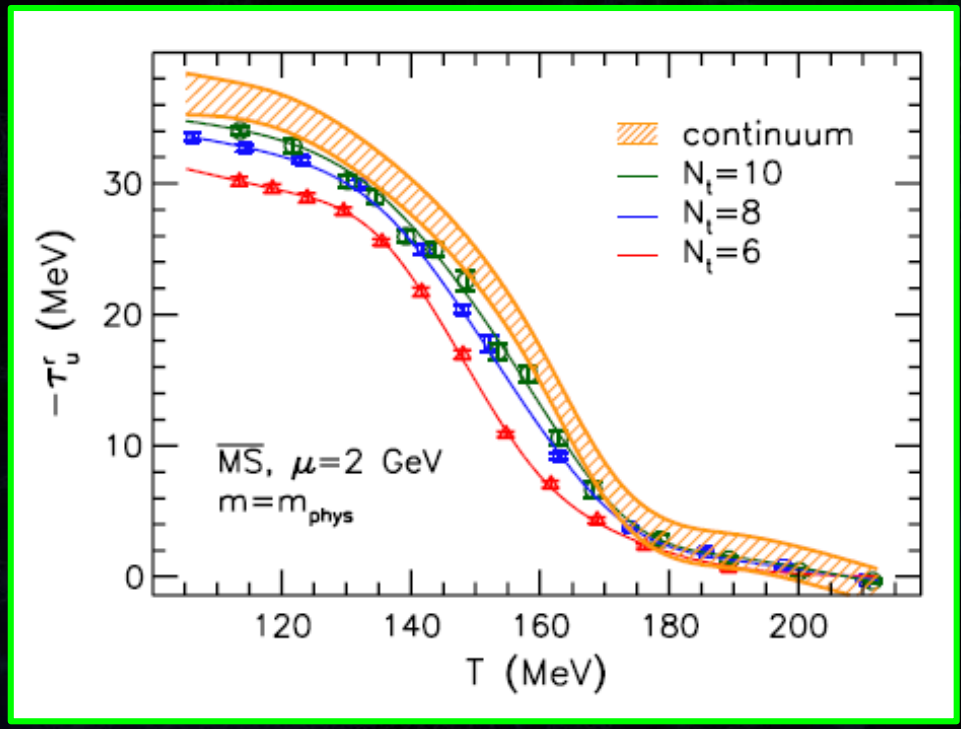
- New condensates are induced by Lorentz violation

$$\langle \bar{q}\sigma_{\mu\nu}q \rangle = \chi \langle \bar{q}q \rangle Q F_{\mu\nu}$$

Magnetic susceptibility

$\chi > 0$ :paramagnetism

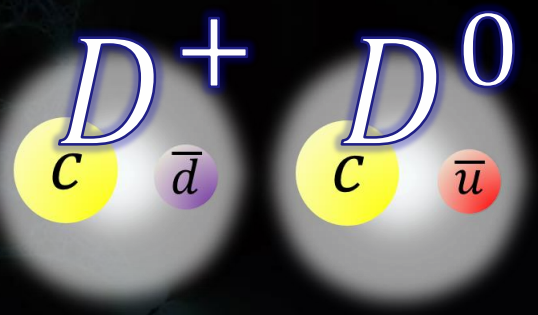
$\chi < 0$ :diamagnetism




G.S. Bali et al., PRD86 (2012) 094512

- QCD vacuum (T=0) is paramagnetism!

# D meson properties in magnetic field




| | Pert. or Non-pert. | Charged or Neutral |
|---|---|---|
| Landau level | Perturbative | Charged only |
| Spin mixing | Perturbative | Charged/Neutral |
| Magnetic catalysis | Non-perturbative | Charged/Neutral |
| Induced condensate | Non-perturbative | Charged/Neutral |

- QCD should contain all the effect
- QCD sum rules can separate perturvative and non-perturbative effect

