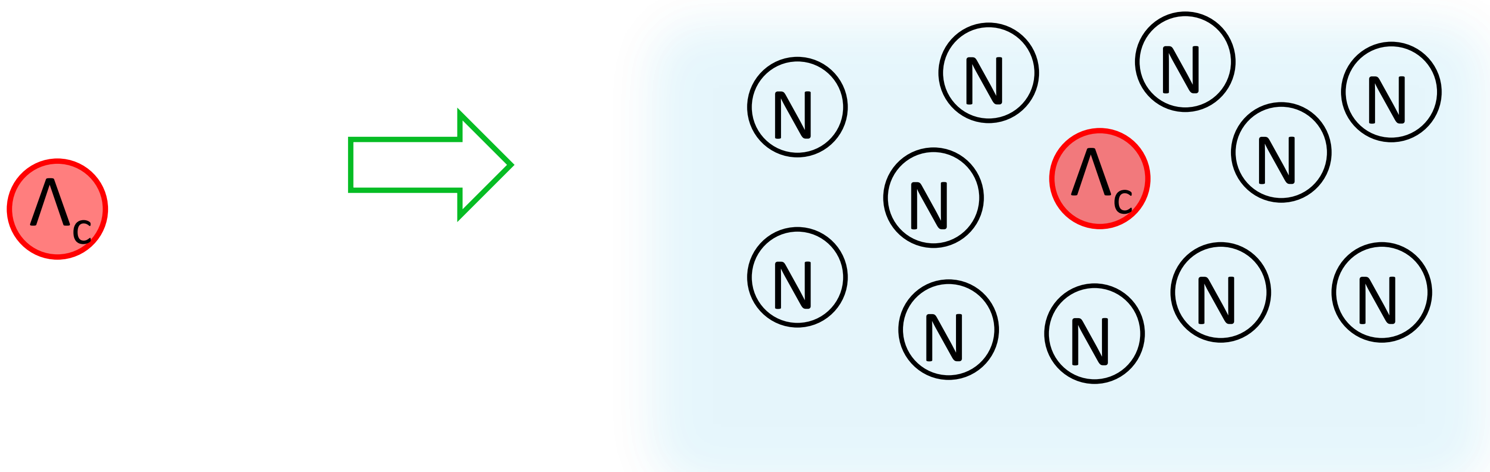
Mass modification of Λ_C baryon in nuclear matter from QCD sum rule

Tokyo Institute of Technology Keisuke Ohtani

Collaborators: Kenji Araki, Makoto Oka

Introduction

Λ_c -nuclei



In vacuum

In nucleus

- Existence of Λ_C –nucleus
- The relation between Λ_C mass and the chiral symmetry

We investigate the mass modification of Λ_C baryon in nuclear matter.

Introduction

Previous works (QCD sum rules)

E. V. Shuryak, Nucl. Phys. **B198**, 83 (1982)

E. Bagan et al., Phys. Lett. **B287**, 176 (1992)

:

Z.-G. Wang, Eur. Phys. J. **C71**, 1816 (2011)

K. Azizi, N. Er, and H. Sundu, arXiv:1605.05535 [hep-ph].

In vacuum

In nuclear matter

Introduction

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In vacuum

In nuclear matter

	λ_{Λ_c} [GeV^3]	$\lambda^*_{\Lambda_c}$ [GeV^3]	m_{Λ_c} [GeV]	$m^*_{\Lambda_c}$ [GeV]	$\Sigma^\nu_{\Lambda_c}$ [MeV]	$\Sigma^S_{\Lambda_c}$ [MeV]
K. Azizi et al.,	0.044 ± 0.012	0.023 ± 0.007	2.235 ± 0.244	1.434 ± 0.203	327 ± 98	-801
Z. G. Wang et al.,	0.022 ± 0.002	0.021 ± 0.001	$2.284^{+0.049}_{-0.078}$	$2.335^{+0.045}_{-0.072}$	34 ± 1	51

There are large discrepancies.

Results in Vacuum

Results in nuclear matter

More precise analyses are needed.

Our analyses

- α_s corrections (NLO) S. Groote, et al., Eur. Phys. J. C58, 355 (2008)
- Dimension 8 condensate
- Parity projection

QCD sum rules

Correlation function: $\Pi(q) = i\int e^{iqx}\langle 0|T[J_{\Lambda_c}(x)\overline{J}_{\Lambda_c}(0)]|0\rangle d^4x$

Parity projected
QCD sum rule

$$J_{\Lambda_Q} = \epsilon^{abc}(u^{Ta}C\gamma_5 d^b)Q^c$$

Gaussian sum rule: $\underline{G_{OPE}(\tau)} = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}}\exp\left(-\frac{(q_0^2-m_c^2)^2}{4\tau}\right)\underline{\rho(q_0)}dq_0$

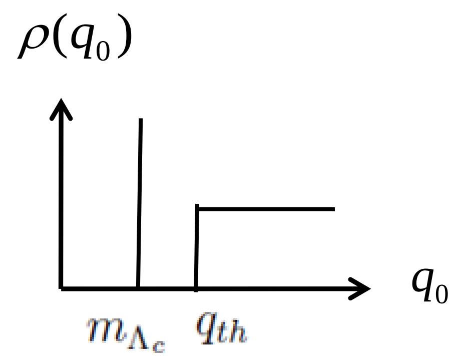
Calculated by operator product expansion(OPE)

Non-perturbative contributions are expressed by condensates.

$$\langle\overline{q}q\rangle \quad \langle\frac{\alpha_s}{\pi}G^2\rangle \quad \langle\overline{q}q\overline{q}q\rangle \quad \cdots$$

