QCD和則による核物質中のΛcの解析

東京工業大学　大谷圭介

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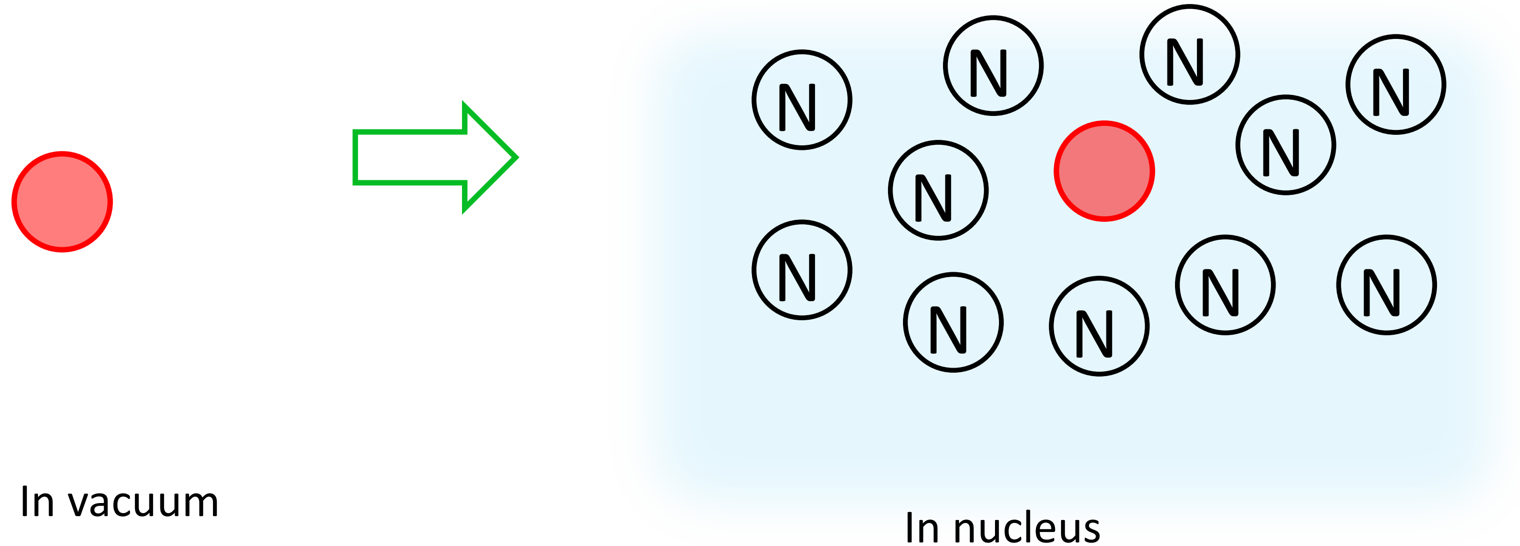
K. Ohtani, K. Araki and M. Oka, arXiv:1704.04902 [hep-ph] (to be published in PRC)

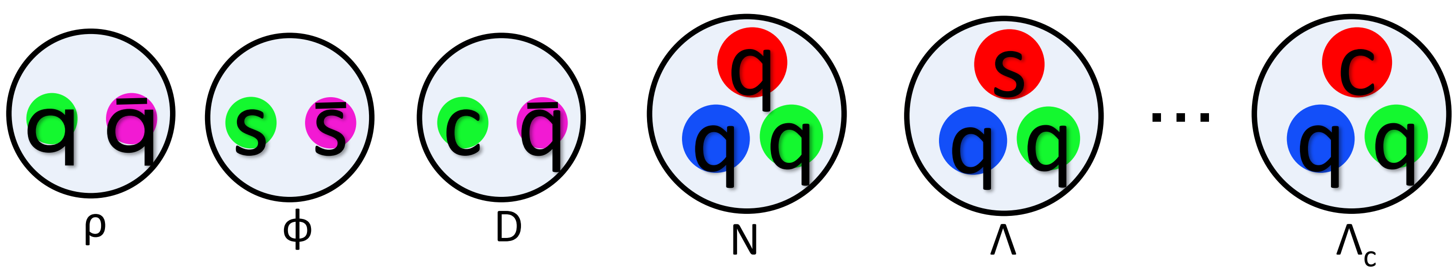
Introduction

Hadrons in nuclear matter:



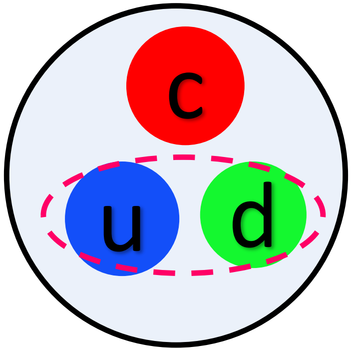
- Interaction between the prove hadron and nucleon
- The relation between the mass of the prove hadron and the partial restoration of chiral symmetry

Many studies about



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

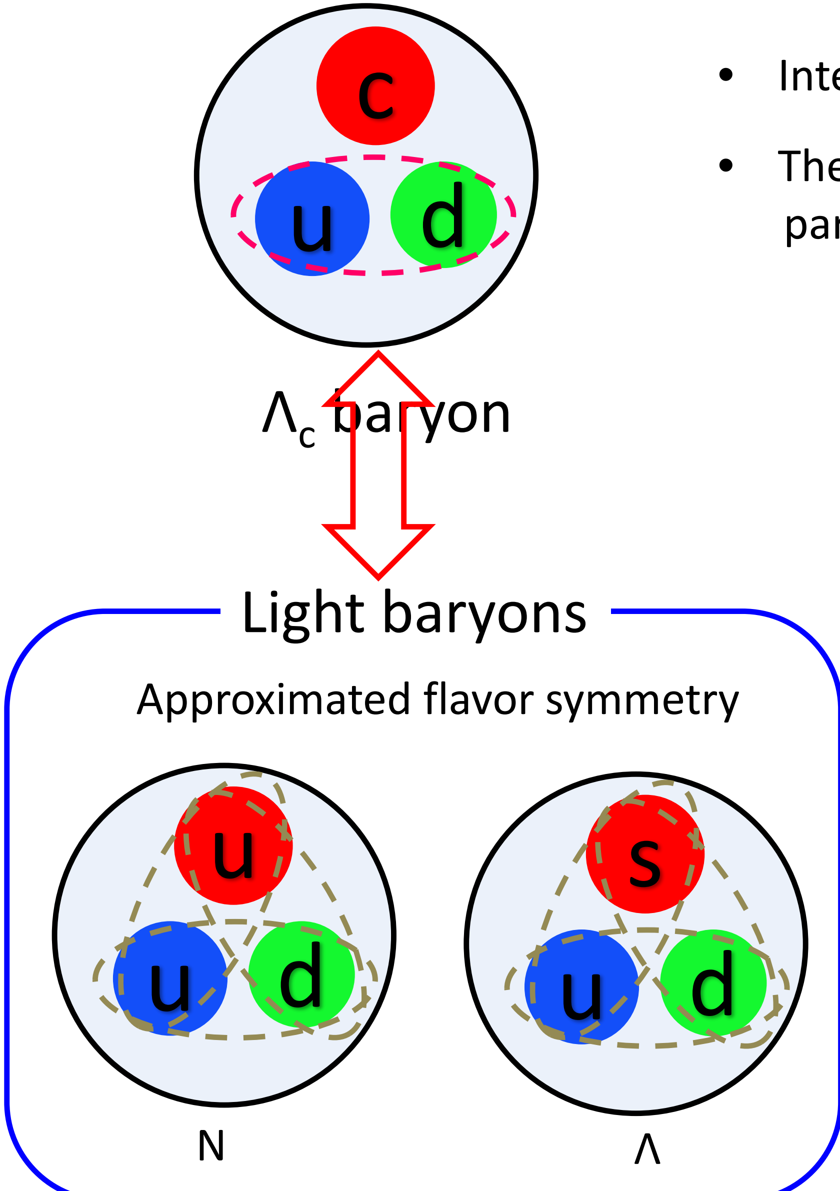
Introduction



Λ_c baryon

- Interaction between Λ_c and nucleon
- The relation between the mass of Λ_c and the partial restoration of the chiral symmetry

