Λ_c baryon in nuclear matter from QCD sum rule

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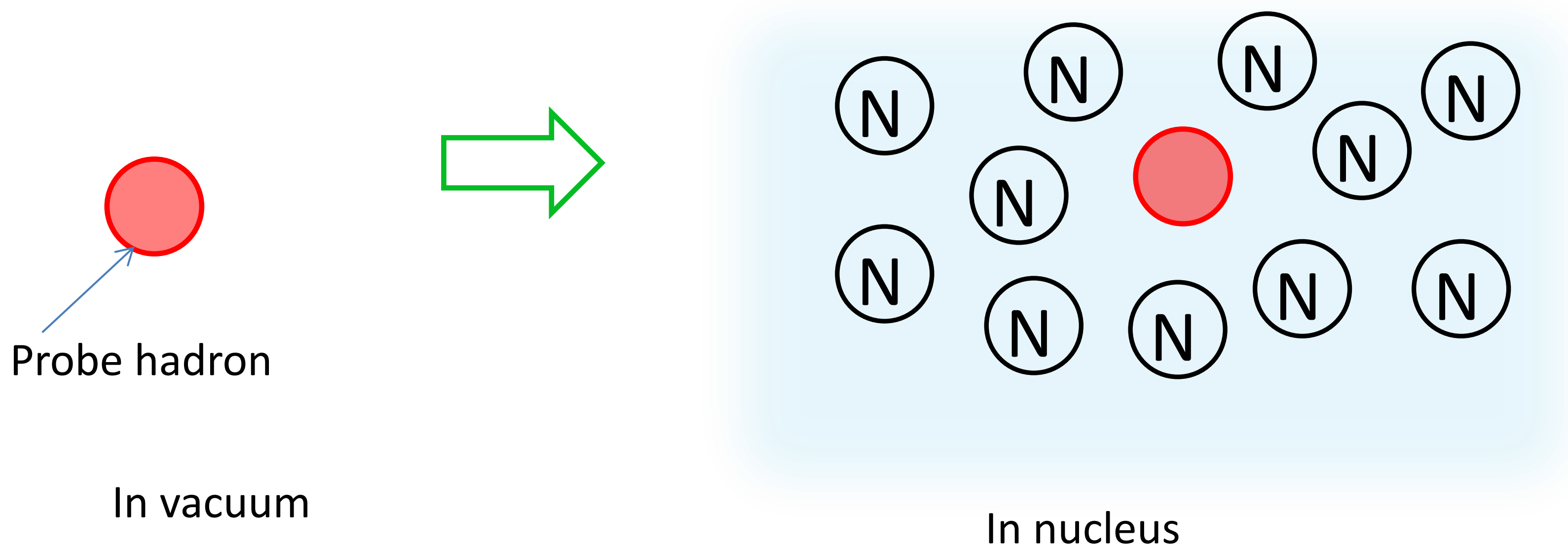
Collaborators: Kenji Araki, Makoto Oka

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

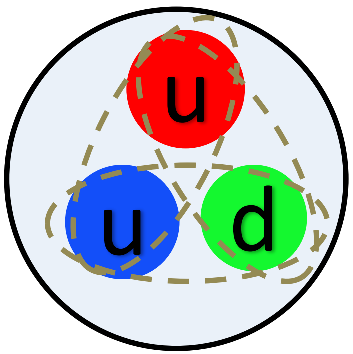
New points in Λ_c baryon

Light baryons

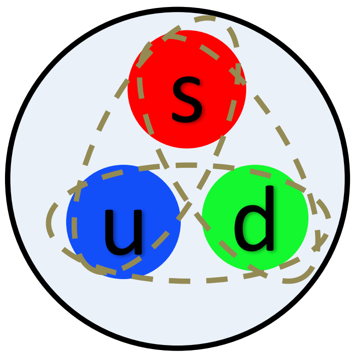
Approximated flavor symmetry

$$m_u \approx m_d < m_s$$

N



Λ



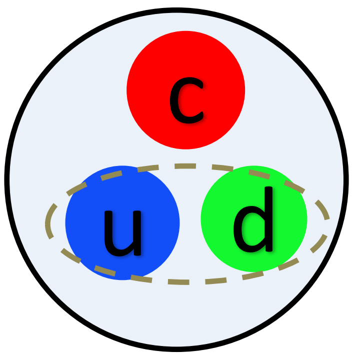
Add the charm quark

Λ_c baryon

Flavor symmetry is largely broken.

$$m_u \approx m_d << m_c$$

Heavy quark spin symmetry



Introduction

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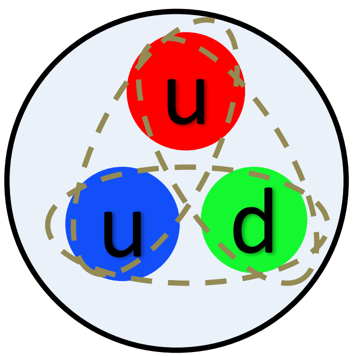
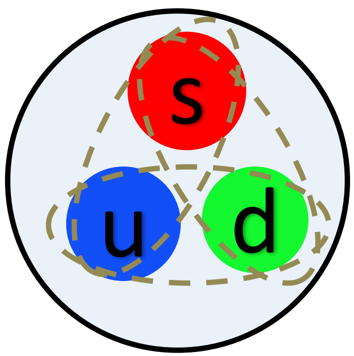


Λ



Add the charm quark

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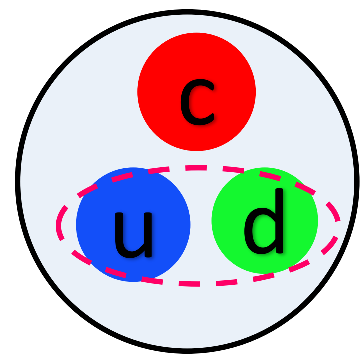
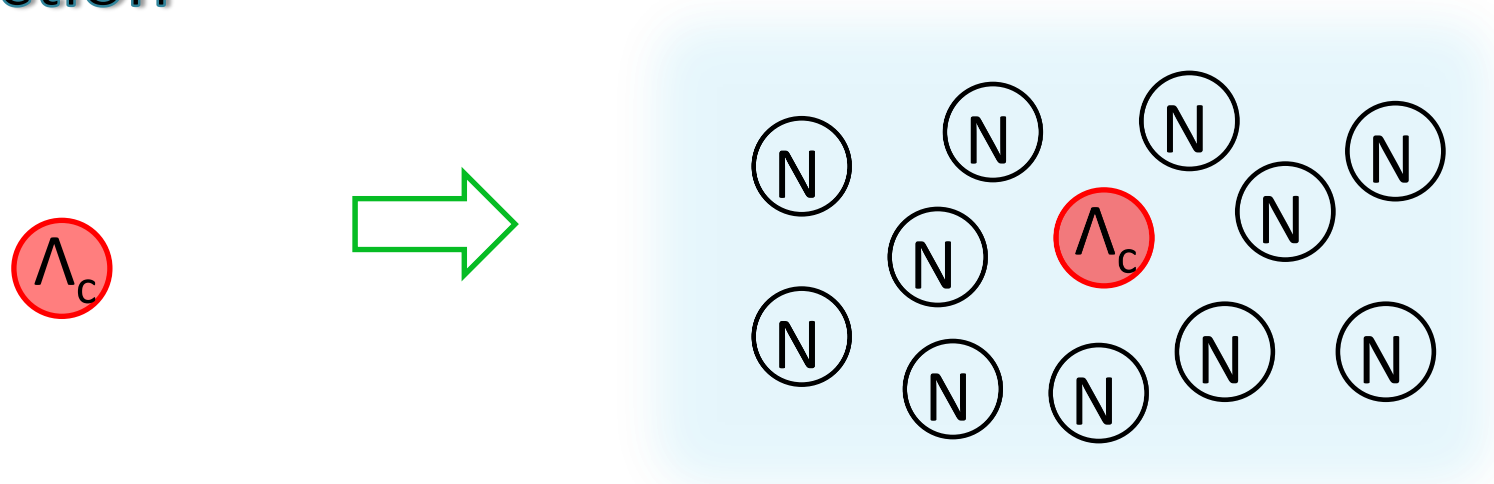


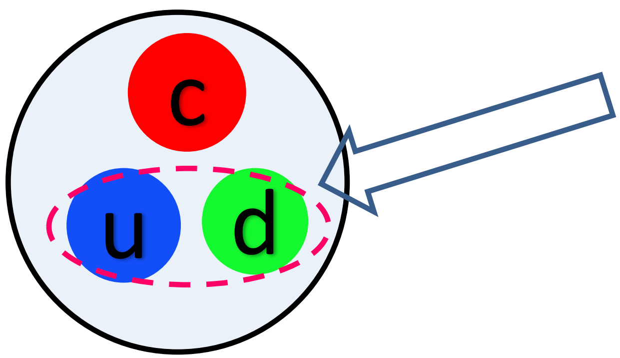
The diquark properties can be investigated.

Introduction



In vacuum

In nuclear matter

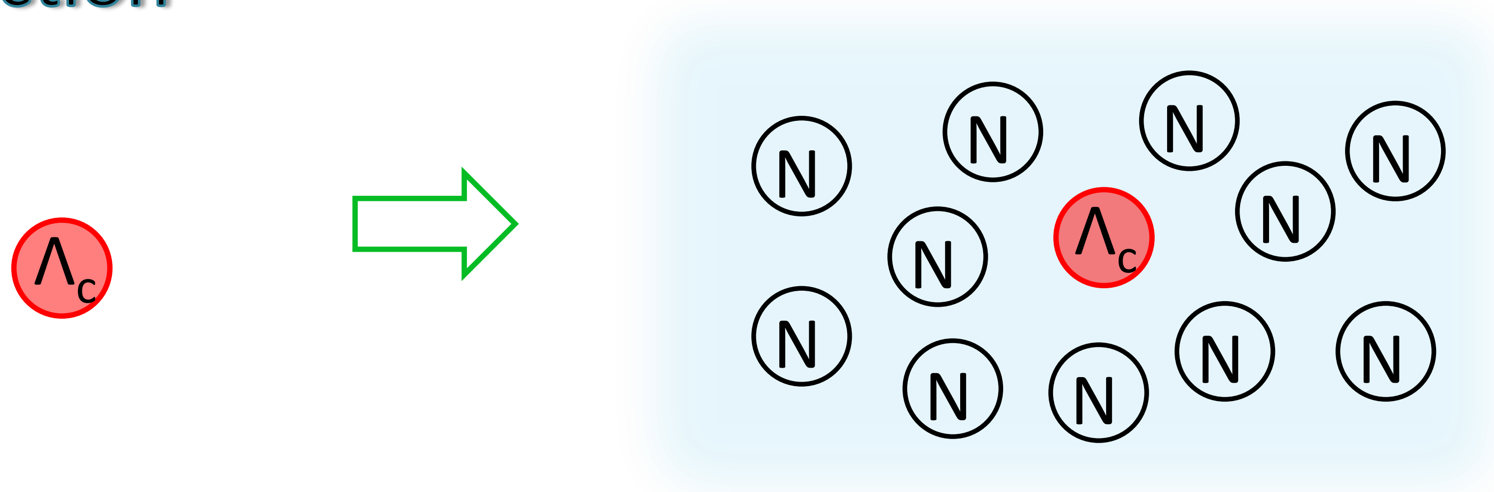


Λ_c

“Partial restoration of chiral symmetry”

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

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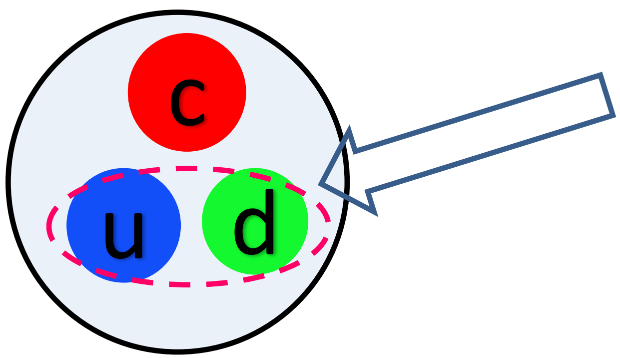

Λ_c

"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].