# 2. QCD sum rule in magnetic field

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

# QCD sum rule

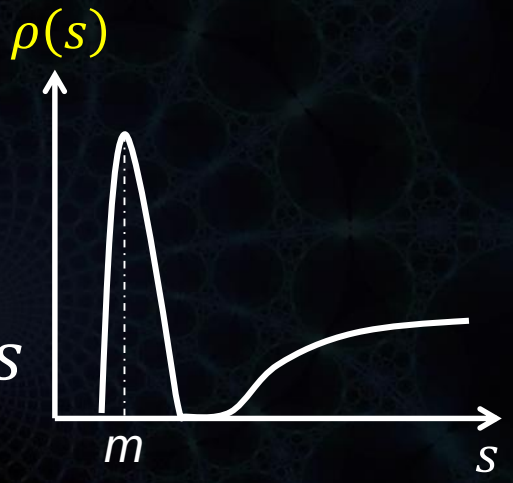
- QCD sum rule

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

$$\Pi_{\mathrm{OPE}}(q^2) = \int_0^\infty \frac{\rho(s)}{s - q^2}\, ds$$

**Transformation**

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




**OPE Input**

**Spectral function Output** → Hadron state

# QCD sum rules in magnetic field

QCD sum rule

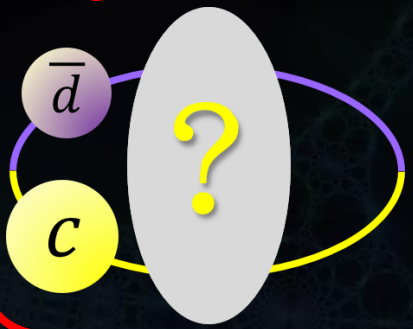
$$\Pi_{\mathrm{OPE}}(M) = \int_0^\infty K(s, M)\, \rho(t)\, ds$$

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

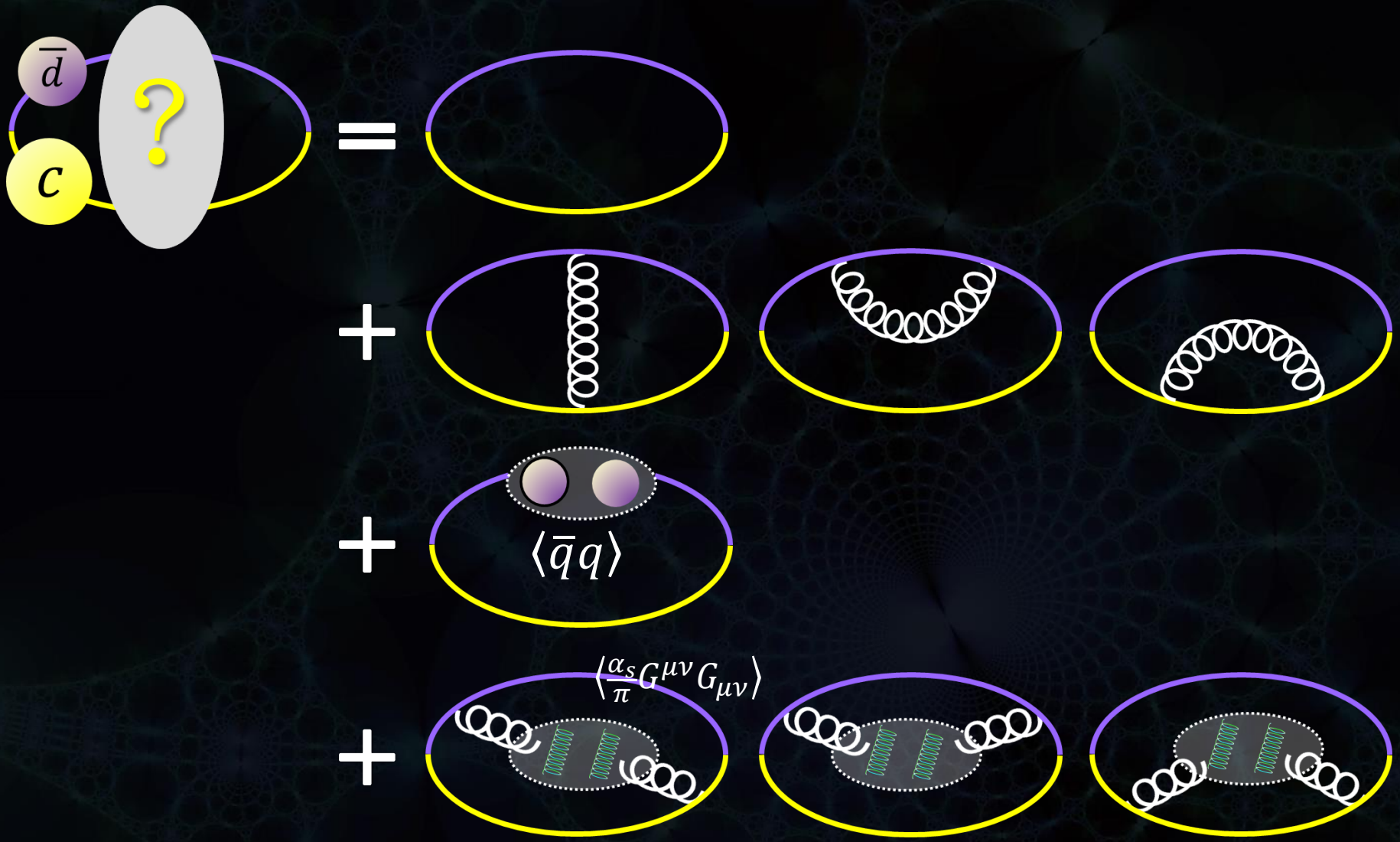
・Ansatz of functional form (pole + continuum)