(In vacuum)

Hadronic spectral function



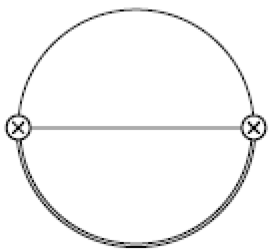
$$\rho(q_0) = |\lambda|^2\delta(q_0 - m_{\Lambda_c}) + \mathrm{Continuum}(\propto\theta(q_0 - q_{th}))$$

Λ_c QCD sum rules in vacuum

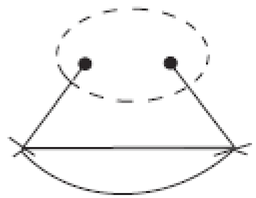
$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Operator product expansion (OPE)

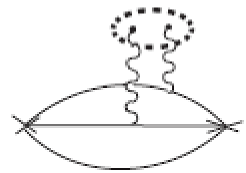
Non-perturbative contributions are expressed by condensates.



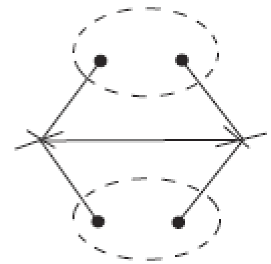
Perturbative (LO)



$\langle \overline{q} q \rangle$



$\langle \frac{\alpha_s}{\pi} G^2 \rangle$



$\langle \overline{q} q \overline{q} q \rangle$

Λ_c QCD sum rules in vacuum

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

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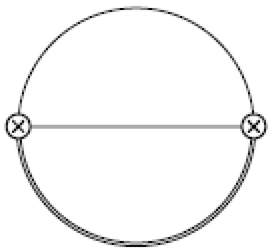

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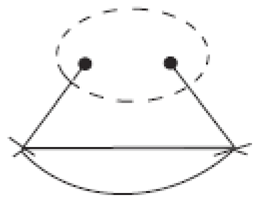
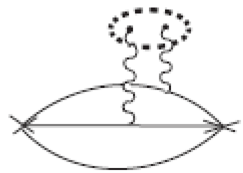
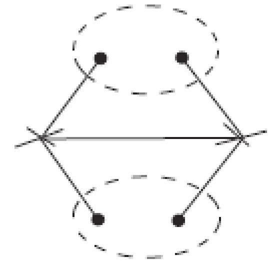


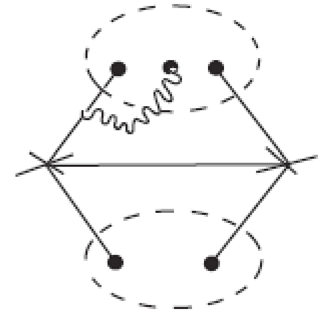
$\langle \overline{q} q \rangle$



$\langle \frac{\alpha_s}{\pi} G^2 \rangle$

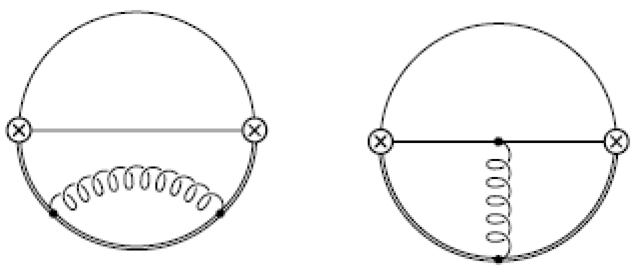


$\langle \overline{q} q \overline{q} q \rangle$



$\langle \overline{q} q \rangle \langle \overline{q} g \sigma \cdot G q \rangle$

Dimension 8 condensate



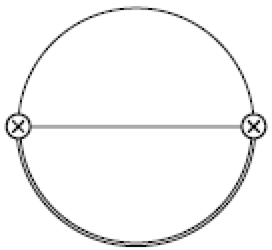
.. : NLO contributions in perturbative term

We carry out the analyses including the contributions of the dimension 8 condensate and NLO.

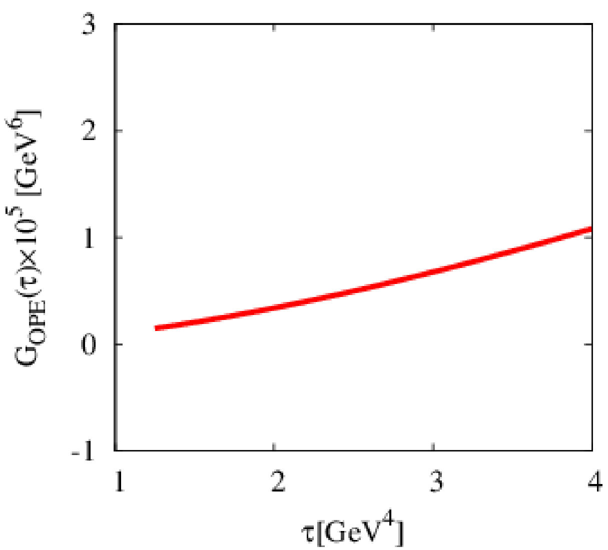
Λ_c QCD sum rules in vacuum

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Operator product expansion (OPE) Non-perturbative contributions are expressed by condensates.