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In nuclear matter

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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	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)
Up to dimension 8 condensate (higher order contribution)
Parity projection

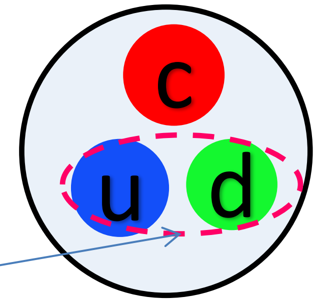
S. Groote, et al., Eur. Phys. J. C58, 355 (2008)

Λ_c QCD sum rules

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

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

Good diquark
(Scalar diquark)



(Schematic figure)

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Parity projected
QCD sum rule

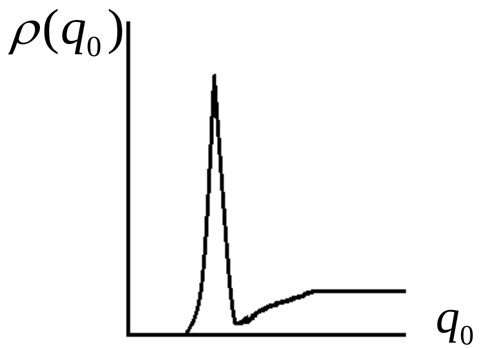
Gaussian sum rule: $\underline{G_{OPE}(\tau)} = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau} \right) \underline{\rho(q_0)} dq_0$

Quark degree of freedom

Hadron degree of freedom

Hadronic spectral function

Typical behavior:



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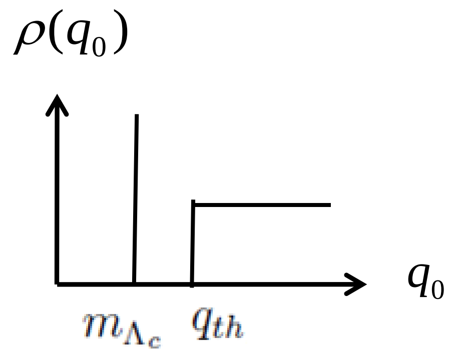
Hadronic spectral function



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

Λ_c QCD sum rules

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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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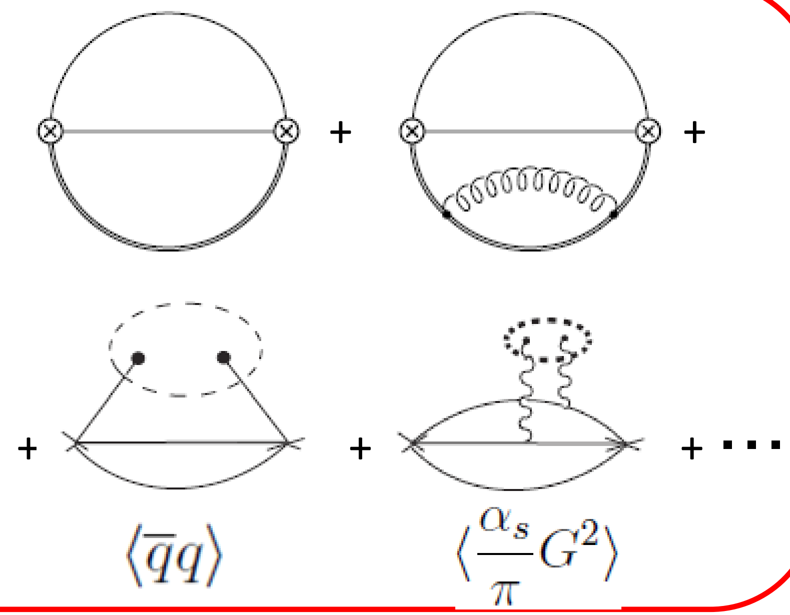
(In vacuum)

$G_{OPE}(\tau) =$



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.

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

$m_c^{pole} = 1.67 \pm 0.07$ GeV

$\alpha_s = 0.5$

$\langle \bar{q}q \rangle_0 = -(0.246 \pm 0.002 GeV)^3$

$m_q = 4.75\text{MeV}$

$\sigma_N = 45\text{MeV}$

$\langle q^\dagger q \rangle_{\rho_N}$	$\rho_N \frac{3}{2}$
$\langle \frac{\alpha_s}{\pi} G^2 \rangle_0$	$0.012 \pm 0.0036\text{GeV}^4$
$\langle \frac{\alpha_s}{\pi} G^2 \rangle_N$	$-0.65 \pm 0.15\text{GeV}$
A_2^q	0.62 ± 0.06
A_2^g	0.359 ± 0.146
A_3^q	0.15 ± 0.02
e_2	0.017 ± 0.047
m_0^2	$0.8 \pm 0.2\text{GeV}^2$
$\langle q^\dagger g\sigma \cdot Gq \rangle_N$	-0.33GeV^2

S. Borsanyi, S. Durr, Z. Fodor, S. Krieg, A. Schafer, E. E. Scholz, and K. K. Szabo, Phys. Rev. D **88**, 014513 (2013).

K. A. Olive *et al.* (Particle Data Group Collaboration), Chin. Phys. C **38**, 090001 (2014).

P. Colangelo and A. Khodjamirian, *At the Frontier of Particle Physics: Handbook of QCD* (World Scientific, Singapore, 2001), Vol. 3, p. 1495.

X. Jin, M. Nielsen, T. D. Cohen, R. J. Furnstahl, and D. K. Griegel, Phys. Rev. C **49**, 464 (1994).

A. Martin, W. Stirling, R. Thorne, and G. Watt, Eur. Phys. J. C **63**, 189 (2009).

P. Gubler, K. S. Jeong, and S. H. Lee, Phys. Rev. D **92**, 014010 (2015).

OPE of Λ_c correlation function

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

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Parity projected
QCD sum rule

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

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?

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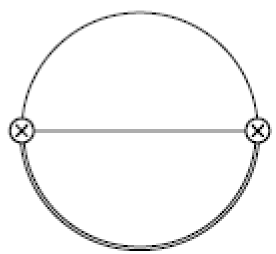
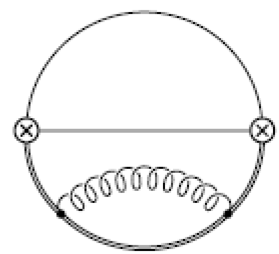
Diagrams of Λ_c OPE:

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



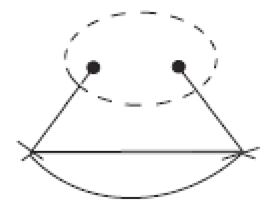
Perturbative (LO)

+



NLO

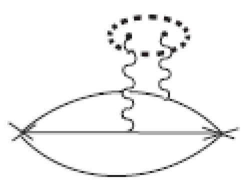
+



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

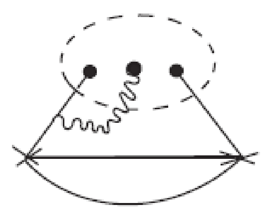
+

+



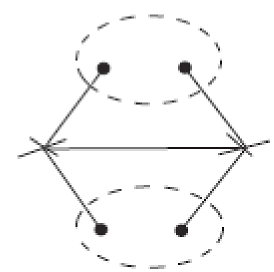
$\langle \frac{\alpha_s}{\pi} G^2 \rangle$

+



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

+



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

+ ⋯

OPE of Λ_c correlation function

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

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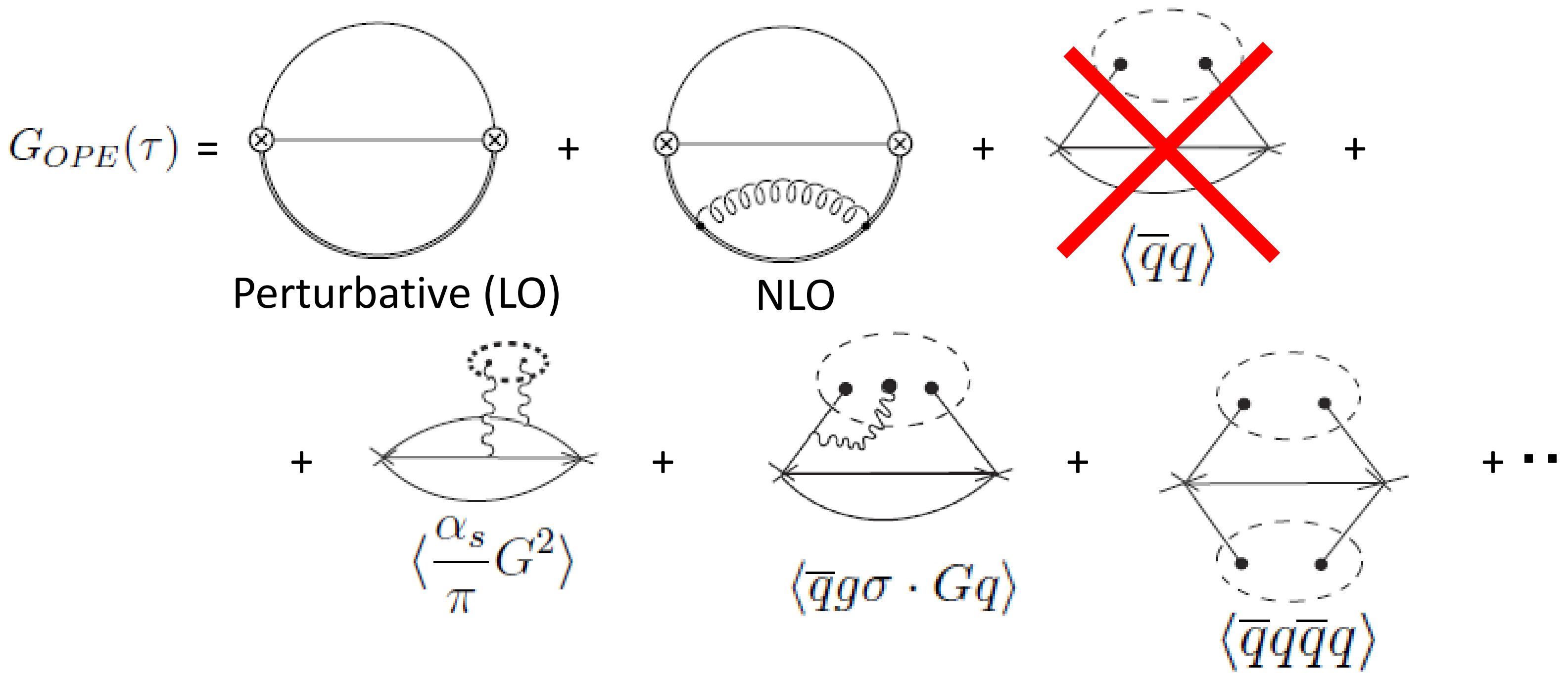


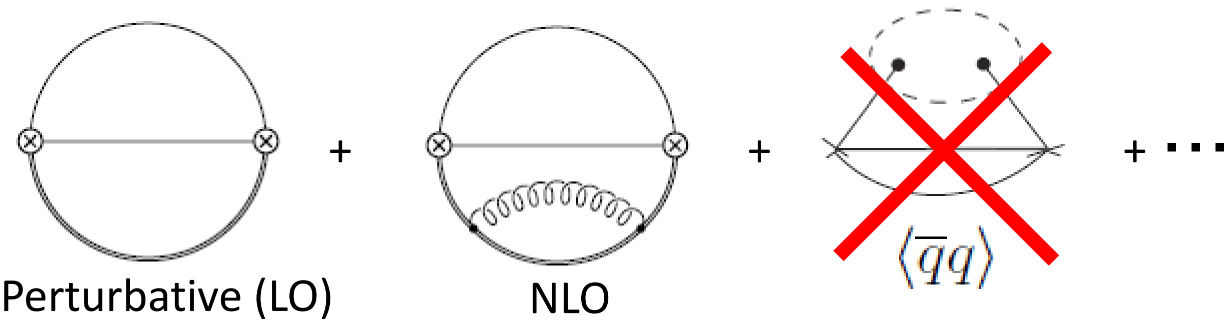
The contributions from chiral condensates are strongly suppressed.

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:

$G_{OPE}(\tau)$ =



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

Diagrams of Λ_c OPE:

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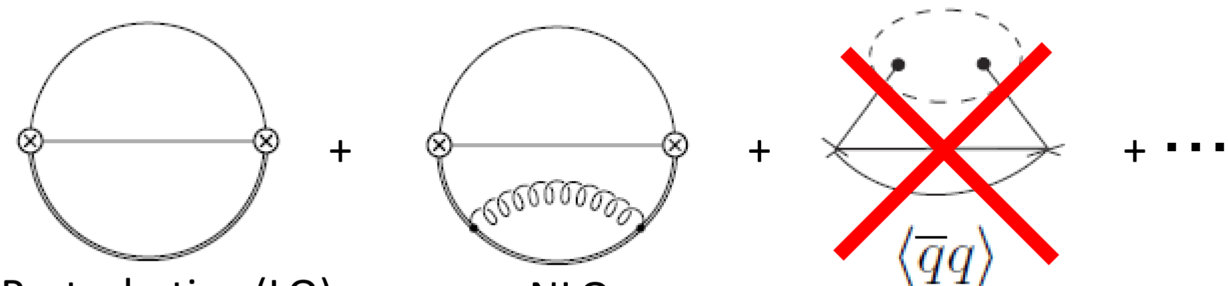

Perturbative (LO)   NLO

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.