・New structure foremed by B-field

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

S. Cho, K. Hattori, S. H. Lee, K. Morita, S. Ozaki, [arXiv:1406.4586]

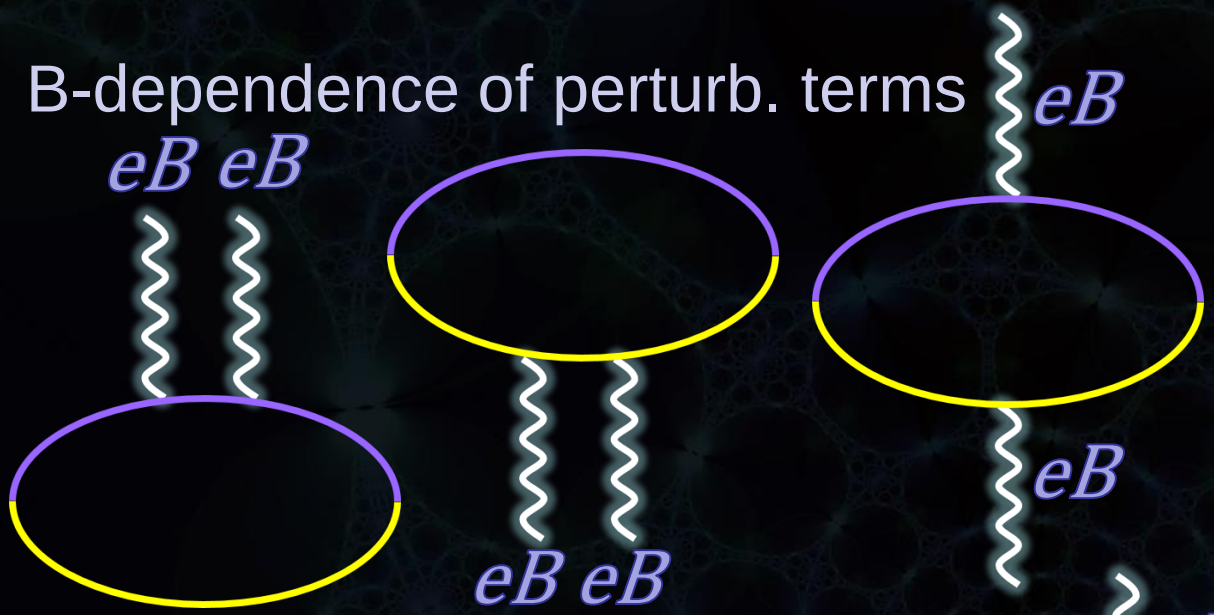
# D meson OPE in vacuum



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

