Λ_c baryon in nuclear matter from QCD sum rule

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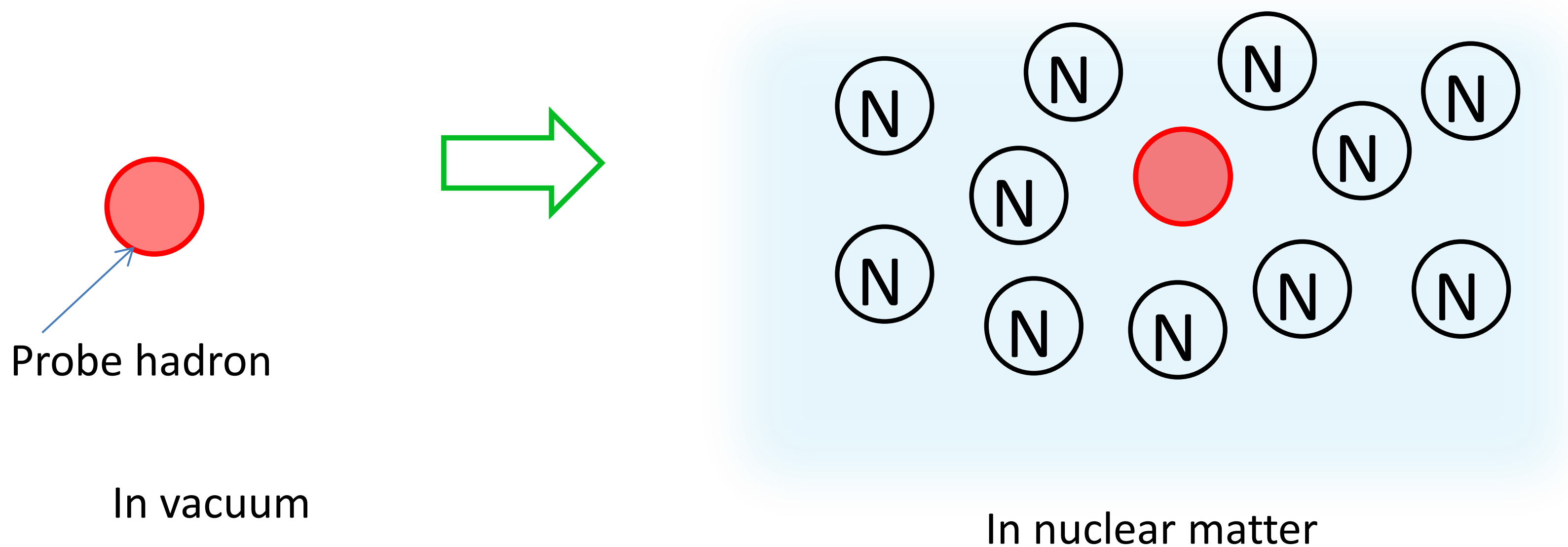
Outline

- Introduction
- Λ_c QCD sum rules
- OPE of Λ_c correlation function
- Results
- Summary

Introduction

Hadrons in nuclear matter



- Interaction between probe hadron and nucleon
- The relation between hadron mass and the spontaneous breaking of chiral symmetry

Introduction

The relation between hadron mass and the spontaneous breaking of chiral symmetry

ρ meson

Relation between mass shift and partial restoration of chiral symmetry

ϕ meson

Relation between mass shift and strangeness content of the nucleon

Nucleon

Discussion about mass differences between chiral partners

Λ baryon

Relation between mass shift and partial restoration of chiral symmetry including strange sector

:

In this study, we investigate Λ_c baryon in nuclear matter.

Introduction

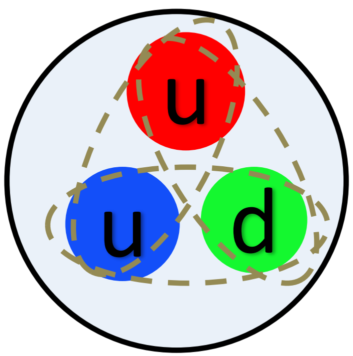
New points in Λ_c baryon

Light baryons

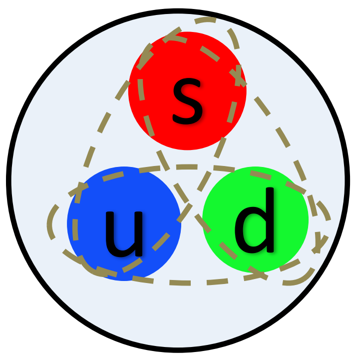
Approximated flavor symmetry

$$m_u \approx m_d < m_s$$

N



Λ



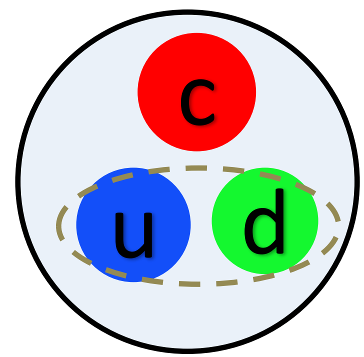
Add the charm quark

Λ_c baryon

Flavor symmetry is largely broken.

$$m_u \approx m_d << m_c$$

Heavy quark spin symmetry



Introduction

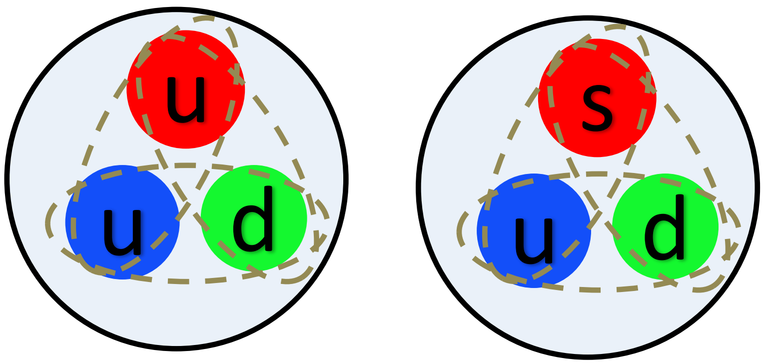
New points in Λ_c baryon

Light baryons

Approximated flavor symmetry

$$m_u \approx m_d < m_s$$

N Λ



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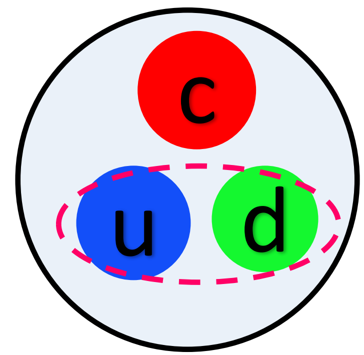
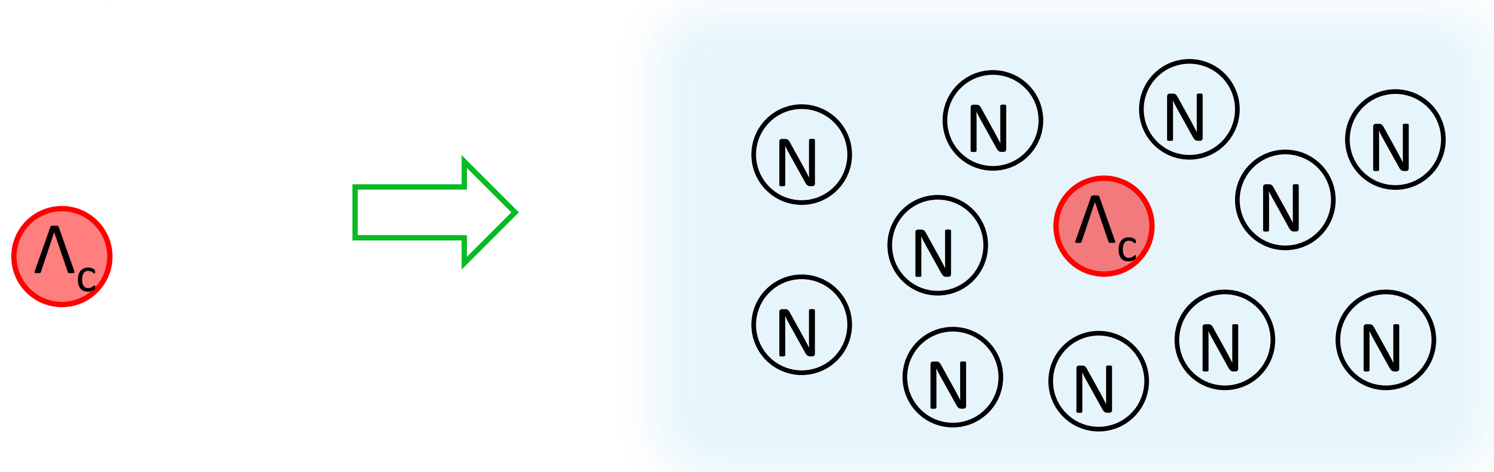