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

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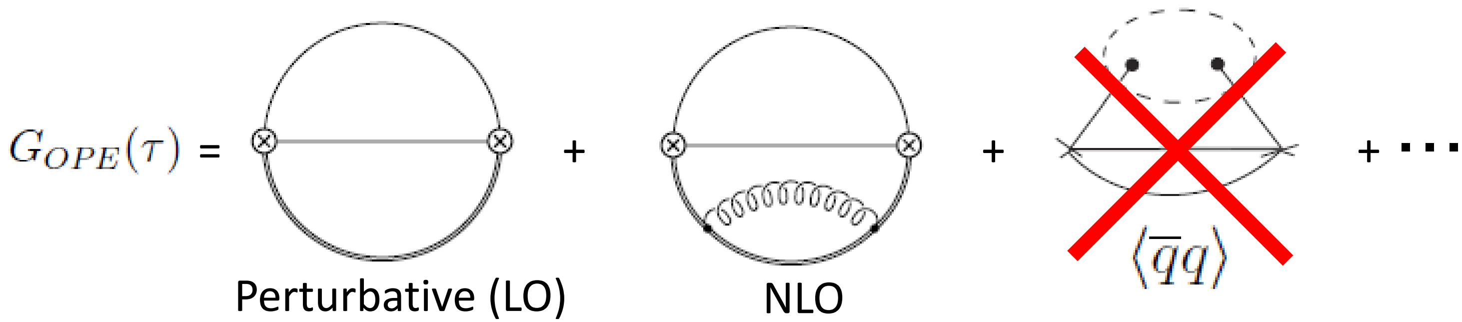
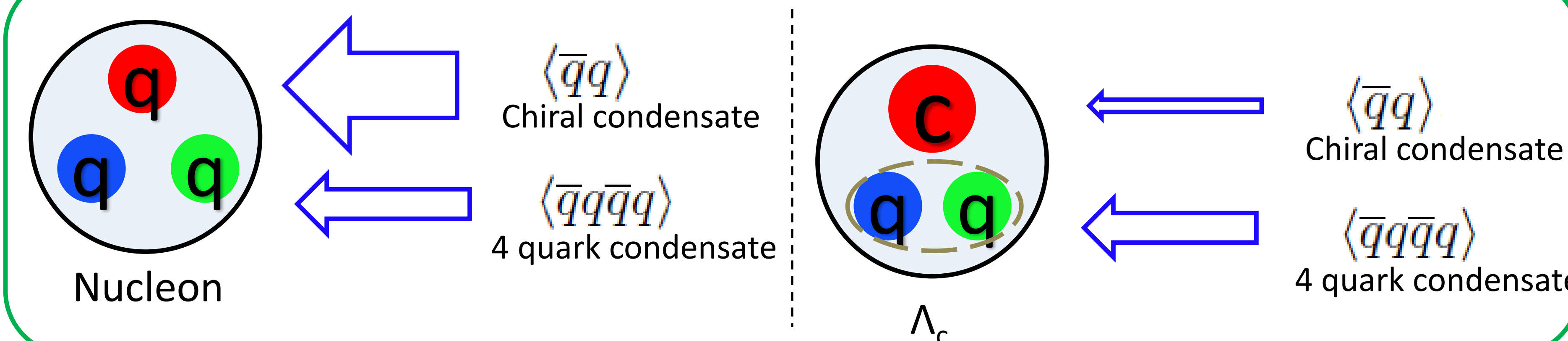


The effect from the partial restoration of the chiral symmetry



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

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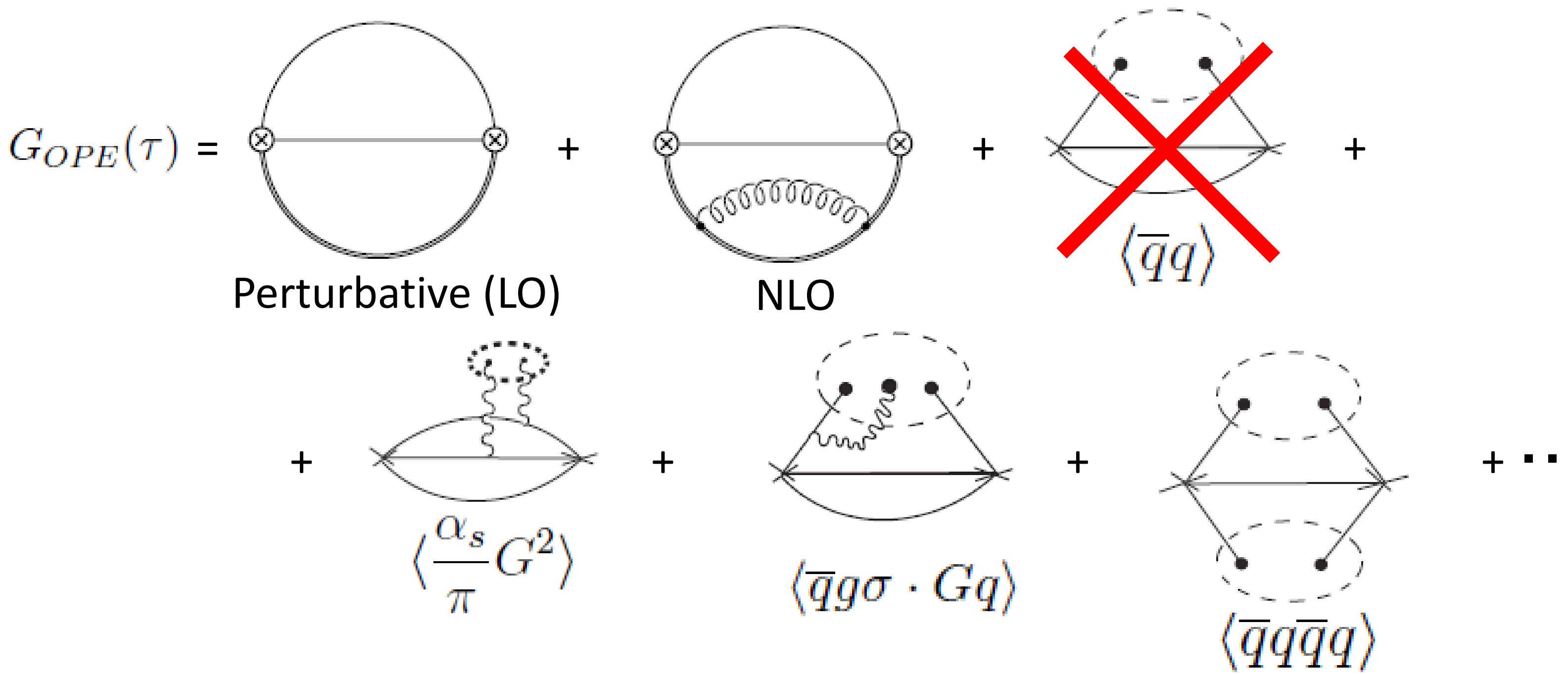
Diagrams of Λ_c OPE:



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

OPE of Λ_c correlation function

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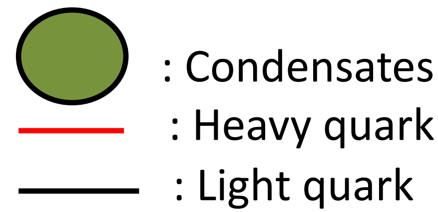
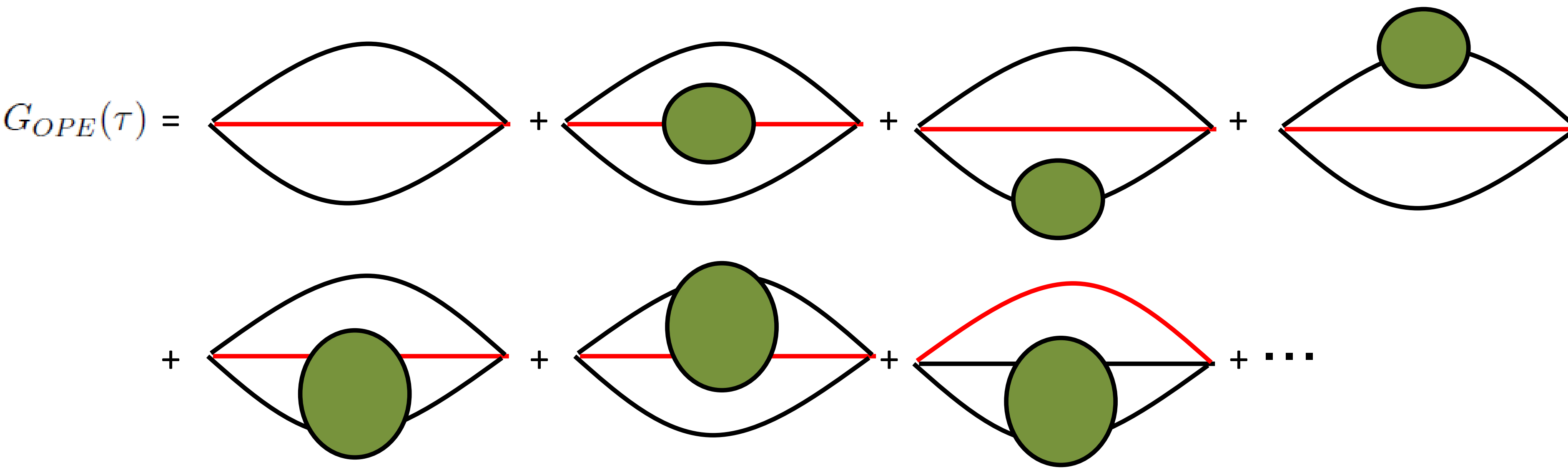
Diagrams of Λ_c OPE:

Contributions from some kinds of condensates are suppressed.



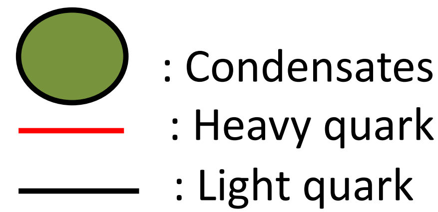


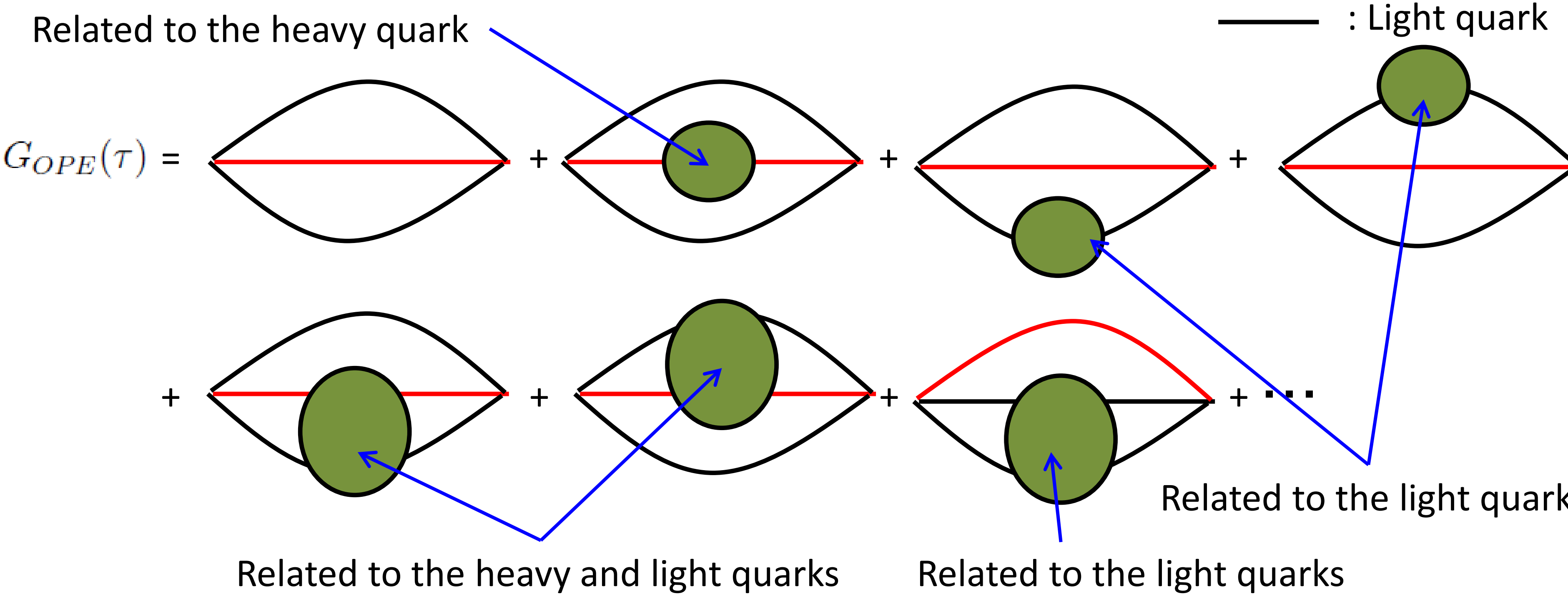
OPE of Λ_c correlation function

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:

Contributions from some kinds of condensates are suppressed.