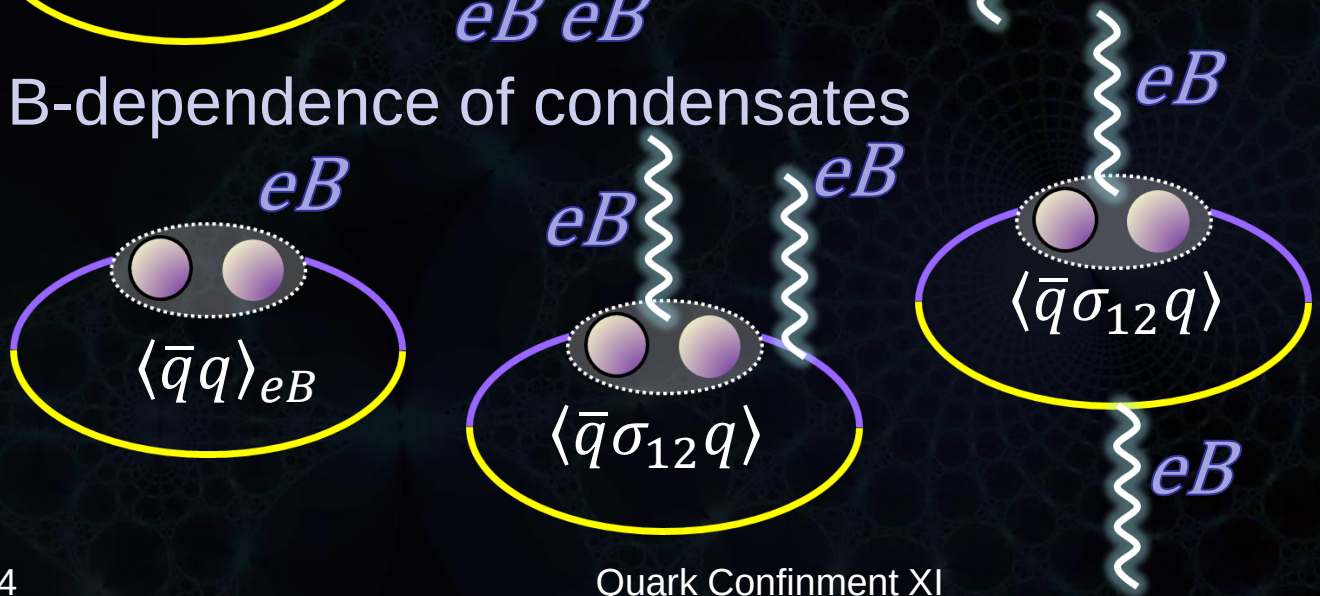
# OPE in magnetic field

- B-dependence of perturb. terms




⇒Landau level + mixing

- B-dependence of condensates

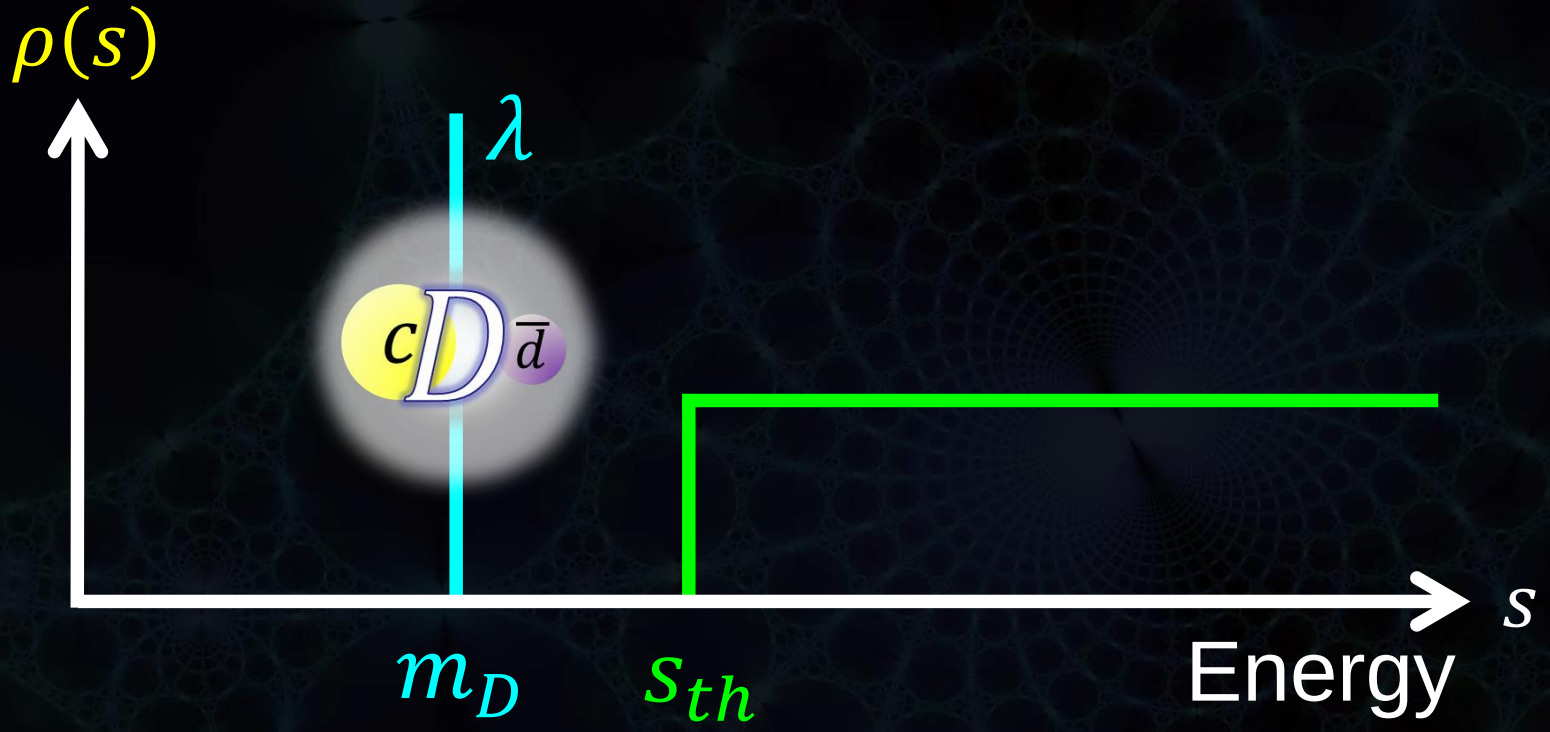


# Phenomenological side (in vacuum)

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