Perturbative (LO)



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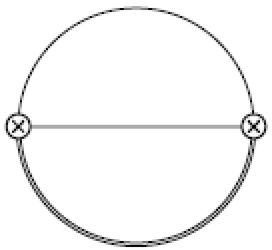

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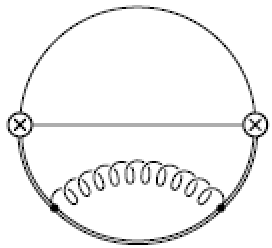
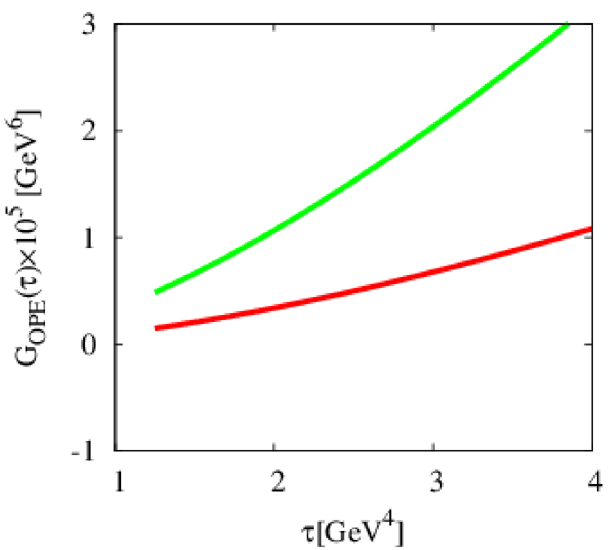


NLO



NLO contributions to its leading order are more than 100%.

Λ_c QCD sum rules in vacuum

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

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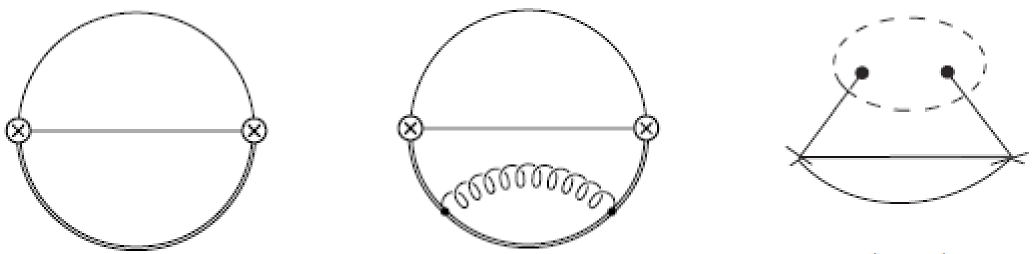

Perturbative (LO) NLO $\langle\overline{q}q\rangle$

Correlation function: $\Pi(q) = i \int e^{iqx} \langle 0 | T[J_{\Lambda_c}(x) \overline{J}_{\Lambda_c}(0)] | 0 \rangle d^4x$

$$J_{\Lambda_Q} = \epsilon^{abc}(u^{Ta} C\gamma_5 d^b) Q^c = \epsilon^{abc}(-u_L^T C\gamma_5 d_L + u_R^T C\gamma_5 d_R) Q^c$$

The property of J_{Λ_Q}

The right handed spinor of u quark is paired with left handed one. $\langle\overline{u}u\rangle$

The right handed spinor of d quark is also paired with left handed one. m_d

The contributions appear as $m_q\langle\overline{q}q\rangle$ and are numerically small.

Λ_c QCD sum rules in vacuum

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

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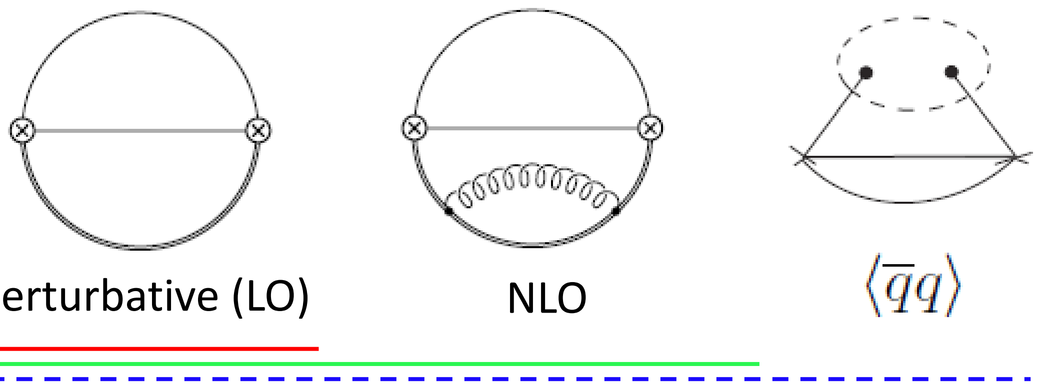
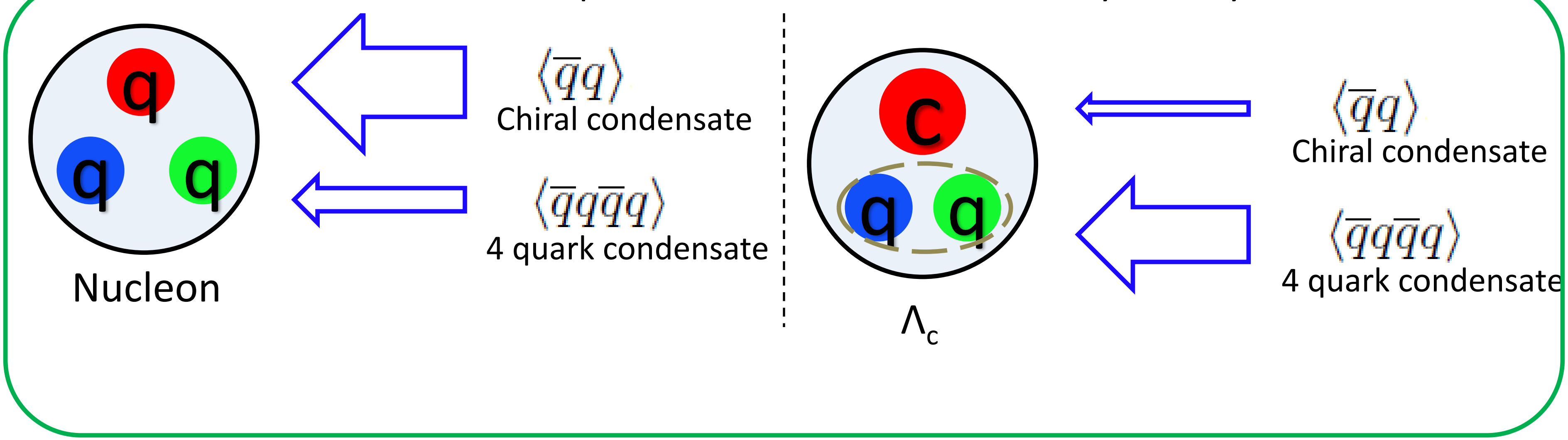