Introduction

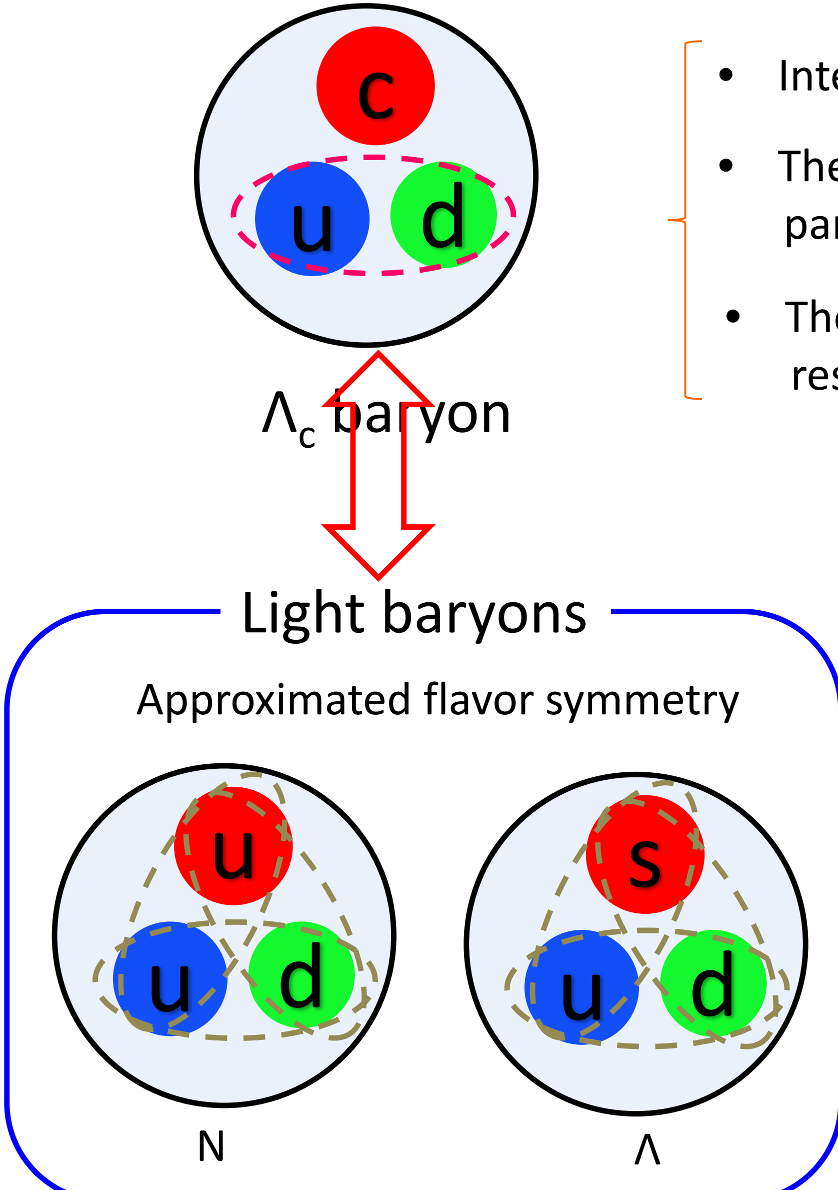


- Interaction between Λ_c and nucleon
- The relation between the mass of Λ_c and the partial restoration of the chiral symmetry

New points in Λ_c baryon:

The di-quark properties may be investigated through the Λ_c baryon analyses

Introduction



- Interaction between Λ_c and nucleon
- The relation between the mass of Λ_c and the partial restoration of the chiral symmetry
- The relation between the di-quark and partial restoration of chiral symmetry.

We investigate Λ_c baryon in nuclear matter by using 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)

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In vacuum

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

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Results in Vacuum

Results in nuclear matter

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

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Results in Vacuum

Results in nuclear matter

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

We improve the Λ_C QCD sum rule and carry out the analyses.

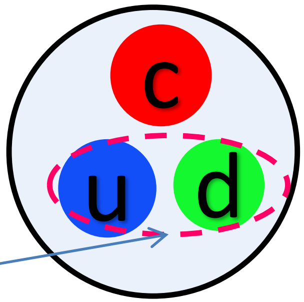
- Recalculation of OPE
- α_s corrections (NLO) — S. Groote, et al., Eur. Phys. J. C58, 355 (2008)
- higher order contributions of condensates
- Parity projection

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)

Λ_c QCD sum rules

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Parity projected
QCD sum rule

⇩

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

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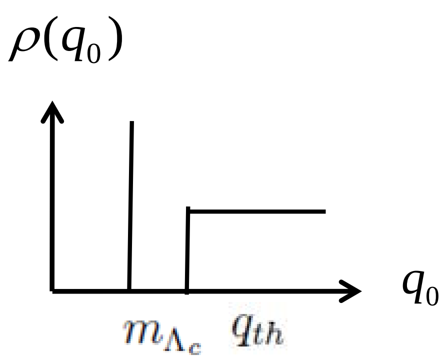
Hadronic spectral function