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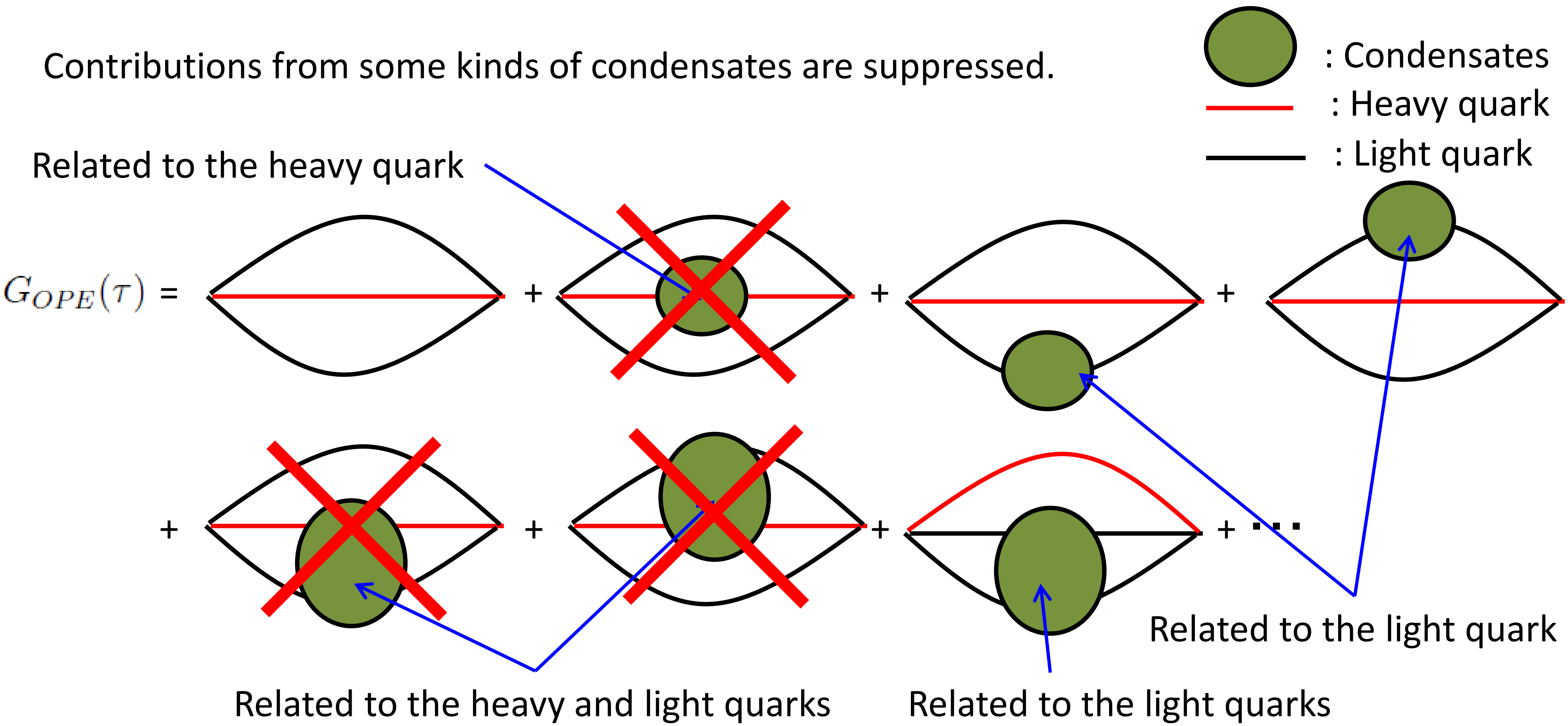

: These contributions are numerically small.

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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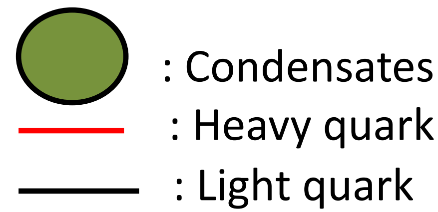
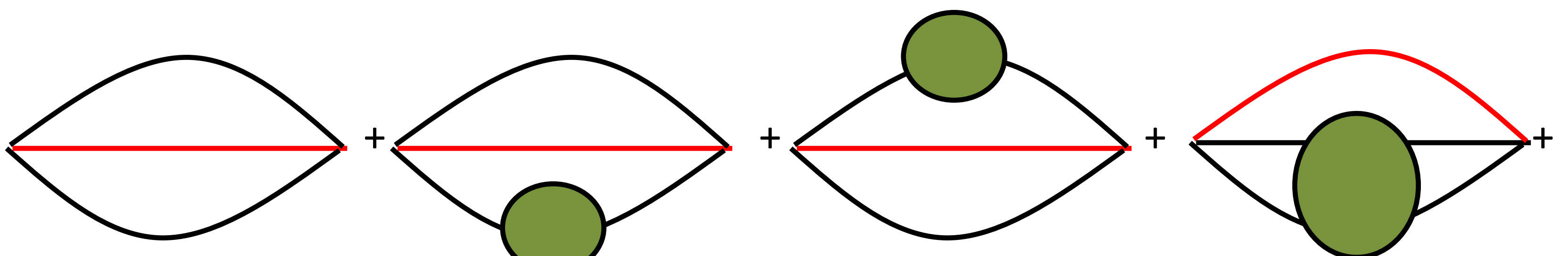


$G_{OPE}(\tau) \approx$



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:

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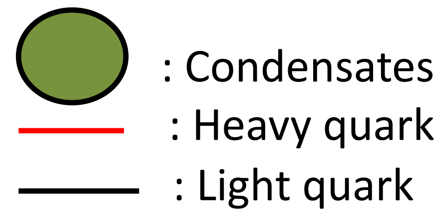
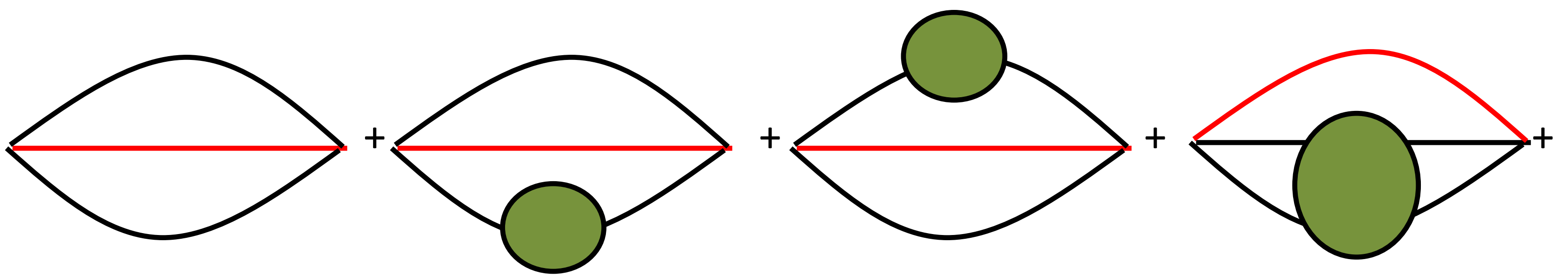
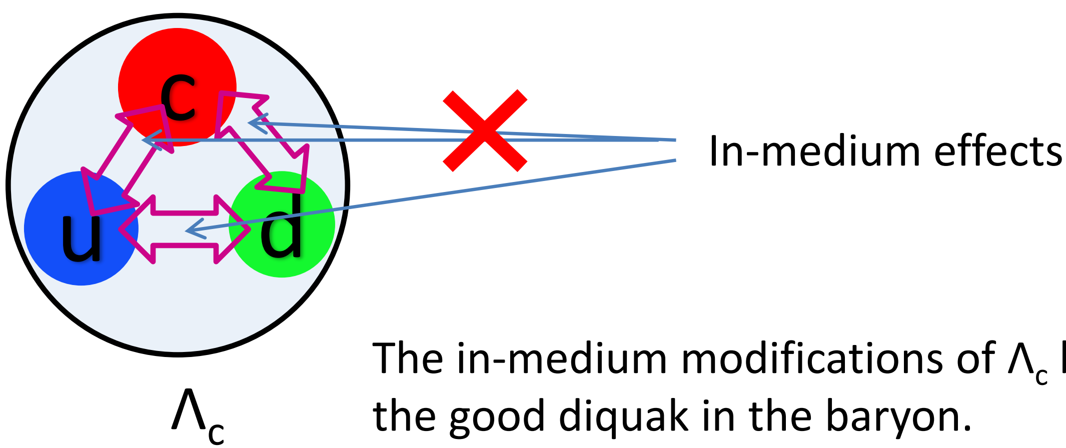


$G_{OPE}(\tau) \approx$ 

Schematic figure:



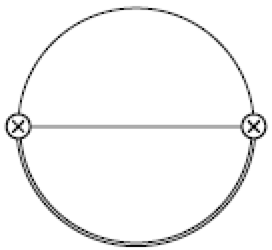
The in-medium modifications of Λ_c baryon are come from the good diquak in the baryon.

OPE of Λ_c correlation function in vacuum

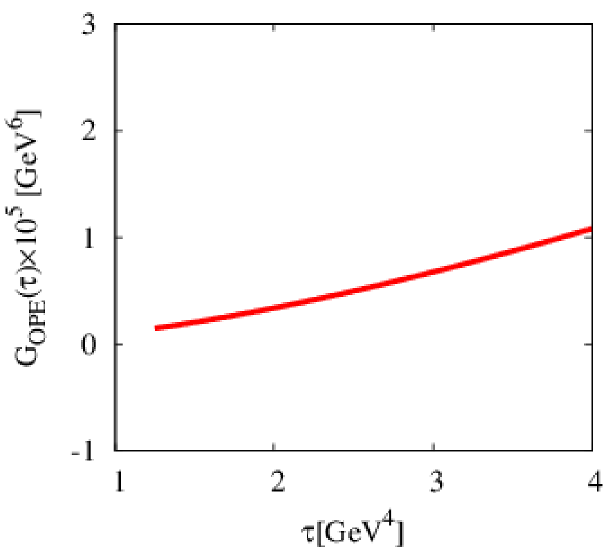
$$G_{OPE}(\tau) = \int_0^\infty \frac{1}{\sqrt{4\pi\tau}} \exp\left(-\frac{(q_0^2 - m_c^2)^2}{4\tau}\right) \rho(q_0) dq_0$$

Operator product expansion (OPE)

Non-perturbative contributions are expressed by condensates.