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

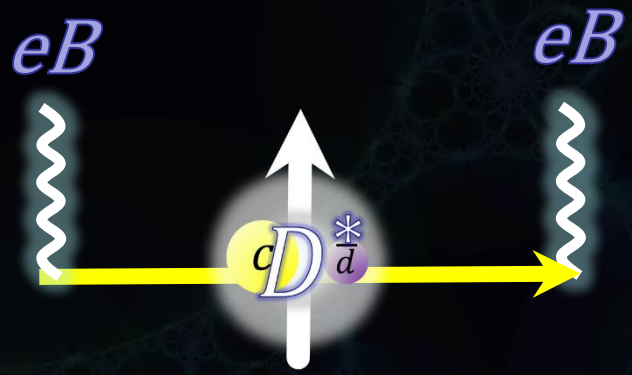
$$\rho(s) = \lambda\delta(s - m_D^2) + \theta(s - s_{th})$$



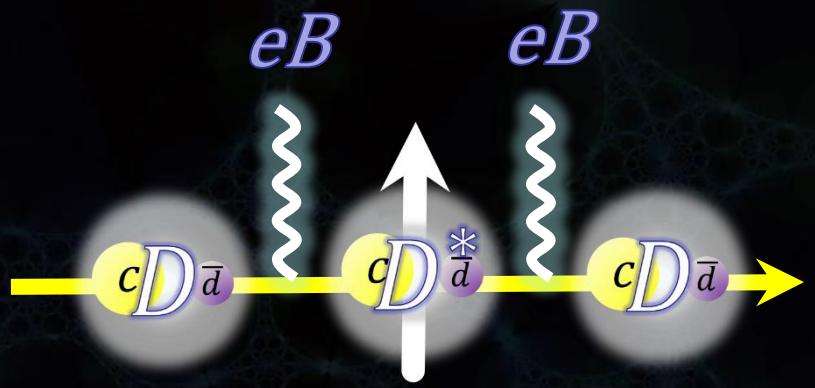
S. Cho, K. Hattori, S. H. Lee, K. Morita, S. Ozaki, [arXiv:1406.4586]