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

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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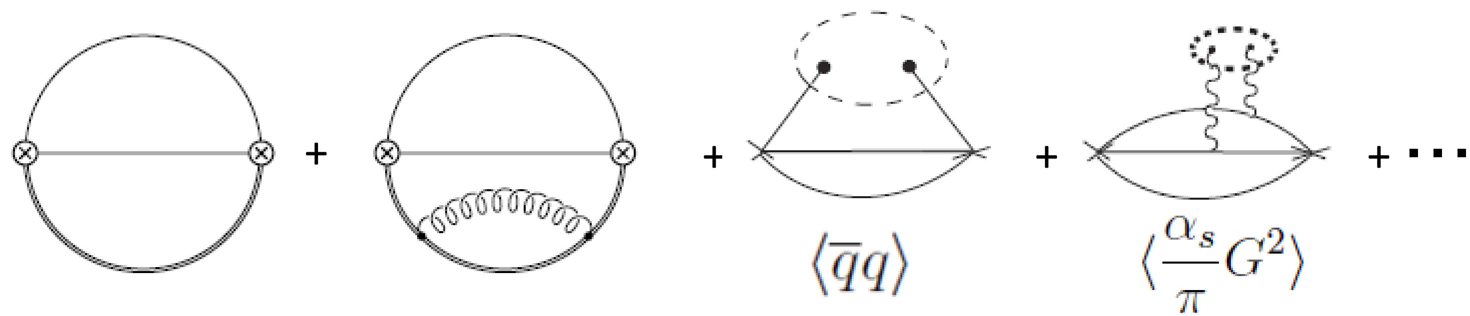
Parity projected QCD sum rule

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

Calculated by operator product expansion(OPE)

$G_{OPE}(\tau)$ =



Non-perturbative contributions are expressed by condensates:

$\langle \overline{q} q \rangle_m$ $\langle \frac{\alpha_s}{\pi} G^2 \rangle_m$ $\langle \overline{q} q \overline{q} q \rangle_m$ ⋯ (In nuclear matter)

Density dependence

$$\langle \overline{q} q \rangle_m = \langle \overline{q} q \rangle_0 + \rho \frac{\sigma_N}{2m_q}$$

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

:

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

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

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Calculated by operator product expansion(OPE)

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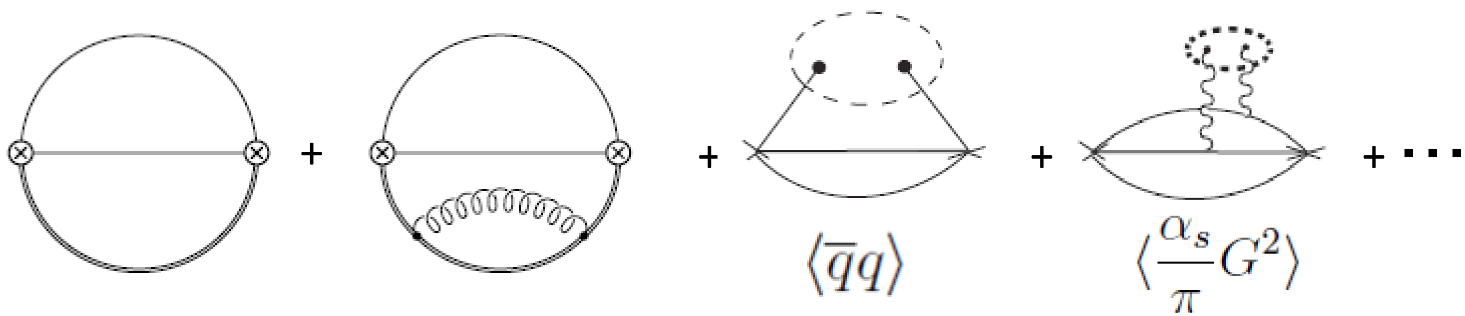


Non-perturbative contributions are expressed by condensates:

$\langle \overline{q}q\rangle_m$ $\langle \frac{\alpha_s}{\pi}G^2\rangle_m$ $\langle \overline{q}q\overline{q}q\rangle_m$ $\cdots$ (In nuclear matter)

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

Density dependence

$$\langle \overline{q}q\rangle_m = \langle \overline{q}q\rangle_0 + \rho\frac{\sigma_N}{2m_q}$$