The effect from the partial restoration of the chiral symmetry



Λ_c QCD sum rules in vacuum

$$G_{OPE}(\tau) = \int_0^{\infty} \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

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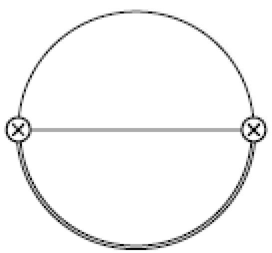

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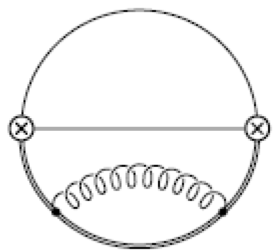
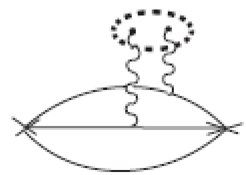
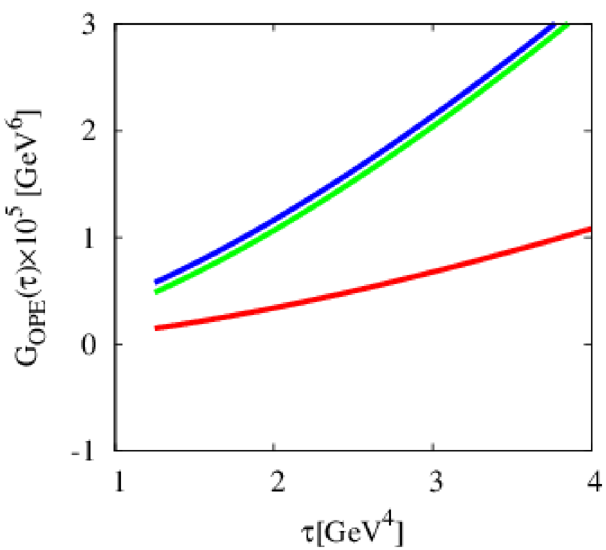


NLO



$\langle \frac{\alpha_s}{\pi} G^2 \rangle$



NLO contributions to its leading order are more than 100%.

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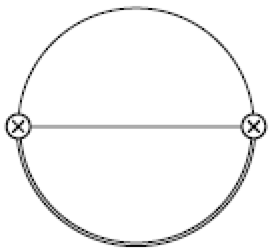

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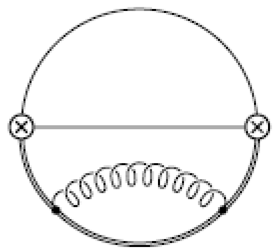
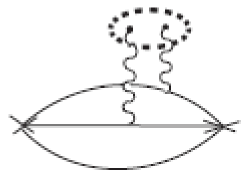
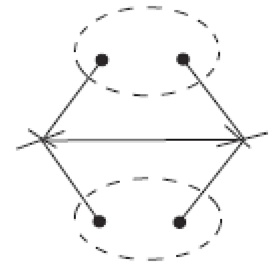


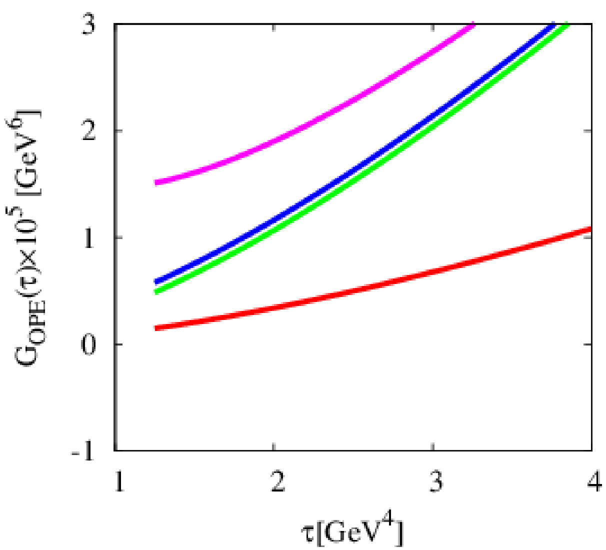
NLO



$\langle \frac{\alpha_s}{\pi} G^2 \rangle$



$\langle \bar{q}q\bar{q}q \rangle$



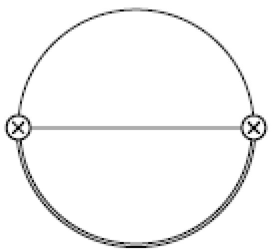
NLO contributions to its leading order are more than 100%.

The contribution of four quark condensate is large.