Perturbative (LO)



OPE of Λ_c correlation function in vacuum

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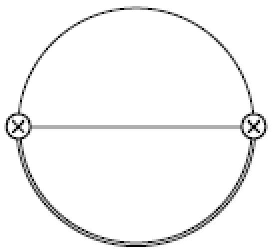

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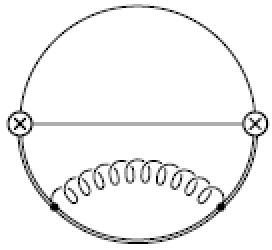
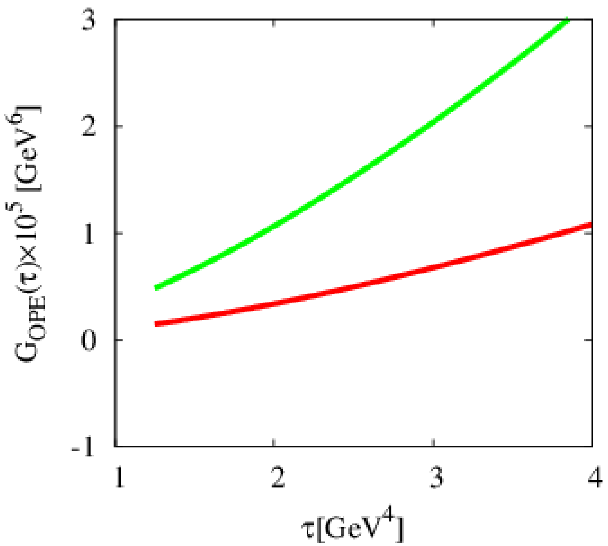


NLO



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

OPE of Λ_c correlation function 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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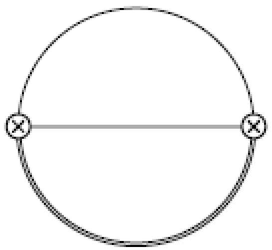
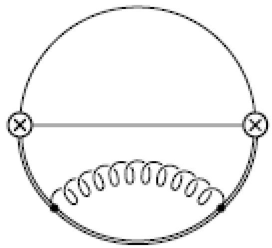
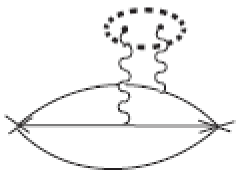


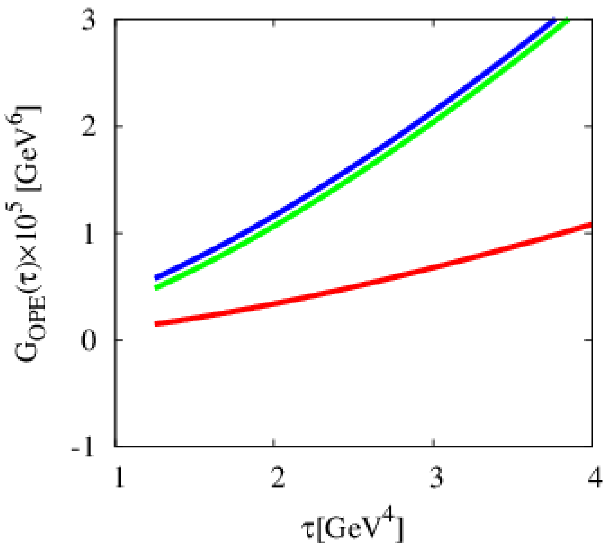
Perturbative (LO)



NLO



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



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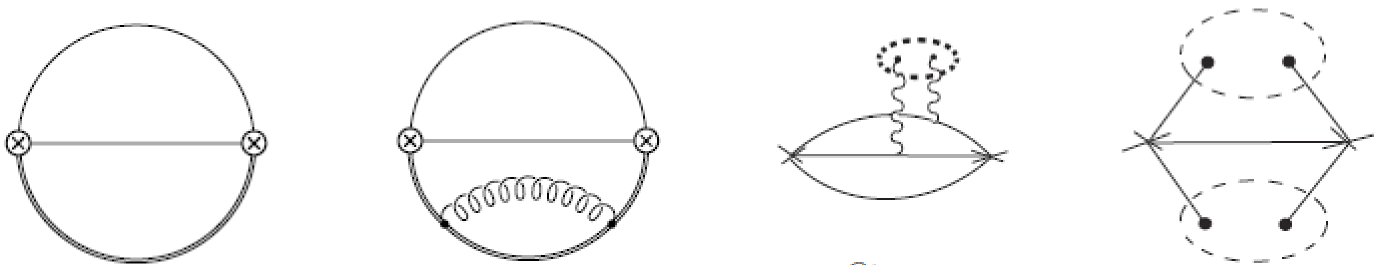
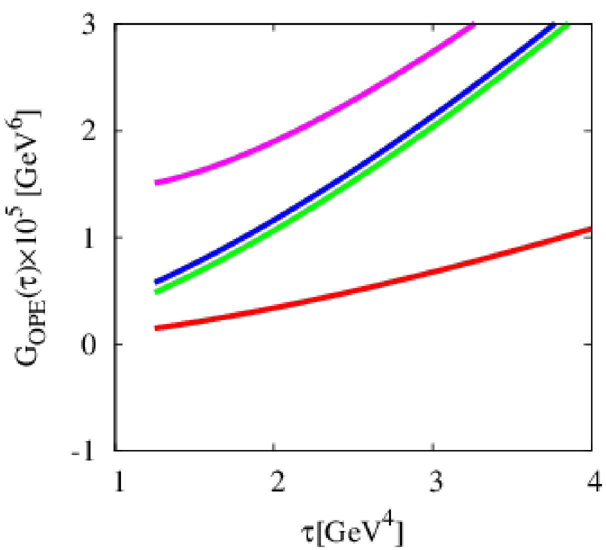
OPE of Λ_c correlation function in vacuum

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

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



Perturbative (LO)   NLO $\langle \frac{\alpha_s}{\pi} G^2 \rangle$ $\langle \bar{q}q\bar{q}q \rangle$



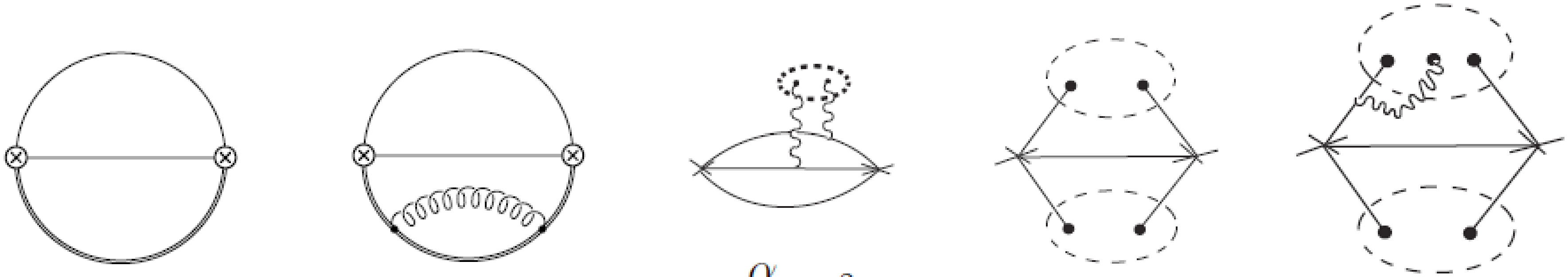
NLO contributions to its leading order are more than 100%.

The contribution of four quark condensate is large.

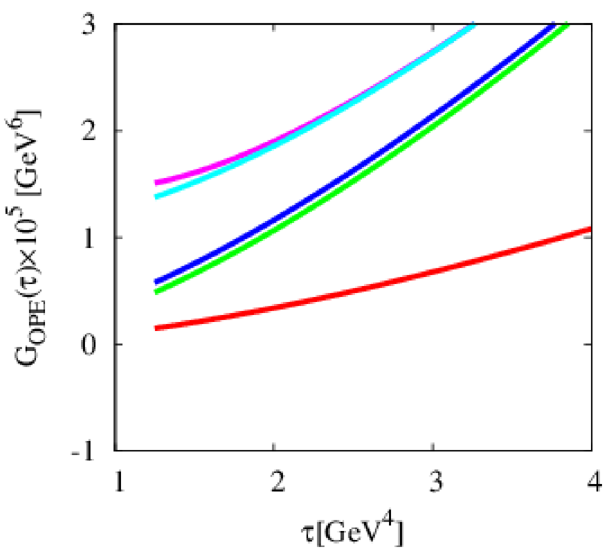
OPE of Λ_c correlation function in vacuum

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

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



Perturbative (LO) 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%.

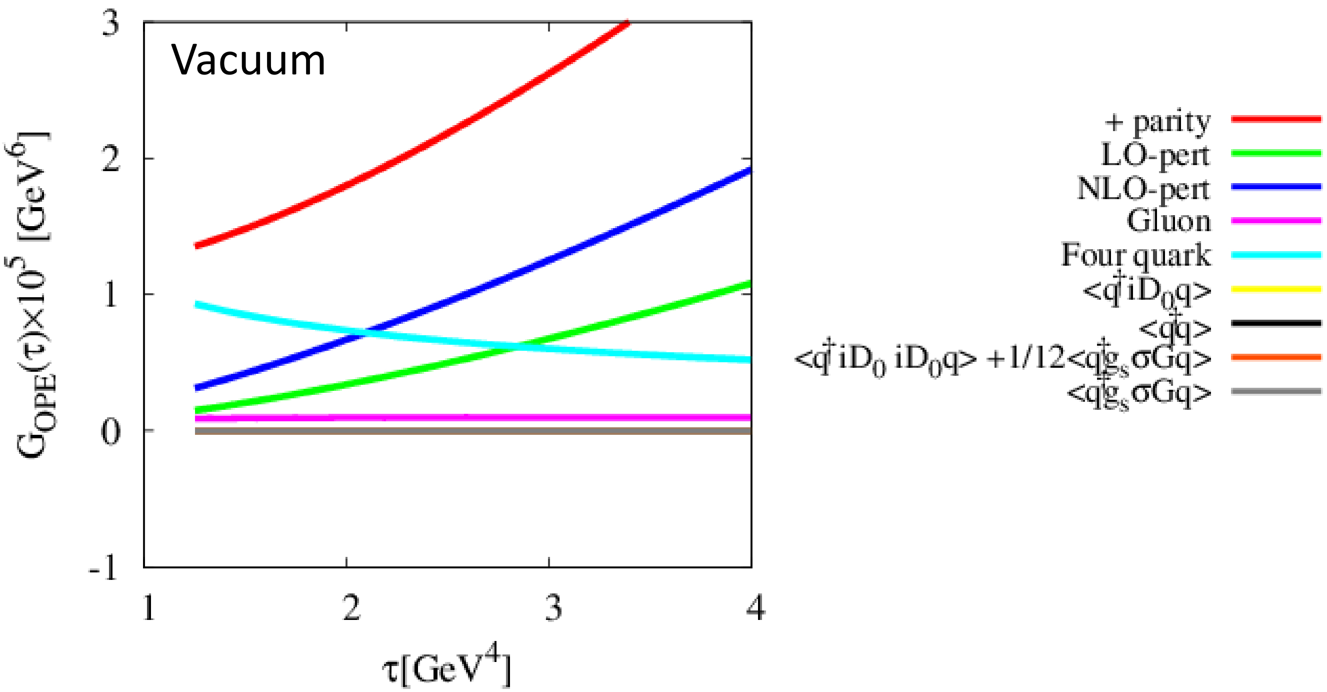
The contribution of four quark condensate is large.

The contribution of the dimension 8 condensate is small.

OPE of Λ_c correlation function in nuclear matter

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

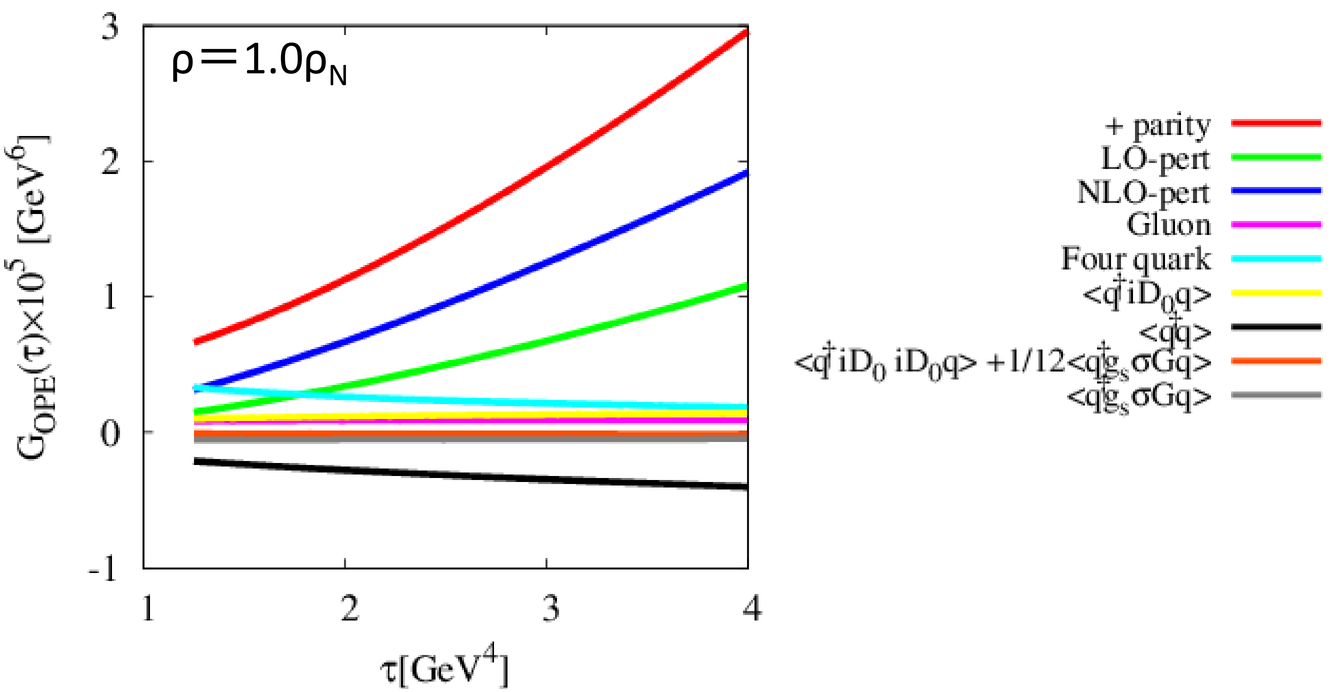
Density dependence of the $G_{OPE}(\tau)$