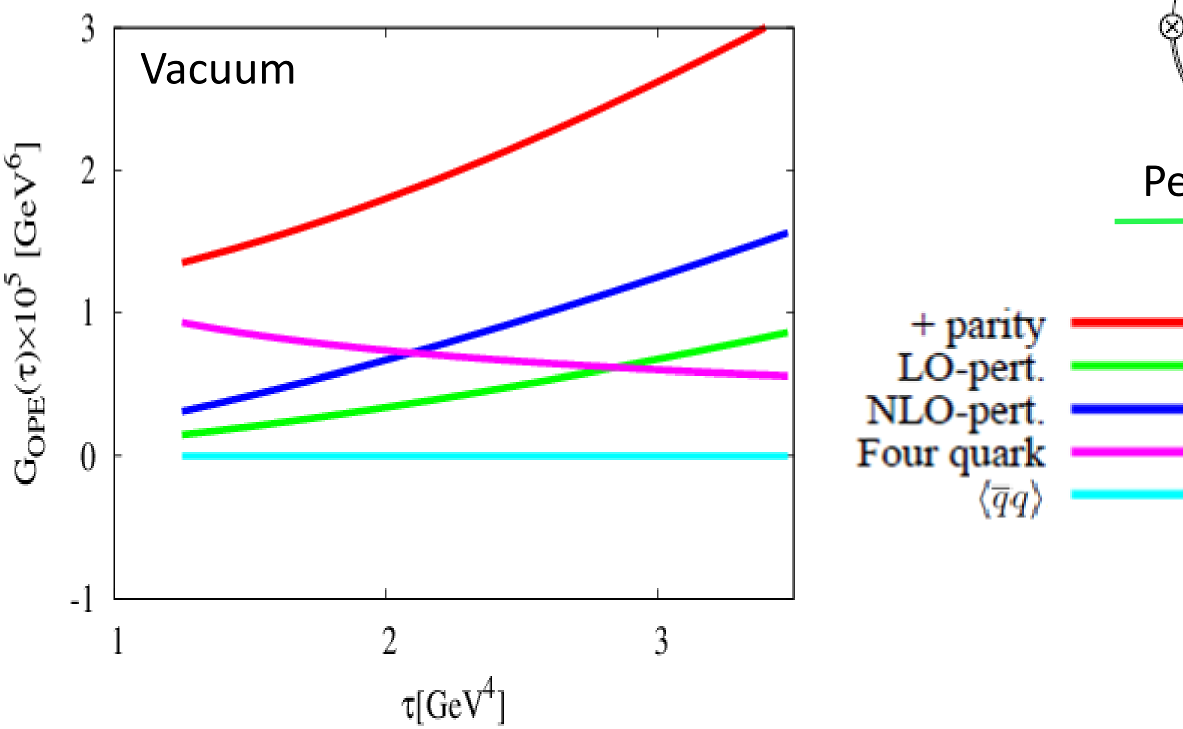
$$\langle q^\dagger q\rangle_m = \rho\frac{3}{2}$$