Λ_c QCD sum rules in vacuum

$$G_{OPE}(\tau) = \int_0^{\infty} \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Operator product expansion (OPE)   Non-perturbative contributions are expressed by condensates.



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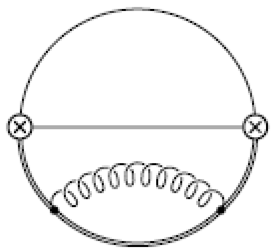
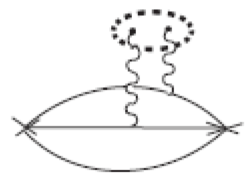
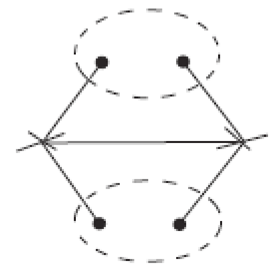


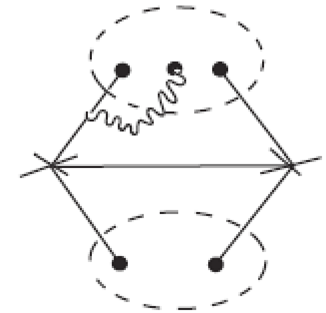
NLO



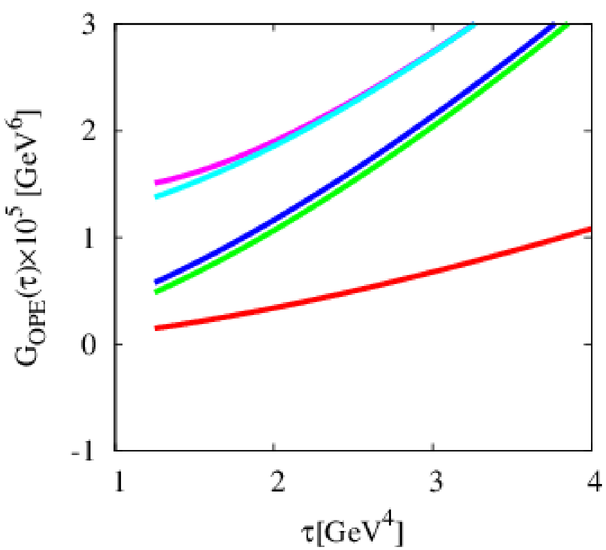
$\langle \frac{\alpha_s}{\pi} G^2 \rangle$



$\langle \bar{q}q\bar{q}q \rangle$



$\langle \bar{q}q \rangle \langle \bar{q}g\sigma \cdot Gq \rangle$



NLO contributions to its leading order are more than 100%.

The contribution of four quark condensate is large.

The contribution of the dimension 8 condensate is small.

Λ_c QCD sum rules in nuclear matter

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Application to the analyses in nuclear matter

Modification: $\langle 0|\mathcal{O}_i|0\rangle \Rightarrow \langle \Psi_0|\mathcal{O}_i|\Psi_0\rangle = \langle \mathcal{O}_i\rangle_m$

New condensates: $\langle 0|\mathcal{O}_i|0\rangle = 0 \Rightarrow \langle \mathcal{O}_i\rangle_m \neq 0$

$$\langle \overline{q}q\rangle_m = \langle \overline{q}q\rangle_0 + \rho\frac{\sigma_N}{2m_q} \qquad \langle\frac{\alpha_s}{\pi}G^2\rangle_m = \langle\frac{\alpha_s}{\pi}G^2\rangle_0 - \rho(0.65\mathrm{GeV}^2)$$

$$\langle \overline{q}g\sigma\cdot Gq\rangle_m = (0.8\mathrm{GeV}^2)\langle\overline{q}q\rangle_m$$

$$\langle q^\dagger q\rangle_m = \rho\frac{3}{2} \qquad \langle q^\dagger iD_0 q\rangle_m = \rho\frac{3}{8}M_N A_2^q \qquad \langle q^\dagger g\sigma\cdot Gq\rangle_m = -\rho(0.33\mathrm{GeV}^2)$$

$$\langle q^\dagger iD_0 iD_0 q\rangle_m + \frac{1}{12}\langle q^\dagger g\sigma\cdot Gq\rangle_m = \rho\frac{1}{4}M_N^2 A_3^q$$

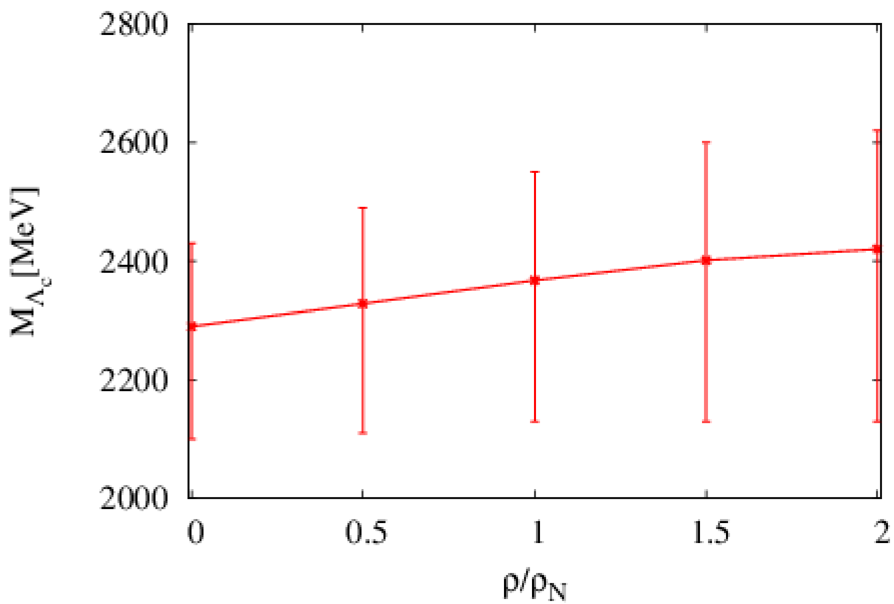
(Linear density approximation)