# Magnetic effect of phenomenological side


$$\propto \frac{1}{q^2 - m_D^2}$$ *D* pole




$$\propto \frac{1}{q^2 - m_{D^*}^2}$$ *D** pole




$$\propto \frac{1}{(q^2 - m_D^2)^2 (q^2 - m_{D^*}^2)}$$

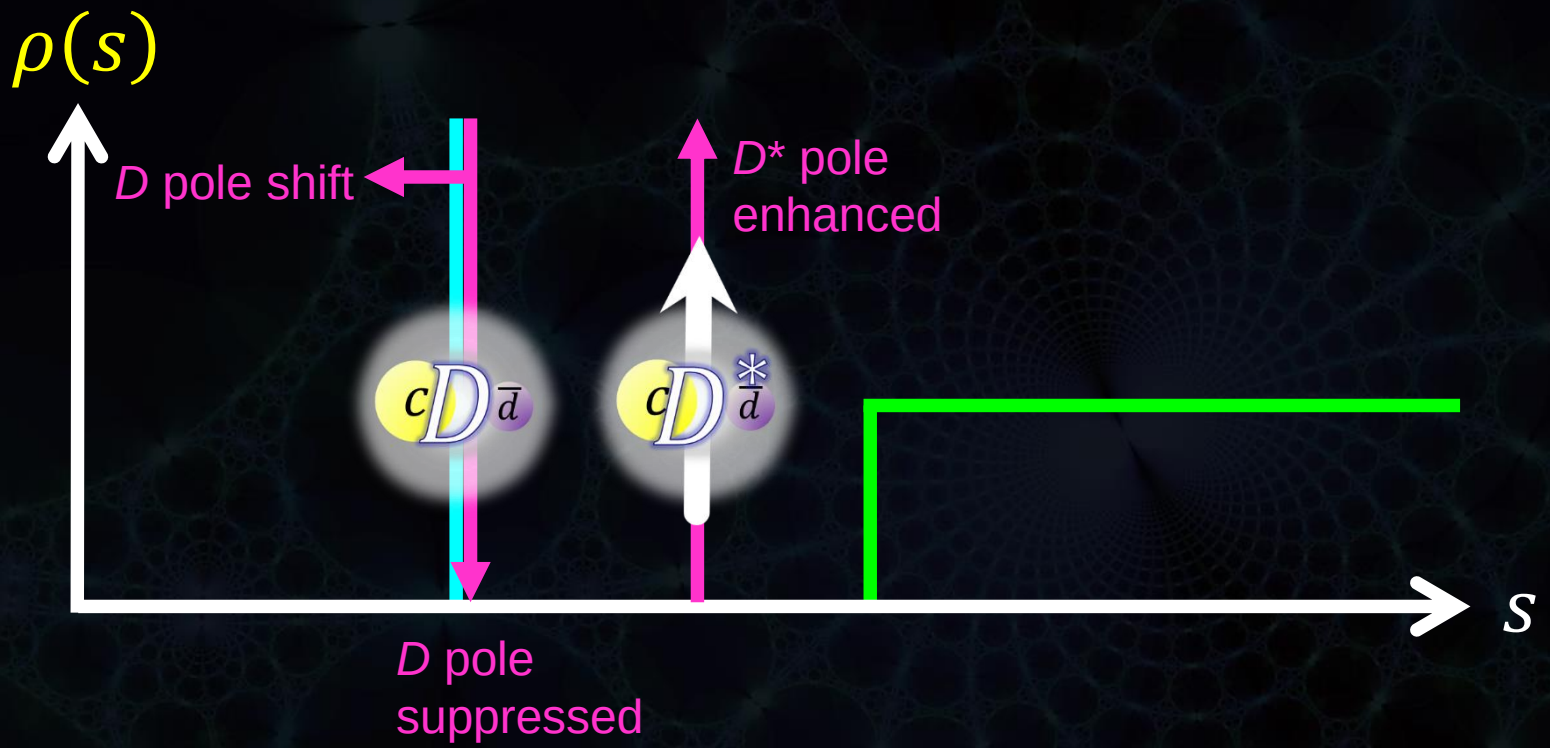
$$\approx \frac{1}{q^2 - m_{D^*}^2} - \frac{1}{q^2 - m_D^2} - \frac{1}{(q^2 - m_D^2)^2}$$