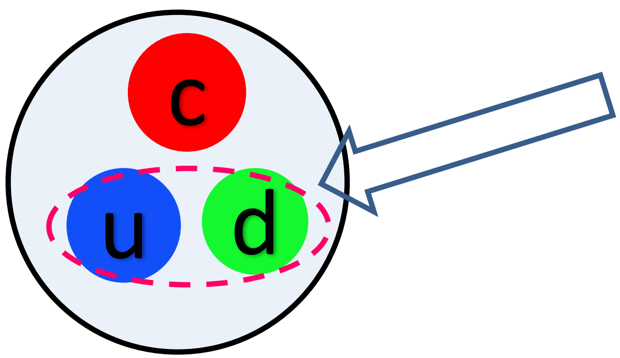
The diquark properties can be investigated.

Introduction



In vacuum

In nuclear matter

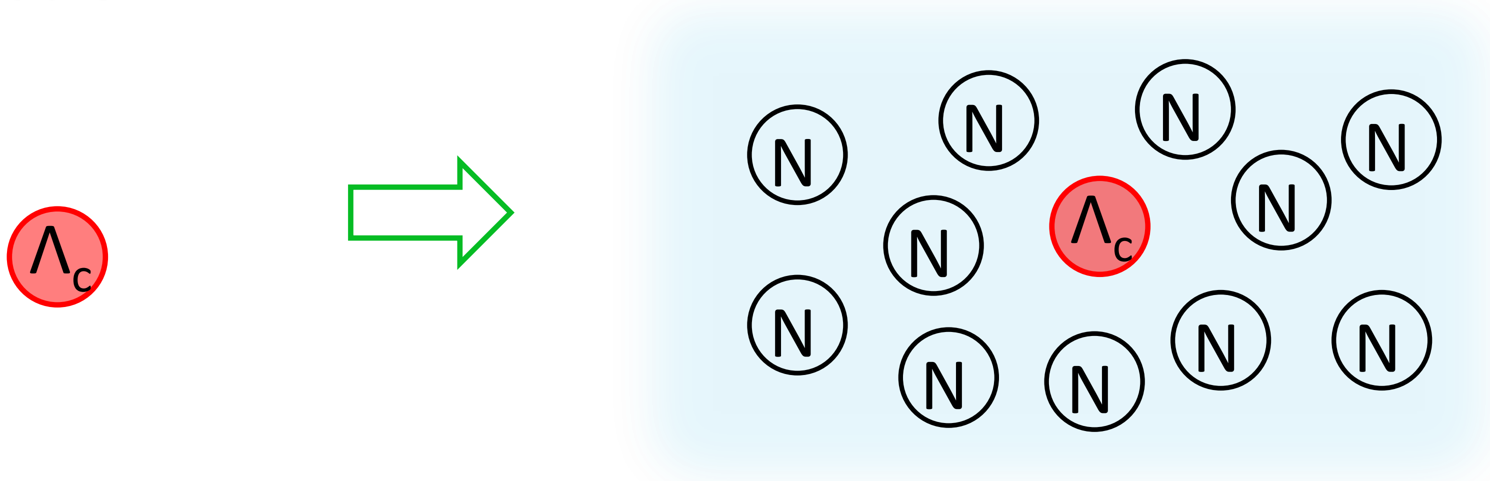


“Partial restoration of chiral symmetry”

Λ_c

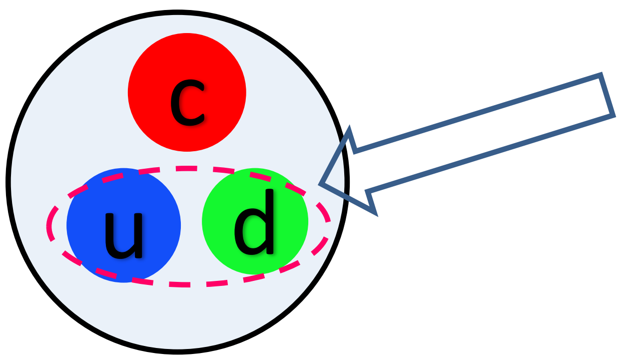
We investigate the mass shift of Λ_c in nuclear matter and discuss the relation between the diquark and partial restoration of chiral symmetry.

Introduction



In vacuum

In nuclear matter



Λ_c

“Partial restoration of chiral symmetry”

Analysis method: QCD sum rule

Introduction

Previous works by QCD sum rule

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 (Shuryak; Bagan et al.; …)

In nuclear matter (Wang; Azizi et al.)

	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	0.022 ± 0.002	0.021 ± 0.001	$2.284^{+0.049}_{-0.078}$	$2.335^{+0.045}_{-0.072}$	34 ± 1	51

Results in Vacuum

Results in nuclear matter

- There are large discrepancies in the results.
- The equations of OPE do not consist with each other.

Our analyses

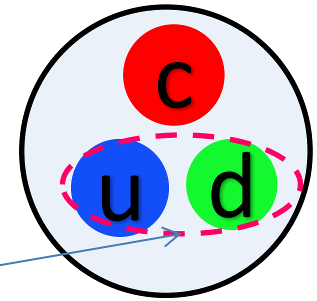
- Recalculation of OPE
- α_s corrections (NLO) S. Groote, et al., Eur. Phys. J. C58, 355 (2008)
- Up to dimension 8 condensate (higher order contribution)
- Parity projection

Λ_c QCD sum rules

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

Λ_c interpolating operator: $J_{\Lambda_c} = \underline{\epsilon^{abc} (u^{Ta} C \gamma_5 d^b)} c^c$

Good diquark
(Scalar diquark)



(Schematic figure)

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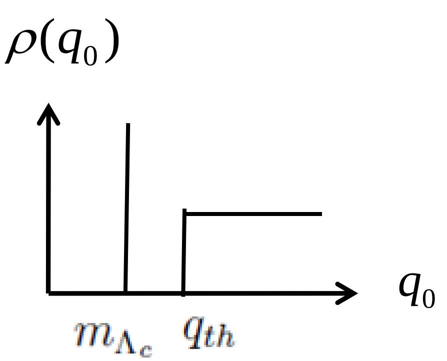
$$J_{\Lambda_c} = \epsilon^{abc}(u^{Ta} C \gamma_5 d^b) c^c$$

Parity projected QCD sum rule

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

Hadronic spectral function



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

Λ_c QCD sum rules

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Λ_c 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 ⇩

$$J_{\Lambda_c} = \epsilon^{abc}(u^{T\,a} C \gamma_5 d^b) c^c$$

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)