Results

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

$$\rho(q_0) = |\lambda|^2 \delta(q_0 - m_{\Lambda_c}) + \mathrm{Continuum}(\propto \theta(q_0 - q_{th}))$$

Density dependence of $\langle \overline{q}q \rangle_m^2$: $\langle \overline{q}q \rangle_m^2 = \left(\langle \overline{q}q \rangle_0 + \rho \frac{\sigma_N}{2m_q} \right)^2$



At ρ=1.0ρ$_{N}$, the sfift $\Delta M_{\Lambda_c} \approx 70\mathrm{MeV}$

The density dependence of M_{Λ_c}

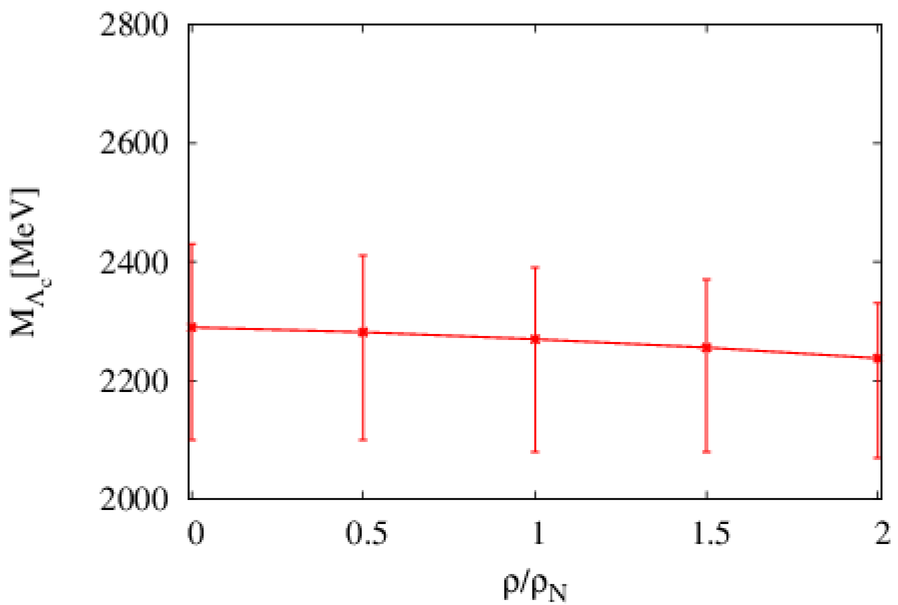
Results

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

$$\rho(q_0) = |\lambda|^2 \delta(q_0 - m_{\Lambda_c}) + \text{Continuum}(\propto \theta(q_0 - q_{th}))$$

Density dependence of $\langle \overline{q}q \rangle_m^2$: $\langle \overline{q}q \rangle_m^2 = \langle \overline{q}q \rangle_0^2$

(Density independent)



The density dependence of M_{Λ_c}

At ρ=1.0ρ$_{N,}$ the sfift $\Delta M_{\Lambda_c} \approx -20\text{MeV}$

Summary

- We analyze the Λ_c spectral function in vacuum and nuclear matter by using QCD sum rules.

- We investigate the density dependence of the mass modification.

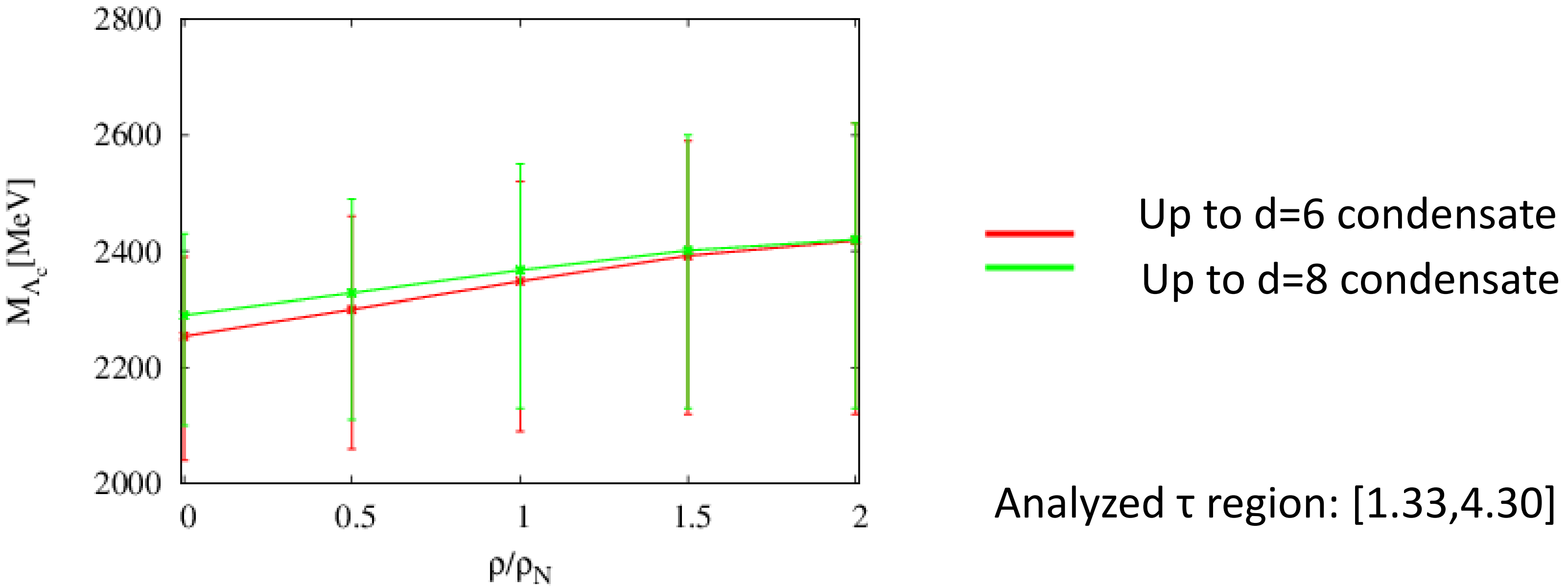
- The mass modification strongly depends on the density dependence of the $\langle \overline{q}q \rangle_m^2$.