*D** pole enhanced | *D* pole suppressed | *D* pole shift

# Phenomenological side (in B-field)

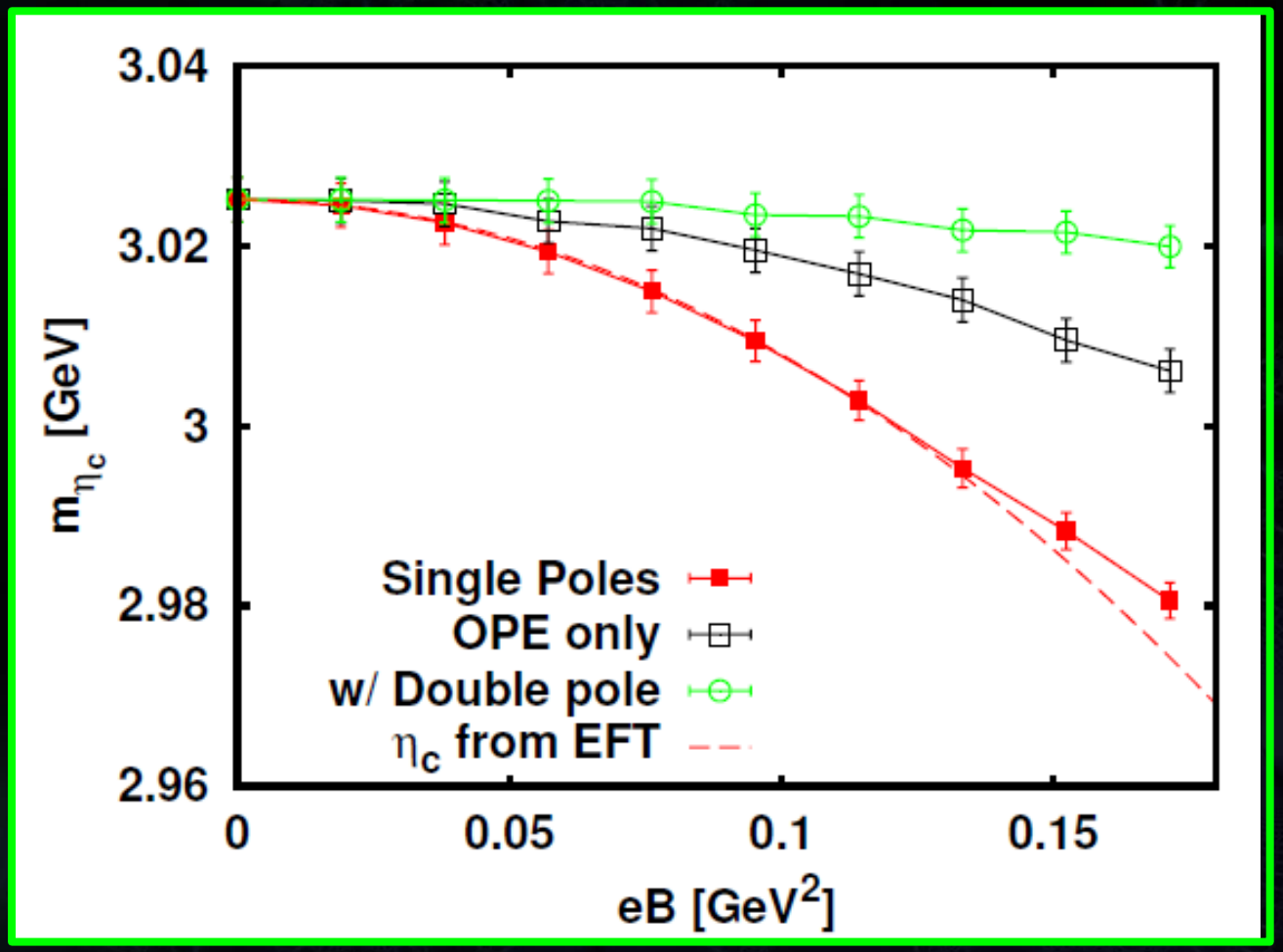
$$\Pi_{\mathrm{OPE}}(M^2) = \int_0^\infty K(s, M^2)\,\rho(s)\,ds$$

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



S. Cho, K. Hattori, S. H. Lee, K. Morita, S. Ozaki, [arXiv:1406.4586]

# Successful example for $\eta_c$ and J/ψ




Subtracted B-effect
⇒no B-effect

1-pole fitting
⇒mixing spectra

Subtracted 2nd peak
⇒$\eta_c$ mass shift

⇒consistent with prediction by effective theory

# 3. Results

*Very Preliminary!!*

# Summary

- We investigated D meson spectral function **in magnetic field** by QCD sum rules
- Landau level and Spin mixing
  ⇒charged（$D^+$）and neutral（$D^0$）mass are changed
- Condensate⇒contribute to meson mass