Λ_c QCD sum rules

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

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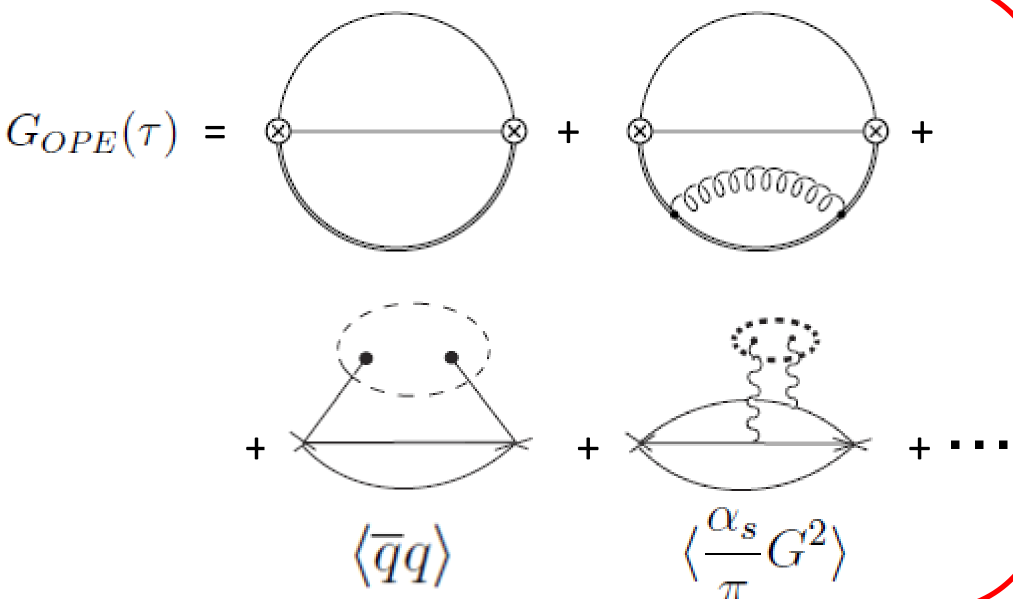

Λ_c QCD sum rules

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

Application to the analyses in nuclear matter

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

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)

Condensates have the density dependence.

⇒ In-medium effects can be expressed by the in-medium modifications of the condensates.

OPE of Λ_c correlation function

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

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

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Non-perturbative effects
In-medium effects

Condensates:

- Non-perturbative contributions are expressed by condensates.
- In-medium effects can be expressed by the in-medium modifications of the condensates.

What kind of condensates does the Λ_c correlation function contains?

Are there contributions from chiral condensate?

How do the in-medium effects appear?

Are the in-medium effects related to only light quarks?

Is the heavy quark treated as spectator?

OPE of Λ_c correlation function

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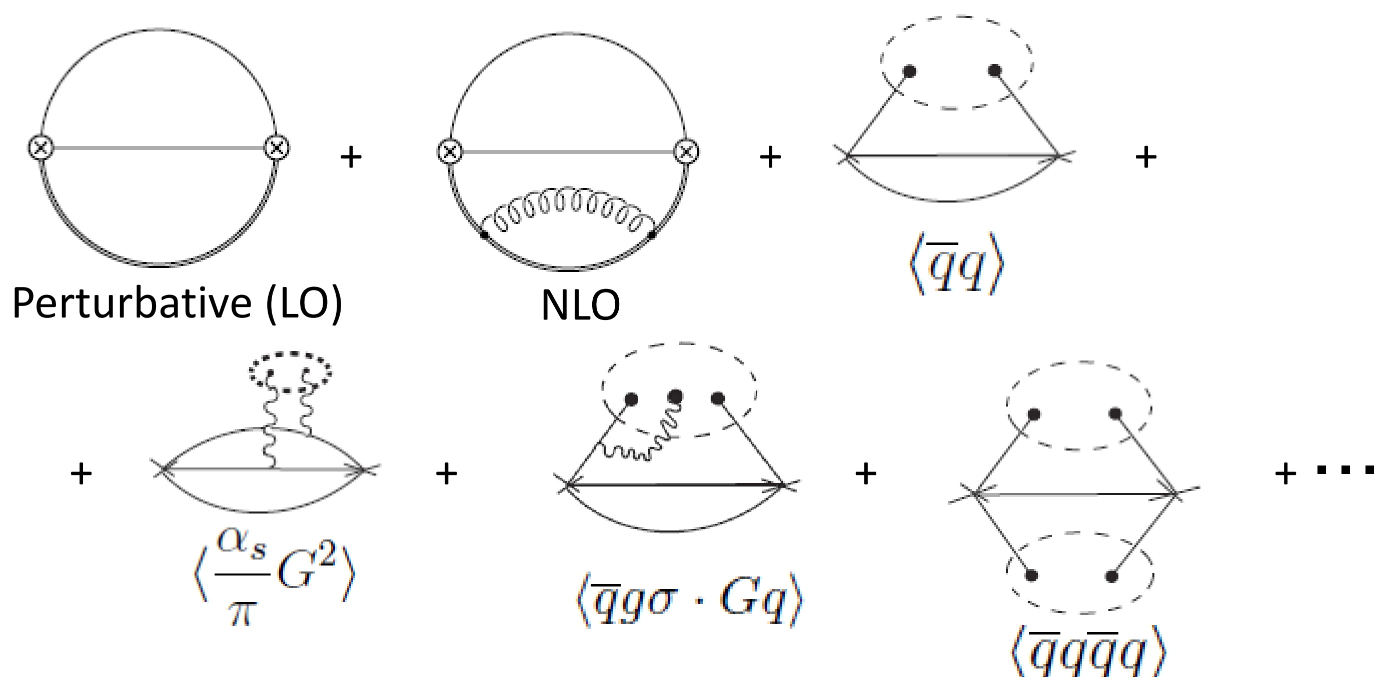
Gaussian sum rule: $G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau} \right) \rho(q_0) dq_0$

Diagrams of Λ_c OPE:

Generally, $G_{OPE}(\tau)$ =

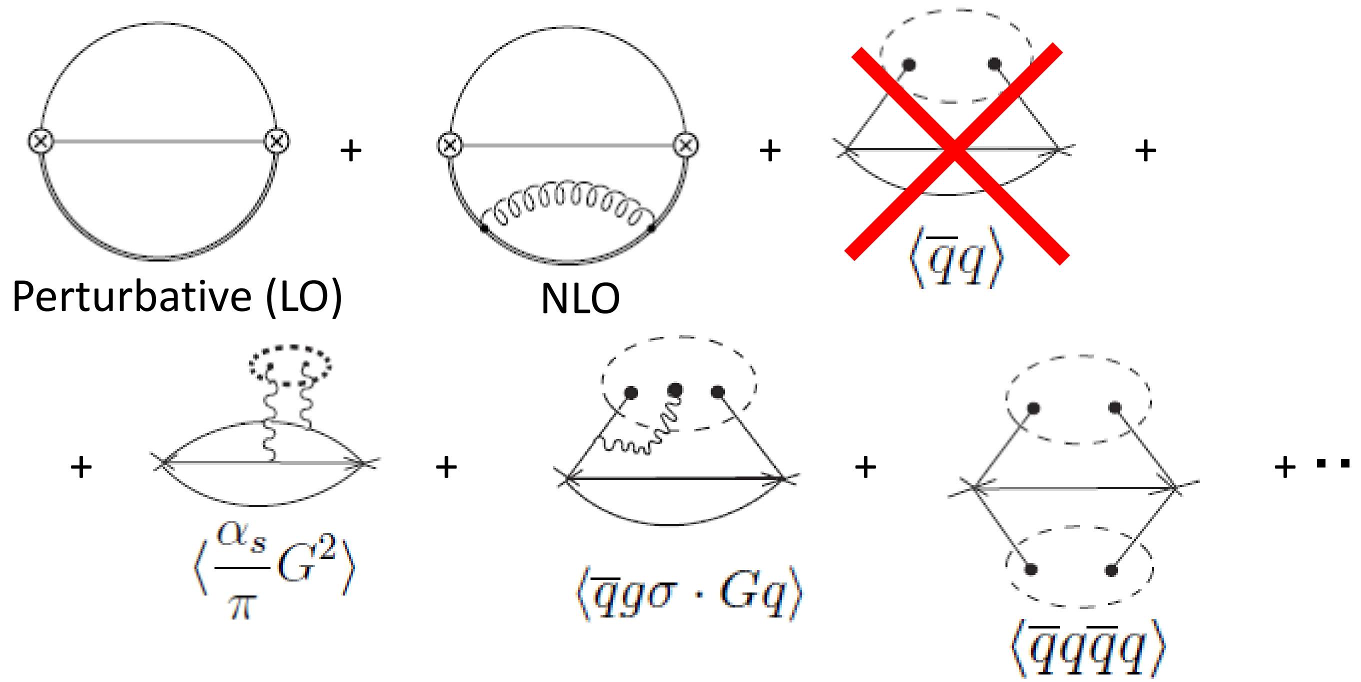


OPE of Λ_c correlation function

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

Diagrams of Λ_c OPE:

$G_{OPE}(\tau)$ =

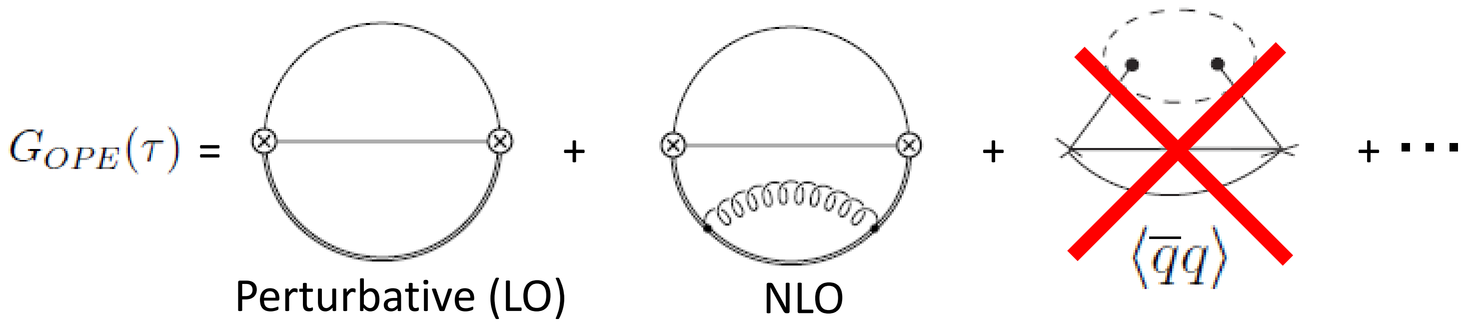


The contributions from chiral condensates are strongly suppressed.

OPE of Λ_c correlation function

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

Diagrams of Λ_c OPE:



Λ_c interpolating operator: $J_{\Lambda_c} = \epsilon^{abc}(u^{Ta} C\gamma_5 d^b)c^c = \epsilon^{abc}(-u_L^T C\gamma_5 d_L + u_R^T C\gamma_5 d_R)c^c$

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.

OPE of Λ_c correlation function

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

Diagrams of Λ_c OPE:

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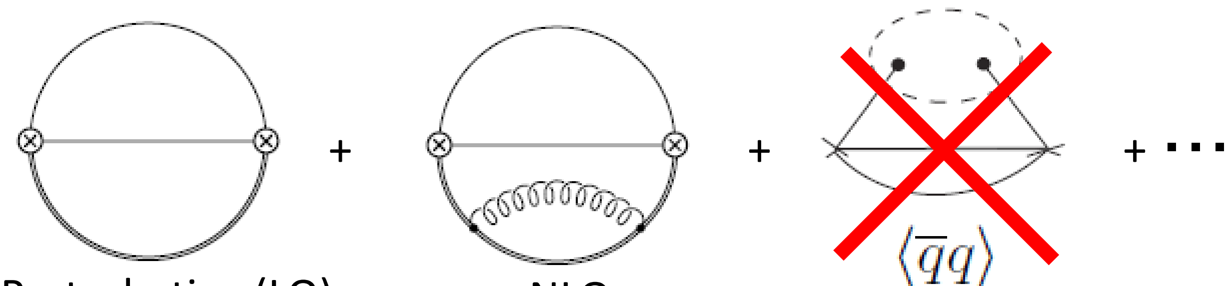


Perturbative (LO) NLO

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

More explicitly, the contributions of $\langle \overline{q} q \rangle$ are expressed as the following form.

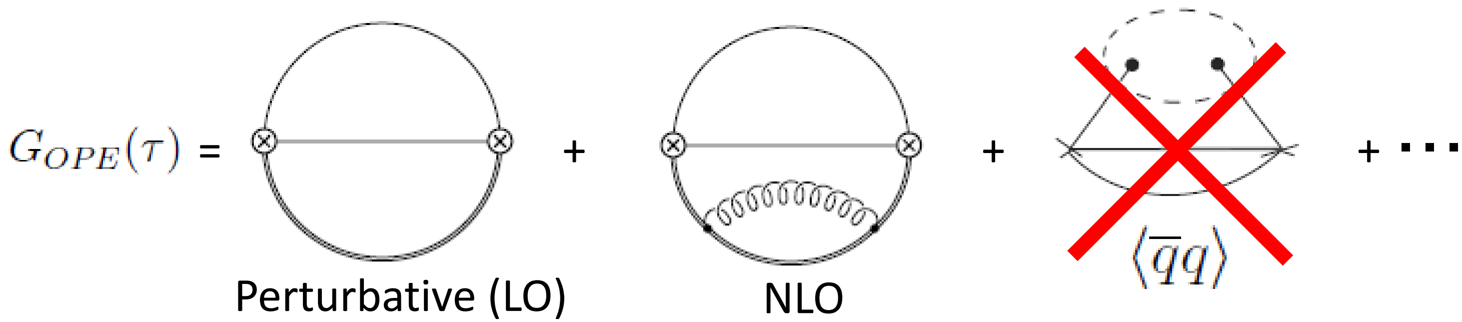
$$\propto \mathrm{Tr}[(\not{q} + m_q)\langle \overline{q} q \rangle] \propto m_q \langle \overline{q} q \rangle$$

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

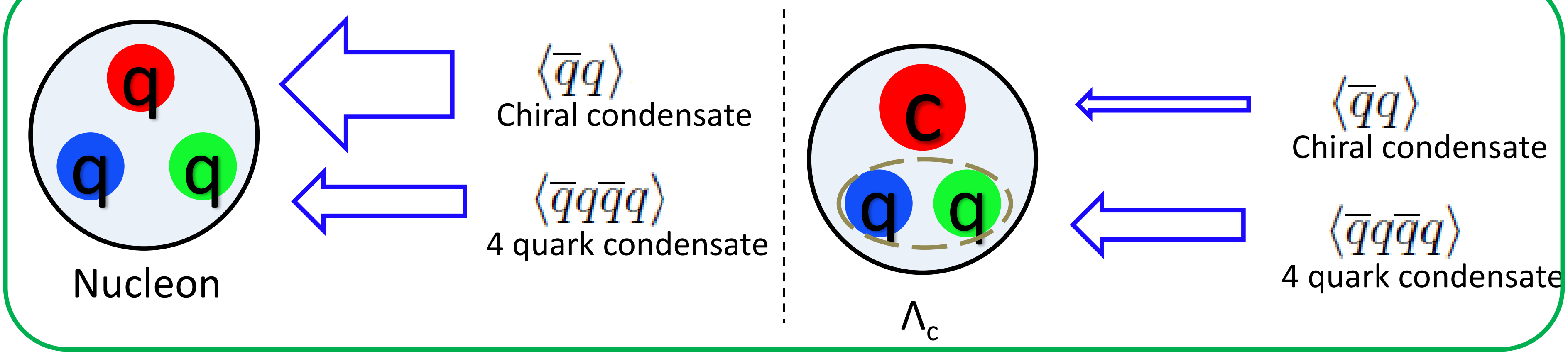
OPE of Λ_c correlation function

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

Diagrams of Λ_c OPE:



The effect from the partial restoration of the chiral symmetry



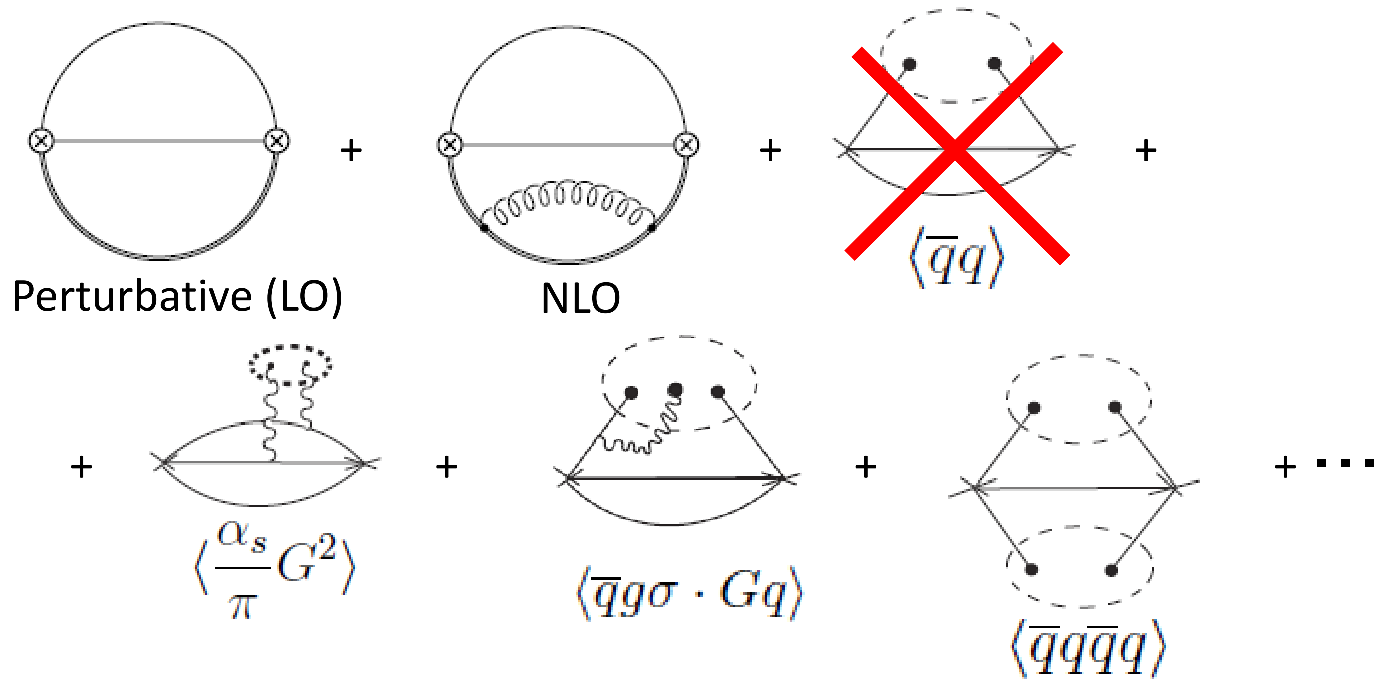
⇨ Λ_c baryon knows the partial restoration of the chiral symmetry breaking through four quark condensates.

OPE of Λ_c correlation function

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

Diagrams of Λ_c OPE:

$G_{OPE}(\tau)$ =



Furthermore, contributions from some kinds of condensates are also suppressed.

OPE of Λ_c correlation function

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Diagrams of Λ_c OPE:

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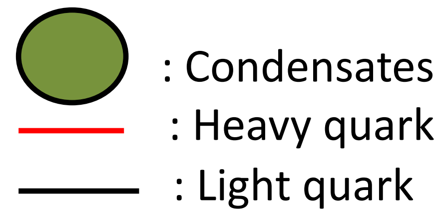

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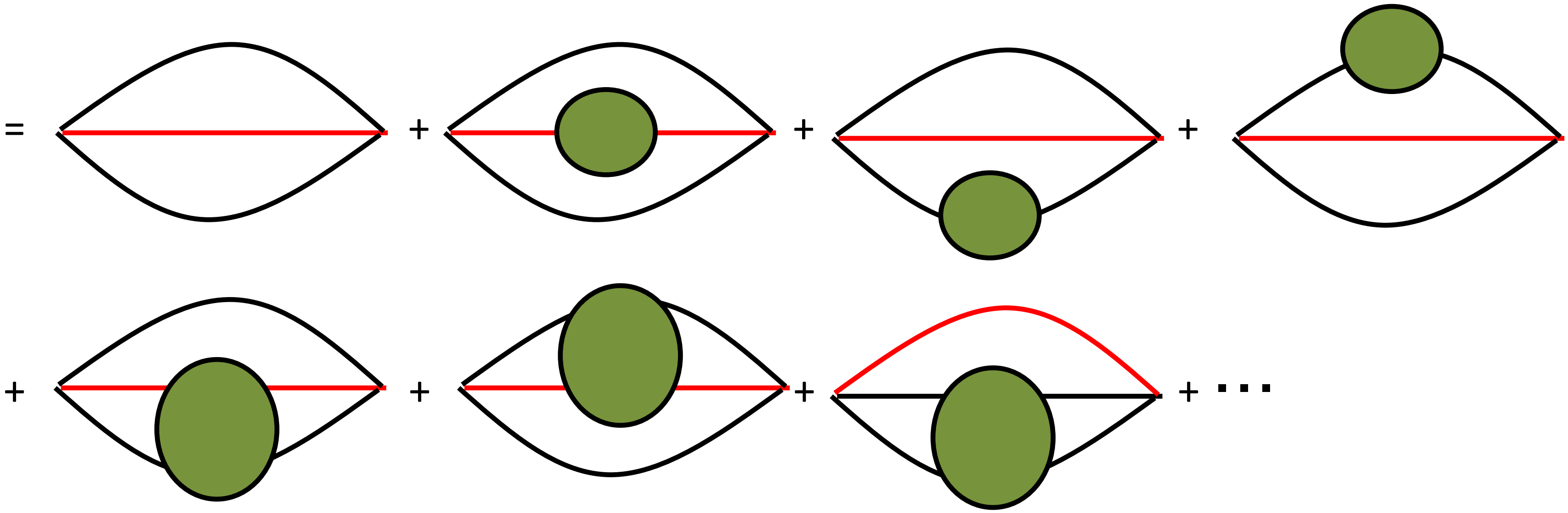

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Diagrams of Λ_c OPE:

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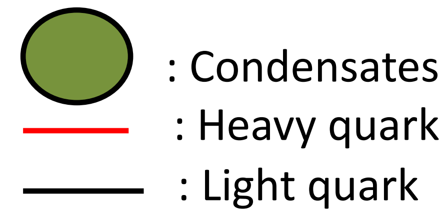