Future plan

- We will study the effective mass and vector self-energy.

Backup slides

The effect by d=8 condensate



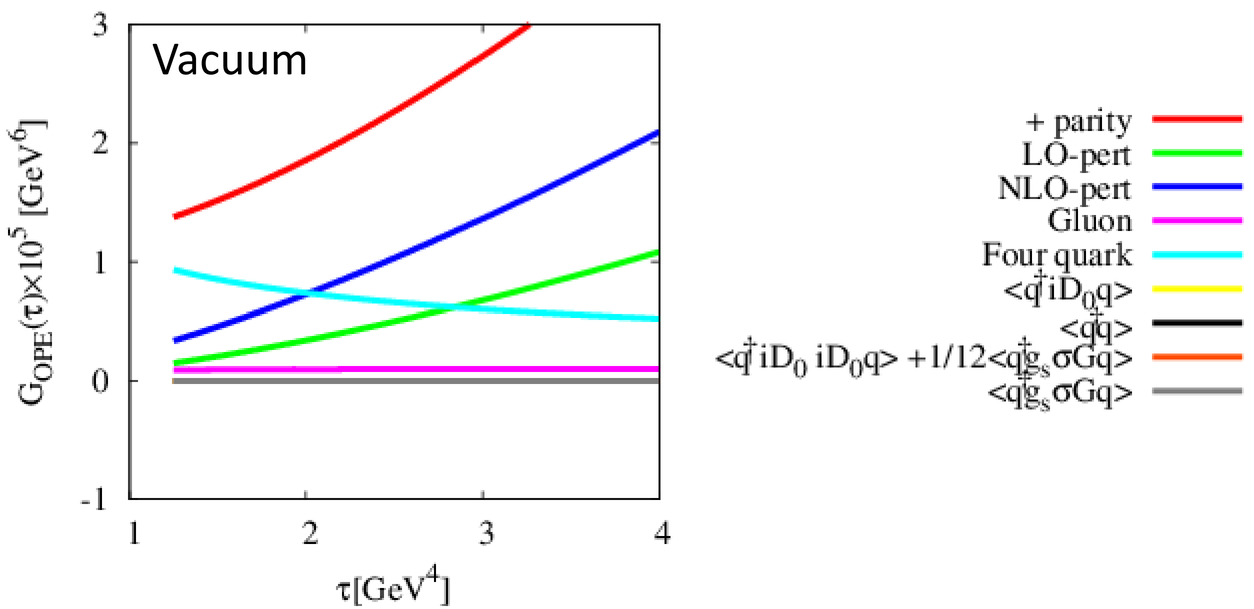
Analyzed τ region: [1.33,4.30]

The d=8 condensate slightly increases the M_{Λ_c}

Backup slides

$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Density dependence of the $G_{OPE}(\tau)$



Backup slides

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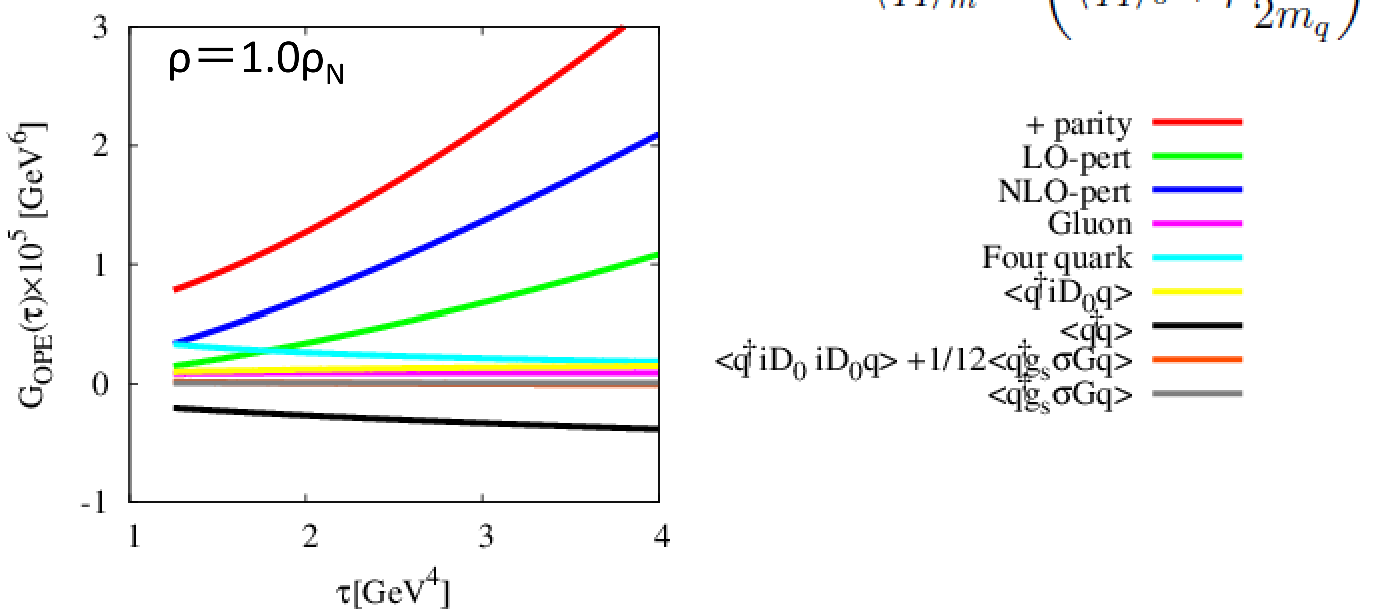
Density dependence of the $G_{OPE}(\tau)$