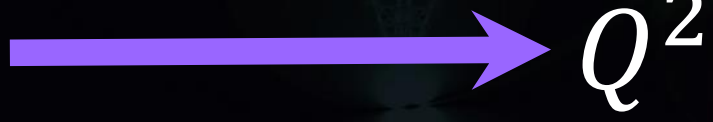
Outlook：To interpret results, To improve sum rule,
D* meson …

# Backup

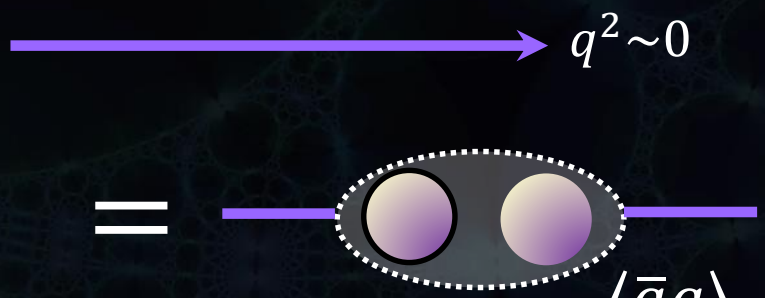
# Concept of OPE (separation of scale)

## Vacuum

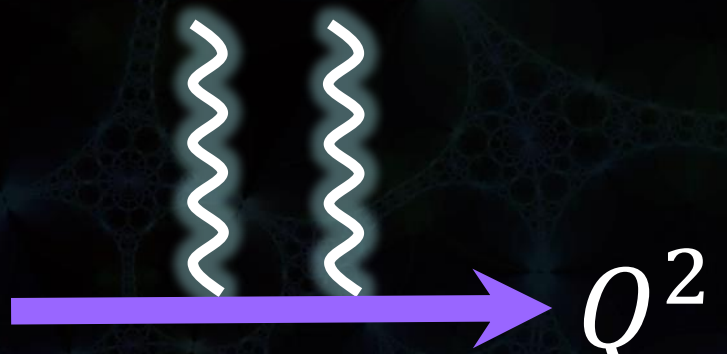
- Higher momentum




- Lower momentum

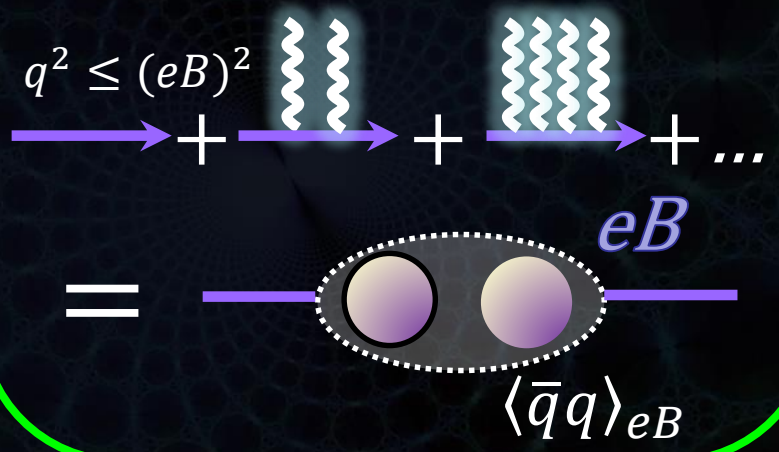


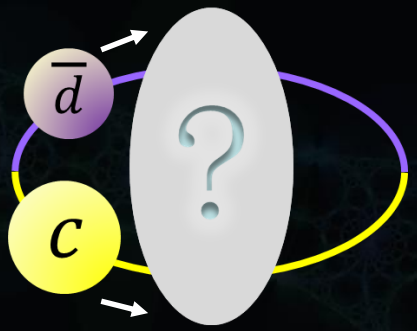

## Magnetic field




Expansion:

$Q^2 \gg (eB)^2$






=

free term (leading term)

+

$\alpha_s$ correction (NLO)

+

chiral condensate

+

mixed condensate (quark-gluon cond.)

+

gluon condensate

+ ...

# 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