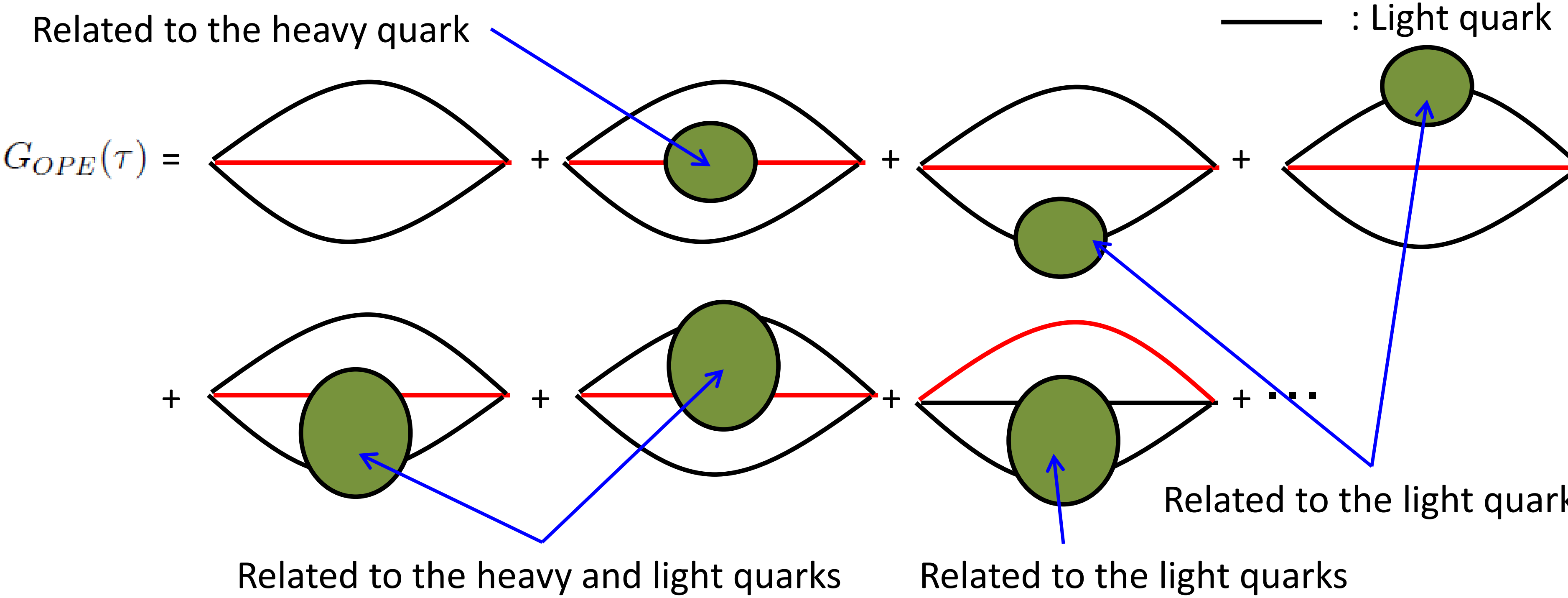

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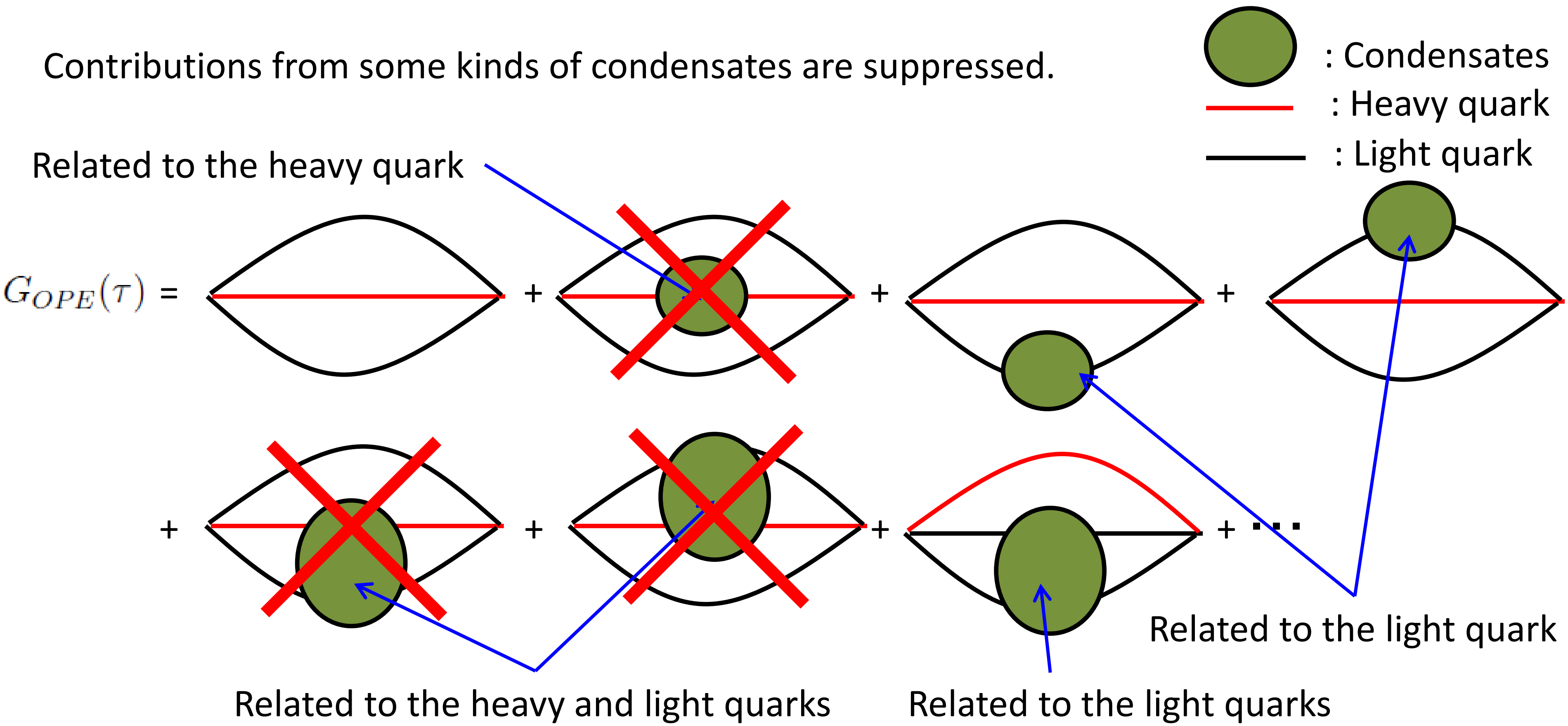
Diagrams of Λ_c OPE:

Contributions from some kinds of condensates are suppressed.



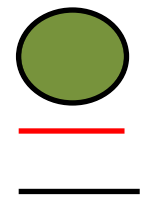
✗ : These contributions are numerically small.

OPE of Λ_c correlation function

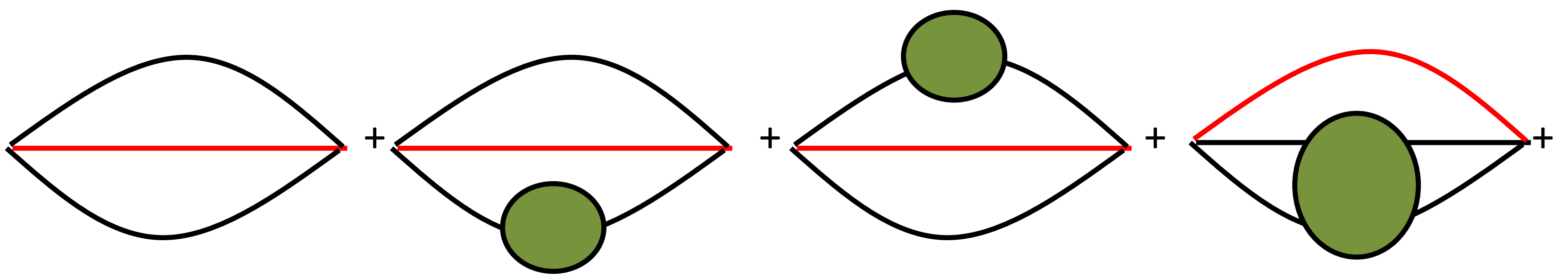
Gaussian sum rule: $$\underline{G_{OPE}(\tau)} = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Diagrams of Λ_c OPE:

Contributions from some kinds of condensates are suppressed.



$G_{OPE}(\tau) \approx$



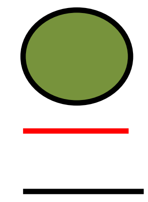
This result indicates that

OPE of Λ_c correlation function

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

Diagrams of Λ_c OPE:

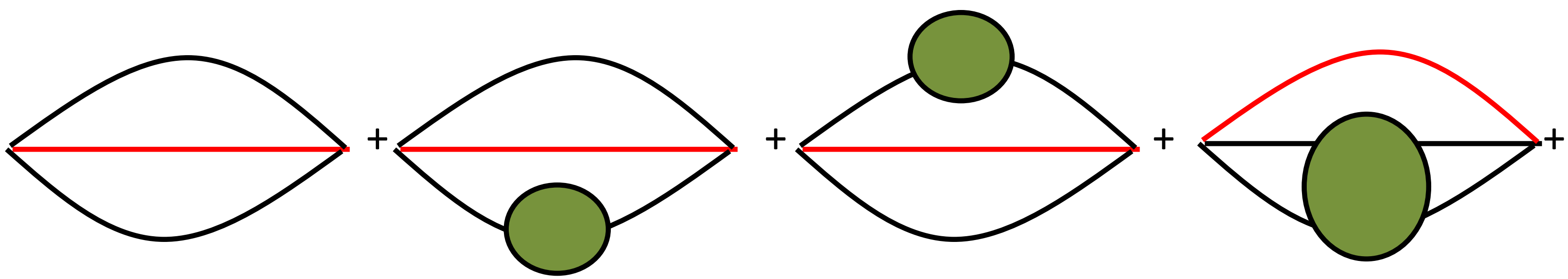
Contributions from some kinds of condensates are suppressed.