OPE of Λ_c correlation function in nuclear matter

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

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



OPE of Λ_c correlation function in nuclear matter

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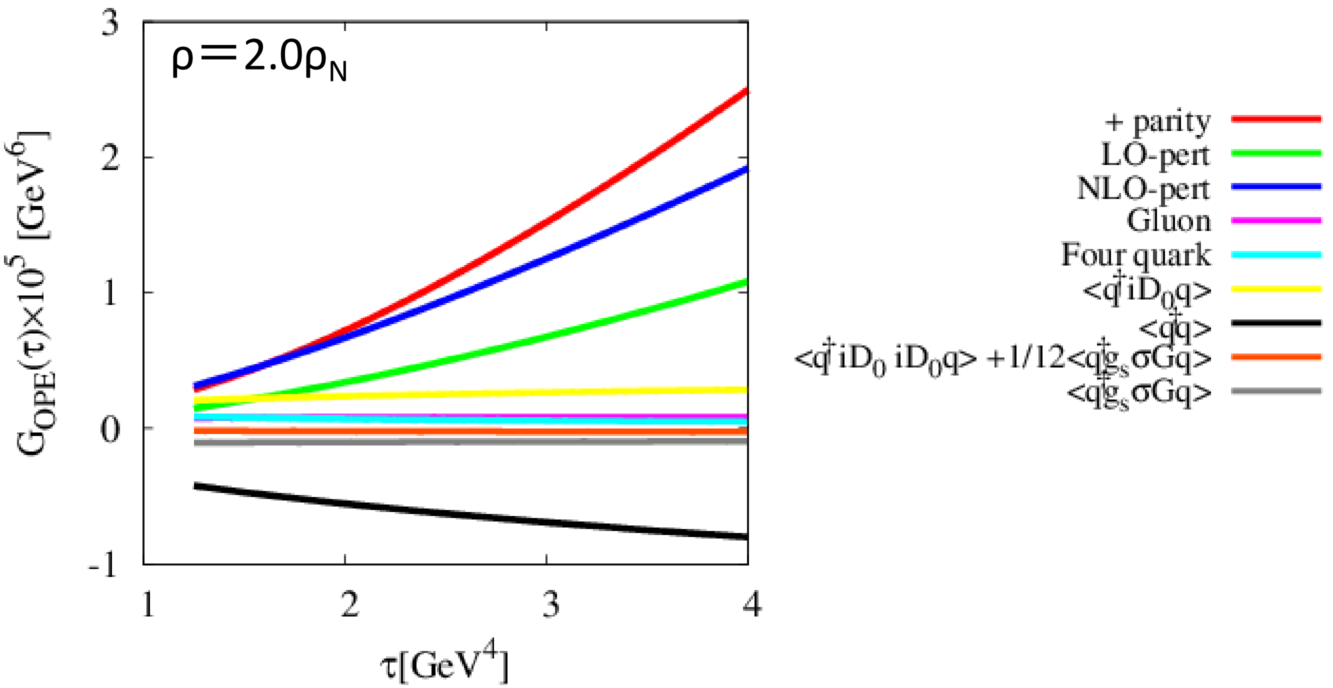
Density dependence of the $G_{OPE}(\tau)$



OPE of Λ_c correlation function in vacuum

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

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

The analyzed parameter region

The minim value of τ is determined based on the convergence of OPE

$$G_{OPE}^{d=8}(\tau)/G_{OPE}^{\pm}(\tau) \ < \ 0.1$$

⇒ Higher order contributions will be small.

The maximum value of τ is determined based on the Pole dominance

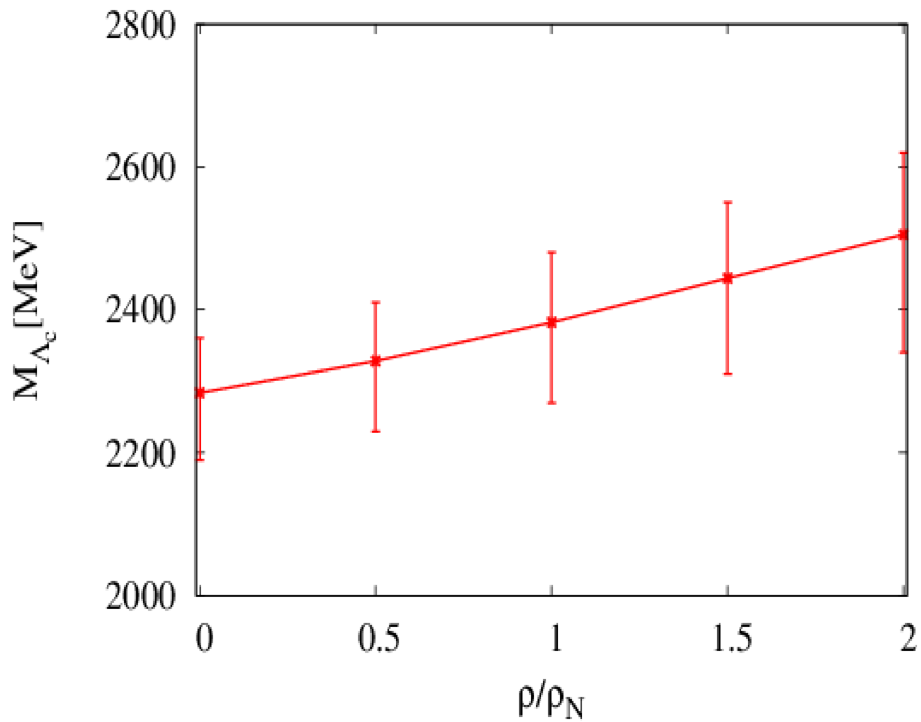
$$G_{\mathrm{SPF}}^{pole}(\tau)/G_{\mathrm{SPF}}(\tau) \ > \ 0.5$$

We use $1.25 < \tau[GeV^4] < 4.22$

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 $\rho = 1.0\rho_N$, the sfift $\Delta M_{\Lambda_c} \approx 100\text{MeV}$

The density dependence of M_{Λ_c}

Results

Comparison with previous works

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

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

Interpolating operator (Z.-G. Wang): $J_{\Lambda_c} = \epsilon^{abc}(u^{Ta} C\gamma_5 d^b)c^c$

Interpolating operator (K. Azizi et al.,):
$$\begin{aligned} J_{\Lambda_Q,\Xi_Q} = \frac{1}{\sqrt{6}}\epsilon^{abc}\Big\{&2\Big(q_1^{aT}Cq_2^b\Big)\gamma_5 Q^c + 2\beta\Big(q_1^{aT}C\gamma_5 q_2^b\Big)Q^c \\ &+\Big(q_1^{aT}CQ^b\Big)\gamma_5 q_2^c + \beta\Big(q_1^{aT}C\gamma_5 Q^b\Big)q_2^c \\ &+\Big(Q^{aT}Cq_2^b\Big)\gamma_5 q_1^c + \beta\Big(Q^{aT}C\gamma_5 q_2^b\Big)q_1^c\Big\} \end{aligned} \tag{2}$$

K. Azizi et al., claim that β=-1 equals to the J_{Λ_c} of Wang and suitable interpolating operator is $-0.6 \leqslant x \leqslant -0.4$ and $0.4 \leqslant x \leqslant 0.6$

$x = \cos\theta$ with $\theta = \tan^{-1}\beta$

Equation of QCD sum rule: Borel sum rule $G_{OPE}(M) = \int_{-\infty}^{\infty} \exp(-\frac{q_0^2}{M^2})\rho(q_0)dq_0$

- Up to LO in perturbative term
- Up to dimension 6 condensates
- Without parity projection

Results

Comparison with previous works

This work

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

Equation of QCD sum rule: Gaussian sum rule

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

- Up to NLO in perturbative term
- Up to dimension 8 condensates
- Parity projection

Results

Comparison with previous works

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

	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

This work:

$$\text{The mass in vacuum: } M_{\Lambda_c} = 2285 \pm 70\text{MeV}$$

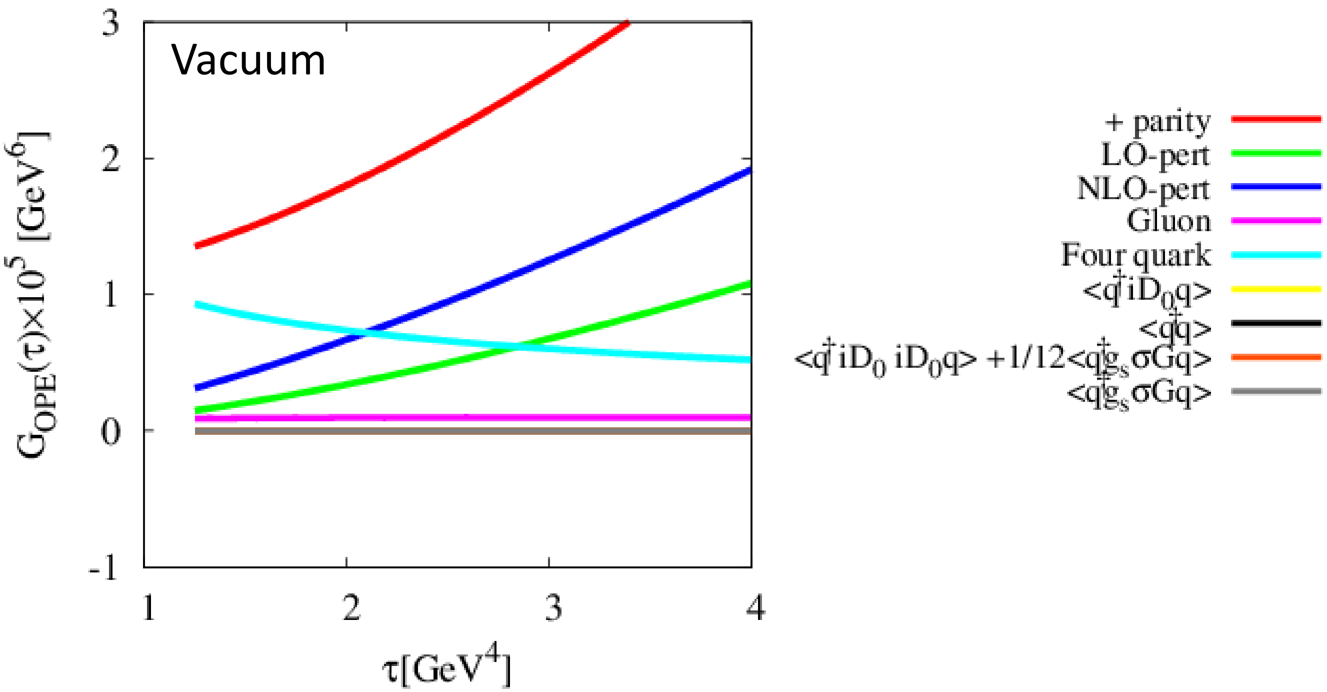
$$\text{The mass in nuclear matter at } \rho_N\text{: } M_{\Lambda_c} = 2380 \pm 100\text{MeV}$$

The mass M_{Λ_c} corresponds to $\sqrt{m^{*2}_{\Lambda_c} + \vec{q}^2} + \Sigma^v_{\Lambda_c}$