$$\langle \overline{q}q \rangle_m^2 = \left(\langle \overline{q}q \rangle_0 + \rho \frac{\sigma_N}{2m_q} \right)^2$$



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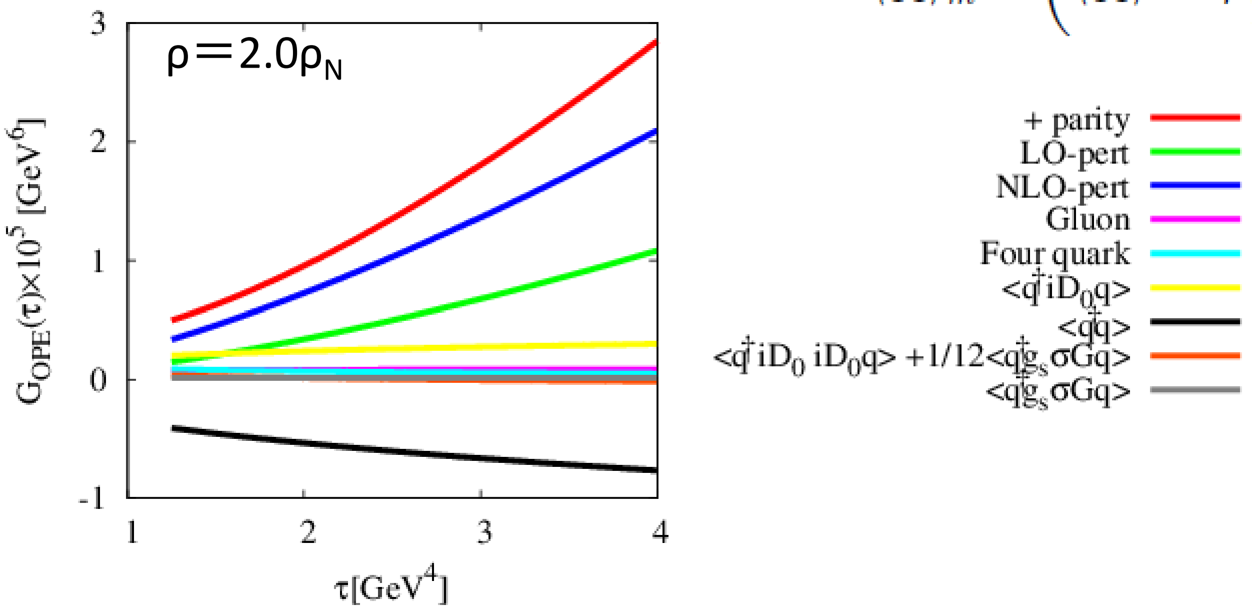
Density dependence of the $G_{OPE}(\tau)$

$$\langle \overline{q}q \rangle_m^2 = \left(\langle \overline{q}q \rangle_0 + \rho \frac{\sigma_N}{2m_q} \right)^2$$



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$$\Pi_{old}(q) = i\int \theta(x_0)\langle T\{j(x)\bar{j}(0)\}\rangle e^{iqx}dx = m\Pi^m_{old}(q_0,|\vec{q}|) + \not{q}\Pi^q_{old}(q_0,|\vec{q}|) + \not{u}\Pi^u_{old}(q_0,|\vec{q}|).$$

$$\rho^i_{old}(q_0,|\vec{q}|) \ \equiv \ \tfrac{1}{\pi}Im[\Pi^i_{old}(q^2)] \quad (i \ = \ m,q,u)$$

$$\rho^+_{old\ OPE} = q_0\rho^q_{old} + m_Q\rho^m_{old} + u_0\rho^u_{old}$$

$$\int_{-\infty}^{\infty}\rho^+_{old\ OPE}(q_0)W(q_0)dq_0 = \int_0^{\infty}\rho^+_{hadron}(q_0)W(q_0)dq_0$$

$$W(q_0) = \frac{1}{\sqrt{4\pi\tau}}\exp\left(-\frac{(q_0^2-m_c^2)^2}{4\tau}\right)$$

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Negative parity $G_{OPE}(\tau)$

$$\rho^{+}_{old\ OPE} = q_0 \rho^{q}_{old} + m_Q \rho^{m}_{old} + u_0 \rho^{u}_{old}$$

$$\rho^{-}_{old\ OPE} = q_0 \rho^{q}_{old} - m_Q \rho^{m}_{old} + u_0 \rho^{u}_{old}$$

$$G_{OPE}(\tau) = \int_{-\infty}^{\infty} \rho_{old\ OPE}(q_0) W(q_0) dq_0$$