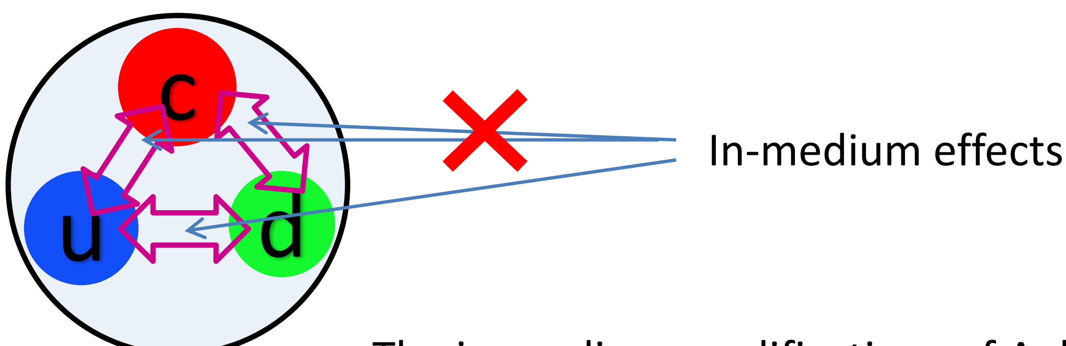
: Condensates

: Heavy quark

: Light quark

$G_{OPE}(\tau) \approx$ 

Schematic figure:



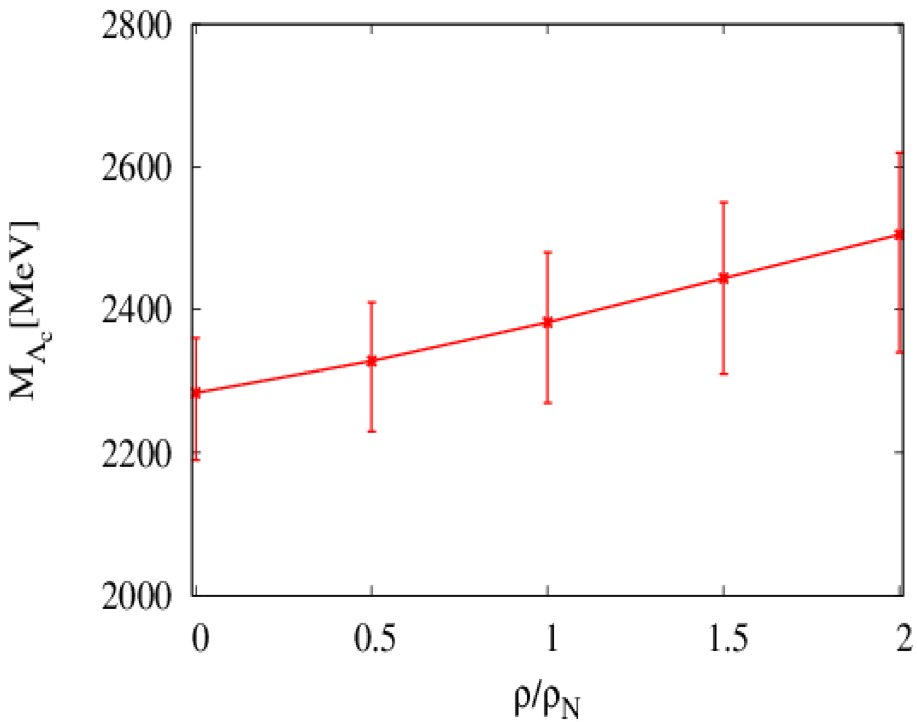
Λ_c

The in-medium modifications of Λ_c baryon are come from the good diquak in the baryon.

Results

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

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



At ρ=1.0ρ_N, the sfift $\Delta M_{\Lambda_c} \approx 100\text{MeV}$

The density dependence of M_{Λ_c}

Summary

- We construct the parity projected Λ_c QCD sum rule.
- From Λ_c sum rule, it is found that the Λ_c knows the partial restoration of chiral symmetry through four quark condensate and mass shift of Λ_c come from the good diquark.
- We analyze the Λ_c spectral function in vacuum and nuclear matter.
- We investigate the density dependence of the mass of Λ_c .
- As the density increases, the mass of Λ_c increases.

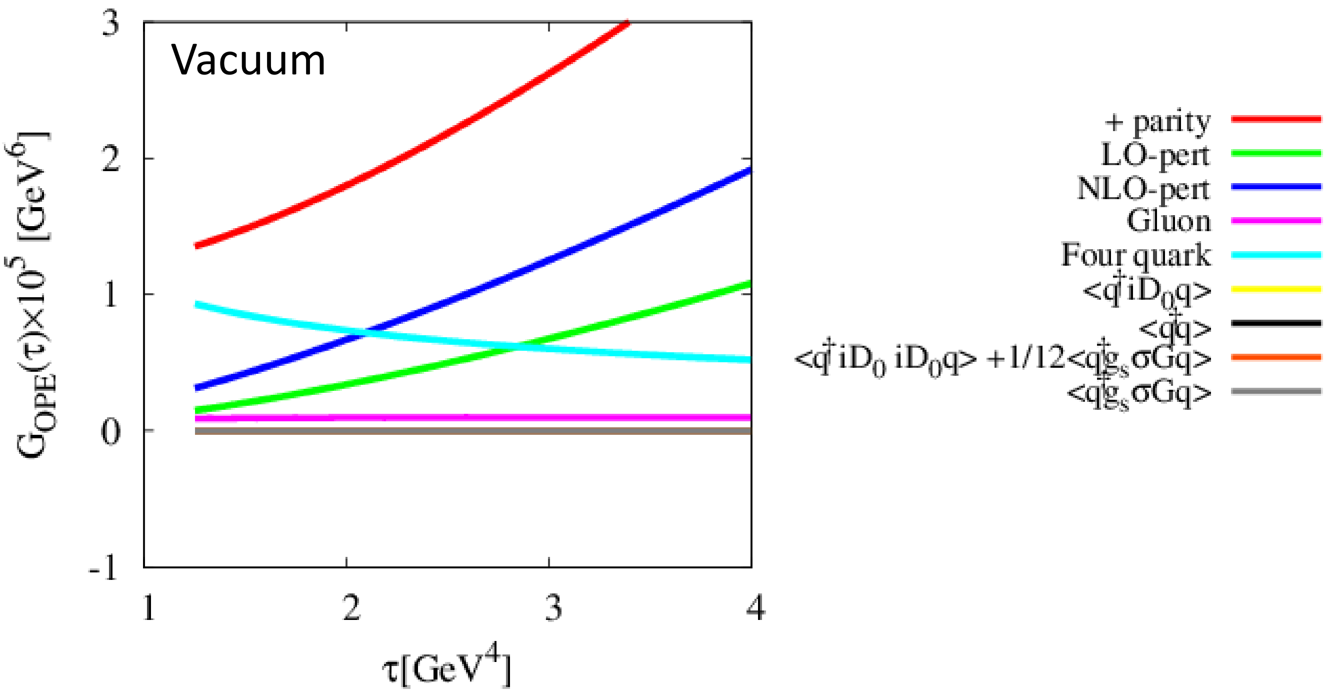
Future plan

- We will compare the case of Λ baryon.