OPE of Λ_c correlation function in nuclear matter

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

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



OPE of Λ_c correlation function in nuclear matter

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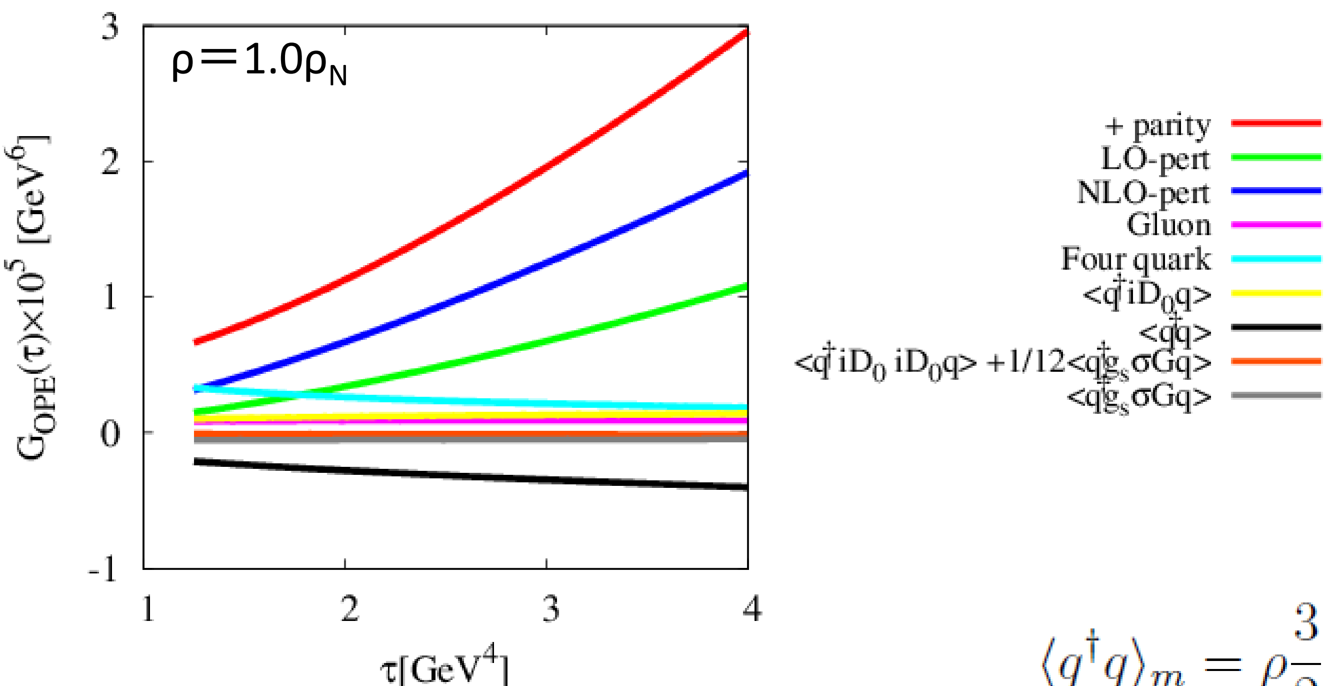
Density dependence of the $G_{OPE}(\tau)$



$$\langle q^\dagger q \rangle_m = \rho \frac{3}{2}$$

The density dependence of four quark condensate strongly affect the results.

Results

Dependence on four-quark condensates

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

Generally, the structure of four quark condensate in baryon correlation function is

$$\epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta d^c_\gamma \overline{d}^d_\delta\rangle$$

Color index: a, b, c, d, e
Supinor index: α, β, γ, δ

The constraint: color singlet, scalar, parity invariance, time reversal invariance

⇨ There are many kinds of four quark condensates:

$$\langle\overline{u}u\overline{d}d\rangle \ \langle\overline{u}\gamma_5 u\overline{d}\gamma_5 d\rangle \ \langle\overline{u}\sigma_{\mu\nu}u\overline{d}\sigma^{\mu\nu}d\rangle \quad \langle\overline{u}\gamma_\mu u\overline{d}\gamma^\mu d\rangle \ \langle\overline{u}\gamma_5\gamma_\mu u\overline{d}\gamma_5\gamma^\mu d\rangle$$

$$\langle\overline{u}\lambda^A u\overline{d}\lambda^A d\rangle \ \ldots$$

Results

Dependence on four-quark condensates

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

Generally, the structure of four quark condensate in baryon correlation function is

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Color index: a, b, c, d, e
Supinor index: α, β, γ, δ

The constraint: color singlet, scalar, parity invariance, time reversal invariance

Generally, "four quark condensate" in equation of QCD sum rule can be described by the linear combination of these condensates.

$$\langle\overline{u}u\overline{d}d\rangle \ \langle\overline{u}\gamma_5 u\overline{d}\gamma_5 d\rangle \ \langle\overline{u}\sigma_{\mu\nu}u\overline{d}\sigma^{\mu\nu}d\rangle \qquad \langle\overline{u}\gamma_\mu u\overline{d}\gamma^\mu d\rangle \ \langle\overline{u}\gamma_5\gamma_\mu u\overline{d}\gamma_5\gamma^\mu d\rangle$$

$$\langle\overline{u}\lambda^A u\overline{d}\lambda^A d\rangle \ \ldots$$

It is difficult to obtain the expectation value of each condensate.

Results

Dependence on four-quark condensates

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

Generally, the structure of four quark condensate in baryon correlation function is

$$\epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta d^c_\gamma \overline{d}^d_\delta \rangle$$

Color index: a, b, c, d, e
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To take into the density dependence of four quark condensate,

Factorization hypothesis:

$$\epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta d^c_\gamma \overline{d}^d_\delta \rangle \to \epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta \rangle \langle d^c_\gamma \overline{d}^d_\delta \rangle \propto \langle u\overline{u}\rangle\langle d\overline{d}\rangle \approx \langle \overline{q}q\rangle^2$$

Vacuum saturation, large N_c limit

$$\langle \overline{q}q\rangle^2_M \approx (\langle \overline{q}q\rangle_0 + \langle \overline{q}q\rangle_N \rho)^2$$
$$= (\langle \overline{q}q\rangle_0 + \frac{\sigma_N}{2m_q}\rho)^2 \approx \langle \overline{q}q\rangle_0^2 + \langle \overline{q}q\rangle_0 \frac{\sigma_N}{m_q}\rho$$

$$\langle \mathcal{O}\rangle_M = \langle M|\mathcal{O}|M\rangle \quad \langle \mathcal{O}\rangle_N = \langle N|\mathcal{O}|N\rangle$$

Results

Dependence on four-quark condensates

Generally, the structure of four quark condensate is $\epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta d^c_\gamma \overline{d}^d_\delta \rangle$

Color index: a, b, c, d, e
Supinor index: α, β, γ, δ

To take into the density dependence of four quark condensate,

Estimation of the expectation values in nucleon

$$\langle \overline{u}u\overline{d}d \rangle_M \approx \langle \overline{u}u\overline{d}d \rangle_0 + \underline{\langle \overline{u}u\overline{d}d \rangle_N}\rho$$

$$\langle \overline{u}\gamma_5 u\overline{d}\gamma_5 d \rangle_M \approx \langle \overline{u}\gamma_5 u\overline{d}\gamma_5 d \rangle_0 + \underline{\langle \overline{u}\gamma_5 u\overline{d}\gamma_5 d \rangle_N}\rho$$

:

These values are investigated by the model calculation.

R. Thomas, T. Hilger, and B. Kampfer, Nucl. Phys. **A795**, 19 (2007).

Results

Dependence on four-quark condensates

Generally, the structure of four quark condensate is $\epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta d^c_\gamma \overline{d}^d_\delta\rangle$

Color index: a, b, c, d, e
Supinor index: α, β, γ, δ

To take into the density dependence of four quark condensate,

Estimation of the expectation values in nucleon

Mean nucleon matrix element (to be color contracted with $\epsilon_{abc}\epsilon_{a'b'c'}$)	PCQM model [$\langle\bar{q}q\rangle_{\mathrm{vac}}$]
$\langle\bar{u}^{a'}u^a\bar{u}^{b'}u^b\rangle_N$	3.993
$\langle\bar{u}^{a'}\gamma_\alpha u^a\bar{u}^{b'}\gamma^\alpha u^b\rangle_N$	1.977

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R. Thomas, T. Hilger, and B. Kampfer, Nucl. Phys. **A795**, 19 (2007).

Results

Dependence on four-quark condensates

Generally, the structure of four quark condensate is $\epsilon^{ace}\epsilon^{bde}\langle u_\alpha^a \overline{u}_\beta^b d_\gamma^c \overline{d}_\delta^d \rangle$

Color index: a, b, c, d, e
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To take into the density dependence of four quark condensate,

Estimation of the expectation values in nucleon

Mean nucleon matrix element (to be color contracted with $\epsilon_{abc}\epsilon_{a'b'c'}$)	PCQM model $[\langle \bar{q}q \rangle_{\mathrm{vac}}]$
$\langle \bar{u}^{a'} u^a \bar{u}^{b'} u^b \rangle_N$	3.993
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Results

Dependence on four-quark condensates

Generally, the structure of four quark condensate is $\epsilon^{ace}\epsilon^{bde}\langle u^a_\alpha \overline{u}^b_\beta d^c_\gamma \overline{d}^d_\delta \rangle$

Color index: a, b, c, d, e
Supinor index: α, β, γ, δ

To take into the density dependence of four quark condensate,

Factorization hypothesis:

Four quark condensate: $“\langle \overline{q}q\overline{q}q \rangle_0” + \langle \overline{q}q \rangle_0 \frac{1}{6}\frac{\sigma_N}{m_q}\rho$

≈ 1.5

Estimation of the expectation values in nucleon

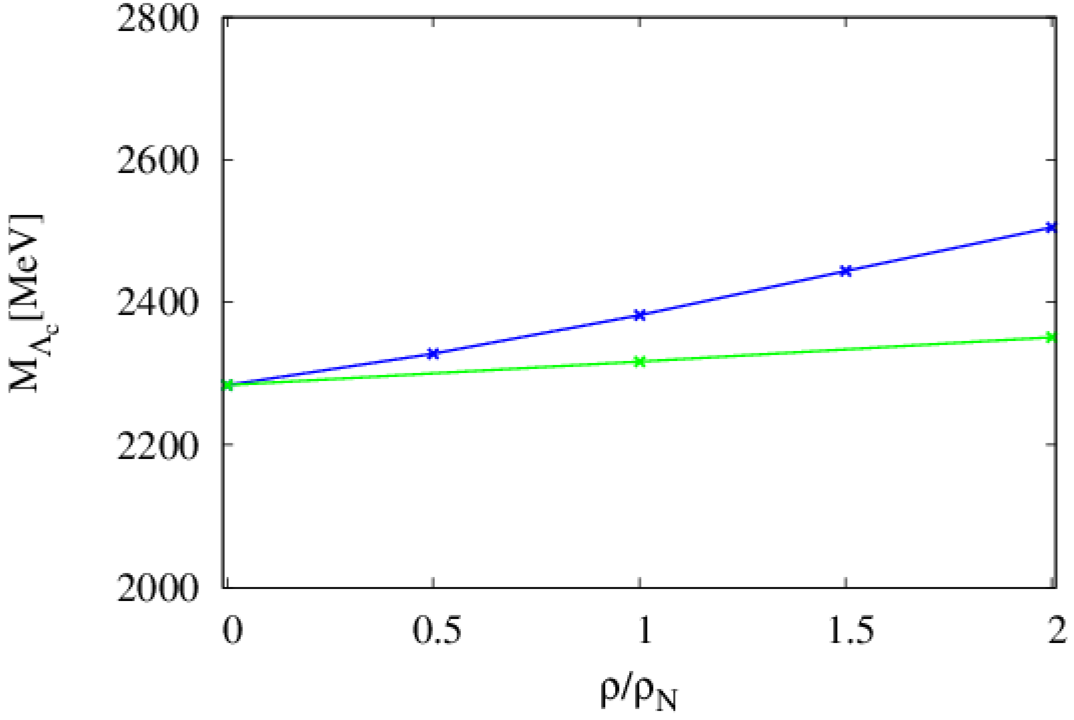
preliminary

Four quark condensate: $“\langle \overline{q}q\overline{q}q \rangle_0” + \langle \overline{q}q \rangle_0 \, 0.234\rho$

The density dependence is weaker than it by factorization hypothesis.

Results

preliminary



Factorization hypothesis:

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

Estimation of the expectation values in nucleon:

At ρ＝1.0ρ_N, the sfift $\Delta M_{\Lambda_c} \approx 30\mathrm{MeV}$

In both cases, the mass increases as the density increases.

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.