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

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

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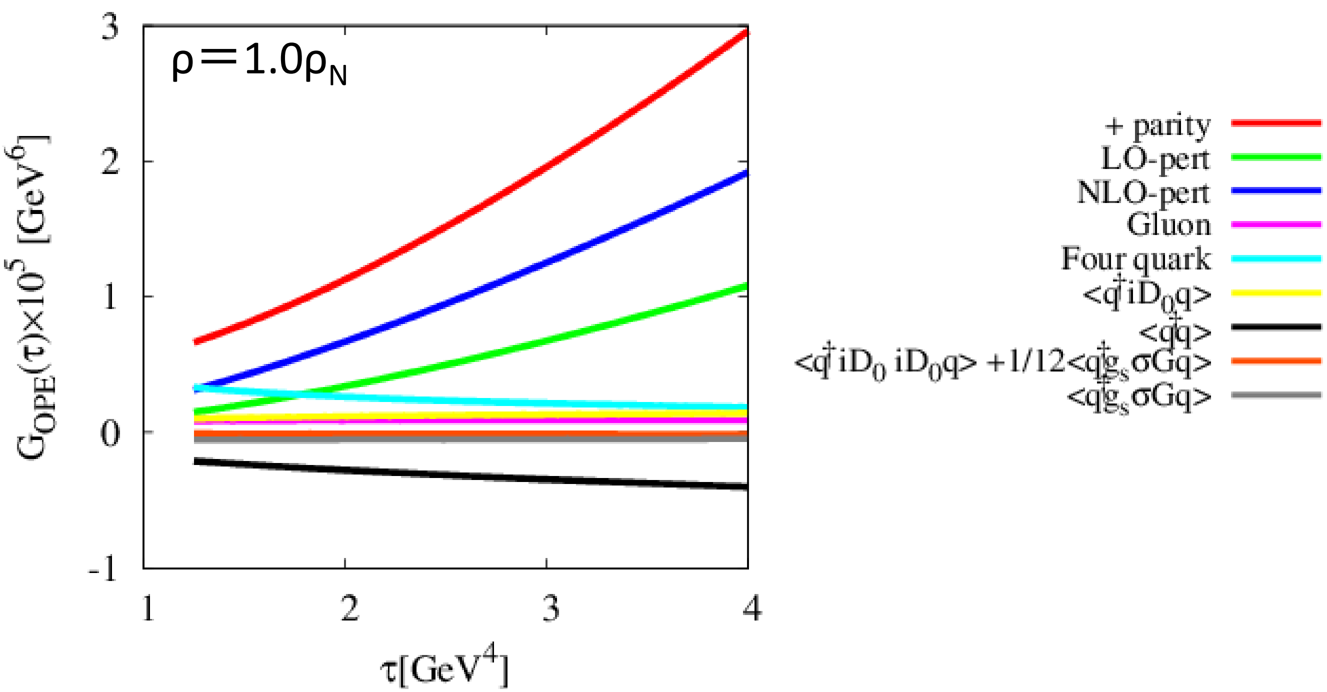

Backup slides

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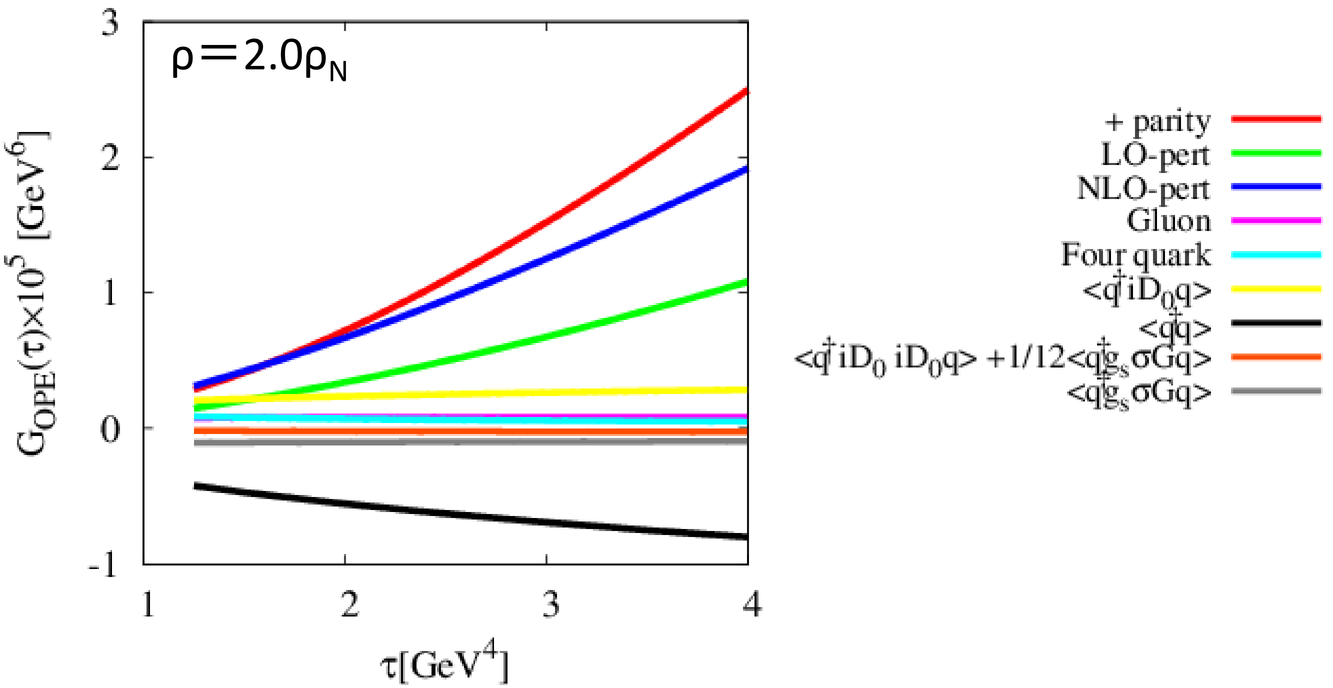
Density dependence of the $G_{OPE}(\tau)$



Backup slides

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

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

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

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

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

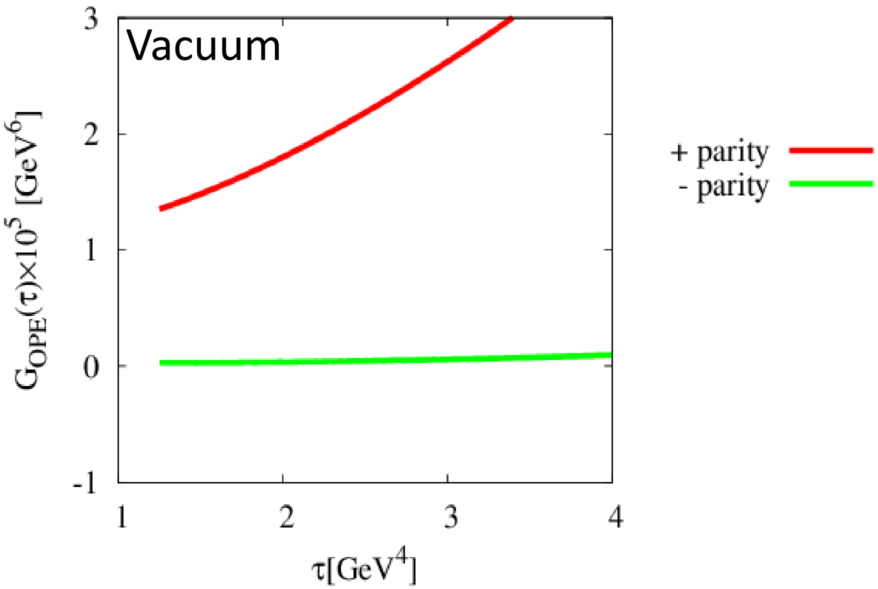
Backup slides

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

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

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

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



Backup slides

$$\chi^2 = \frac{1}{n_{set} \times n_\tau} \sum_{j=1}^{n_{set}} \sum_{i=1}^{n_\tau} \frac{(G^j_{OPE}(\tau_i) - G^j_{SPF}(\tau_i))^2}{\sigma^j(\tau_i)^2}$$

$$\sigma^j(\tau_i)^2 = \frac{1}{n_{set} - 1} \sum_{j=1}^{n_{set}} (G^j_{OPE}(\tau_i) - \overline{G_{OPE}}(\tau_i))^2$$

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

n_{set} : The number of the condensate sets which are randomly generated with errors

n_τ : The number of the point τ in the analyzed τ region

Error bar: $|\chi^2 - 1| < 0.1$