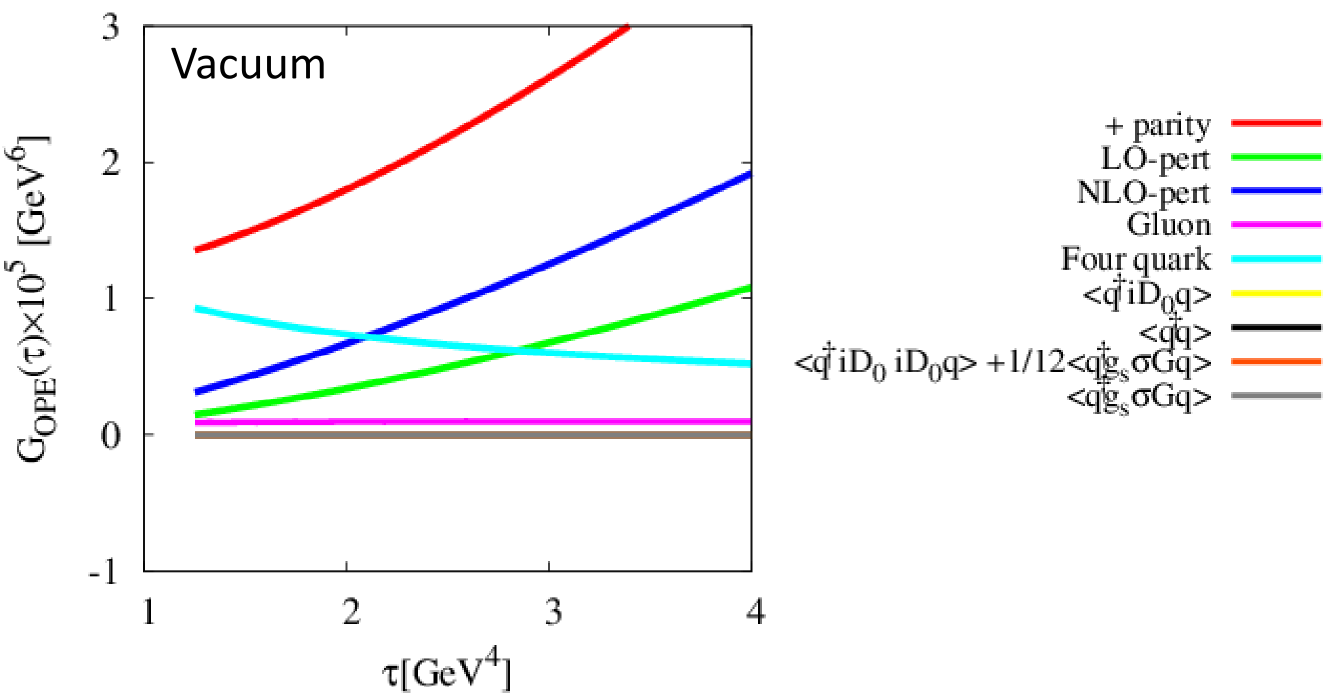
Future plan

- 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

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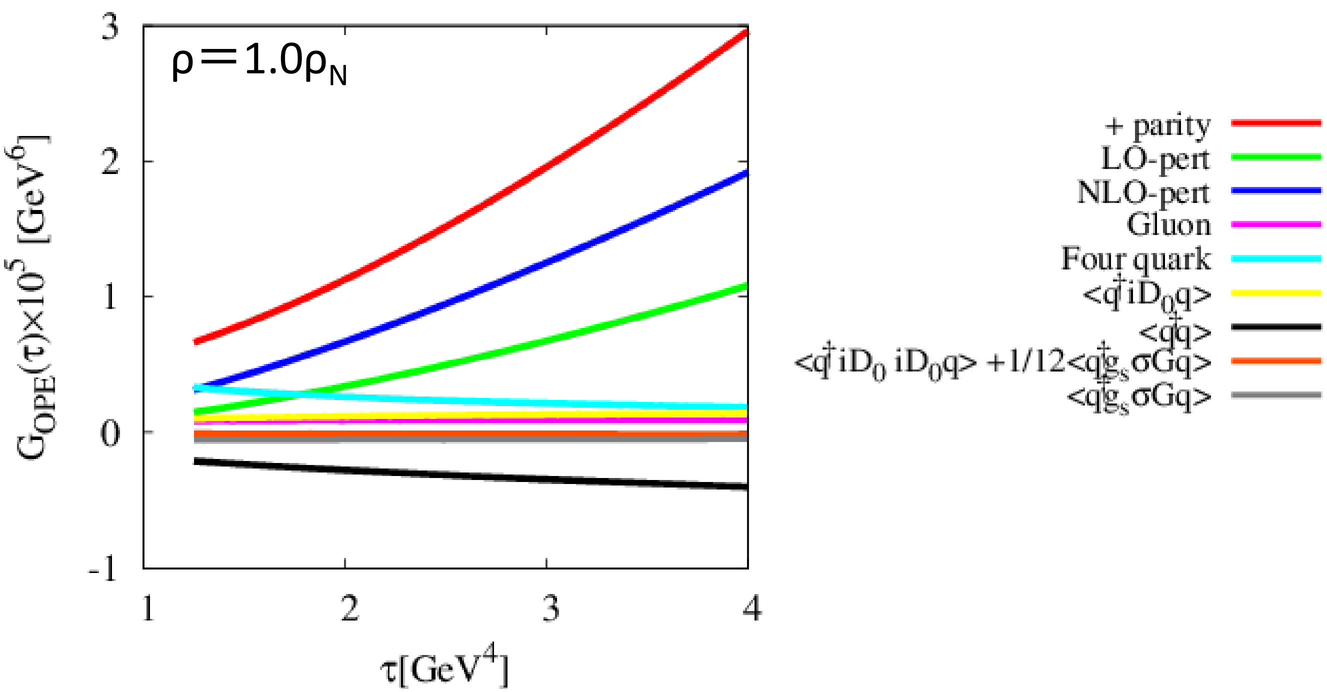

Backup slides

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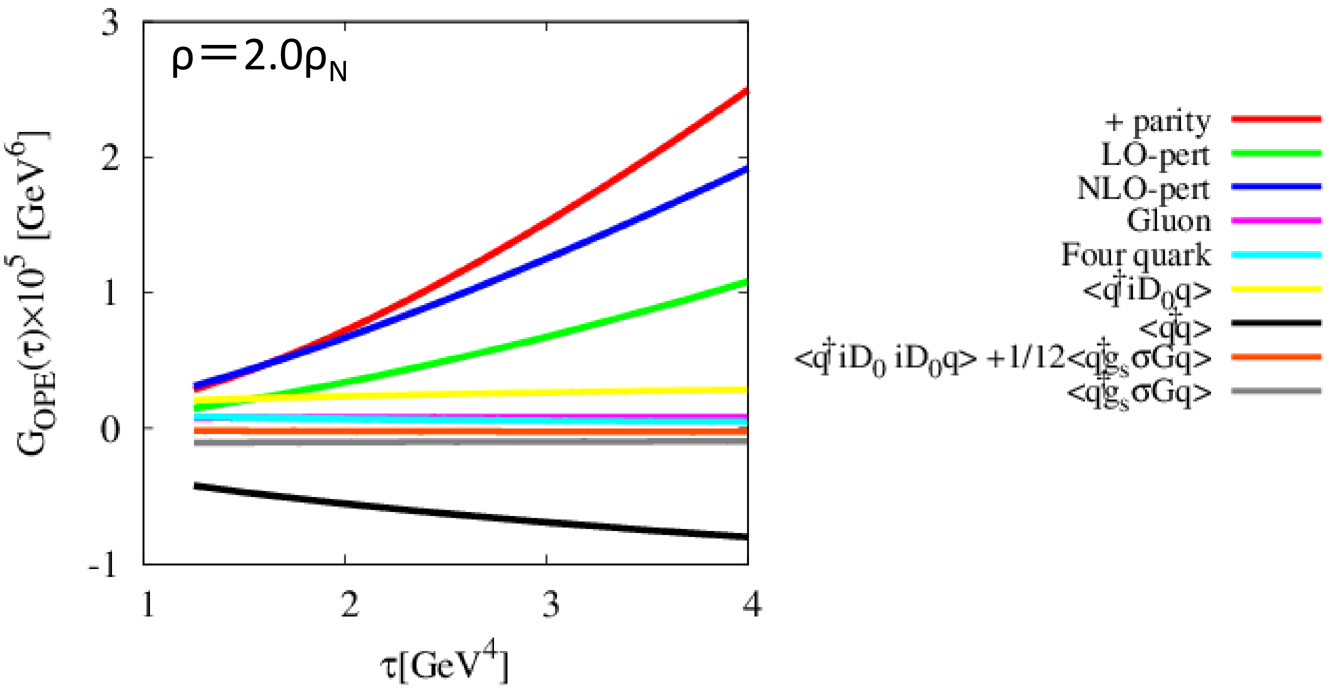


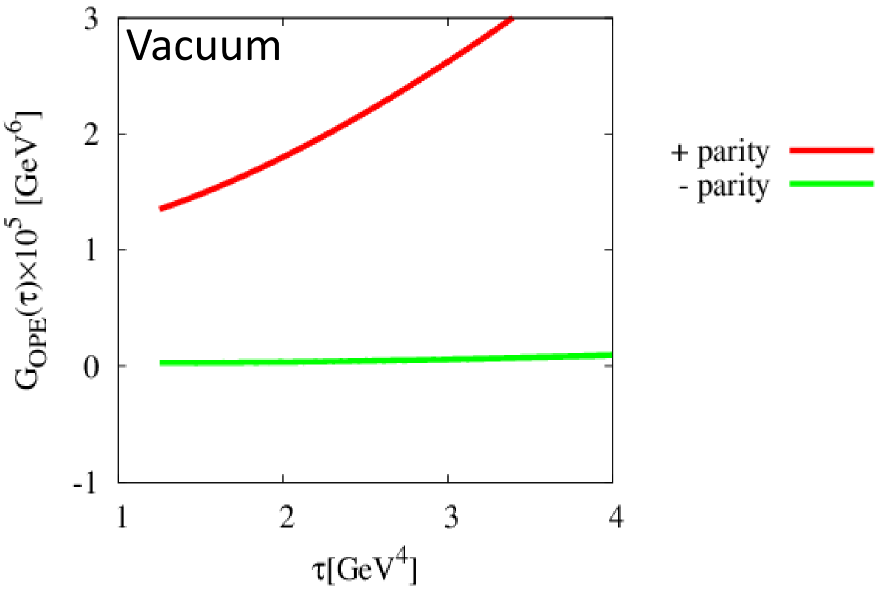
Backup slides

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

Backup slides

Four quark condensate

Projection

Color

$$\overline{q}^{a'}q^a\overline{q}^{b'}q^b = \frac{1}{9}(\overline{q}q\overline{q}q)\delta_{aa'}\delta_{bb'} + \frac{1}{32}(\overline{q}\lambda^A q\overline{q}\lambda^A q)\lambda^B_{aa'}\lambda^B_{bb'}$$

Supinor

$$\overline{q}^{a'}_{1\alpha}q^a_{2\beta}\overline{q}^{b'}_{3\gamma}q^b_{4\delta} = \frac{1}{16}\sum_{\Gamma,\Gamma'}\left(\overline{q}^{a'}_1\Gamma q^a_2\overline{q}^{b'}_3\Gamma' q^b_4\right)\Gamma_{\beta\alpha}\Gamma'_{\delta\gamma}$$

$$\Gamma = 1, \gamma_5, \gamma_\mu, i\gamma_5\gamma_\mu, \sigma_{\mu\nu}$$

$$\overline{q}^{a'}_{1\alpha}q^a_{2\beta}\overline{q}^{b'}_{3\gamma}q^b_{4\delta}$$

$$= \frac{1}{16}\sum_{\Gamma,\Gamma'}\epsilon_\Gamma\ \epsilon_{\Gamma'}\left(\frac{1}{9}\left(\overline{q}_1\Gamma q_2\overline{q}_3\Gamma' q_4\right)\delta^{aa'}\delta^{bb'} + \frac{1}{32}\left(\overline{q}_1\lambda^A\Gamma q_2\overline{q}_3\lambda^A\Gamma' q_4\right)\lambda^B_{aa'}\lambda^B_{bb'}\right)\Gamma_{\beta\alpha}\Gamma'_{\delta\gamma}$$

Backup slides

Λ_Q interpolating operator:

$$J^1_{\Lambda_Q} = \epsilon^{abc}(q^{T\,a} C q^b)\gamma_5 Q^c,$$

$$J^2_{\Lambda_Q} = \epsilon^{abc}(q^{T\,a} C \gamma_5 q^b) Q^c,$$

$$J^3_{\Lambda_Q} = \epsilon^{abc}(q^{T\,a} C \gamma_5 \gamma_\mu q^b)\gamma_\mu Q^c$$