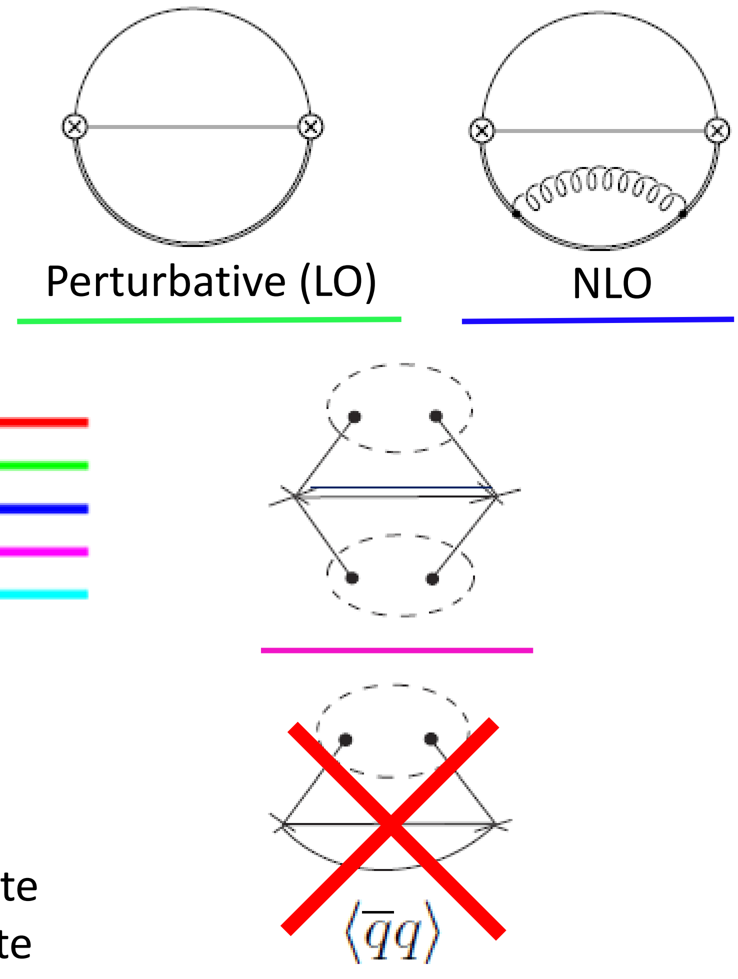
$\vdots$

OPE of Λ_c correlation function

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

Behavior of $G_{OPE}(\tau)$:





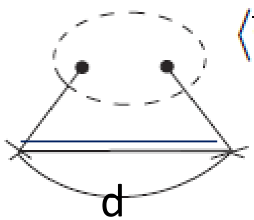
- Large contribution of four quark condensate
- Small contribution of two quark condensate

OPE of Λ_c correlation function

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

Suppression of contribution of chiral condensate:

Diagram:



$\langle \overline{u} u \rangle$

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

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

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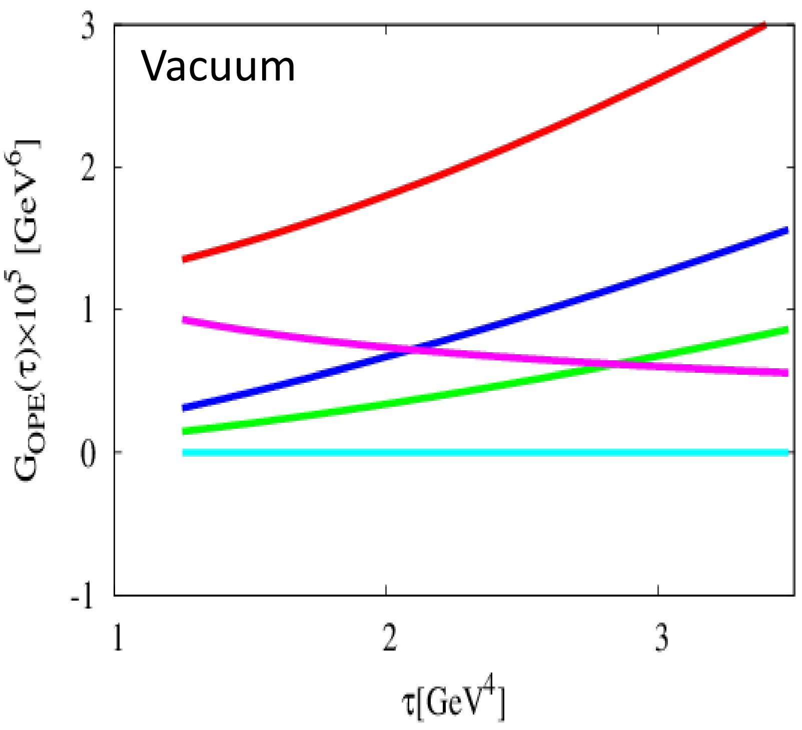

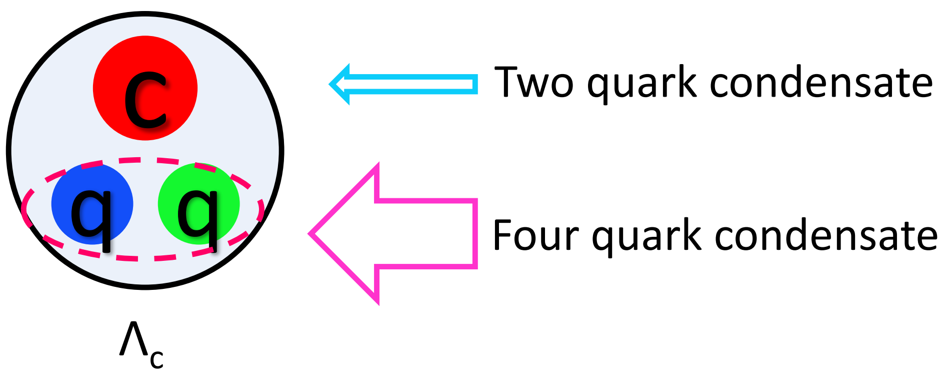

Λ_c feels in-medium modification from the four quark condensate.

OPE of Λ_c correlation function

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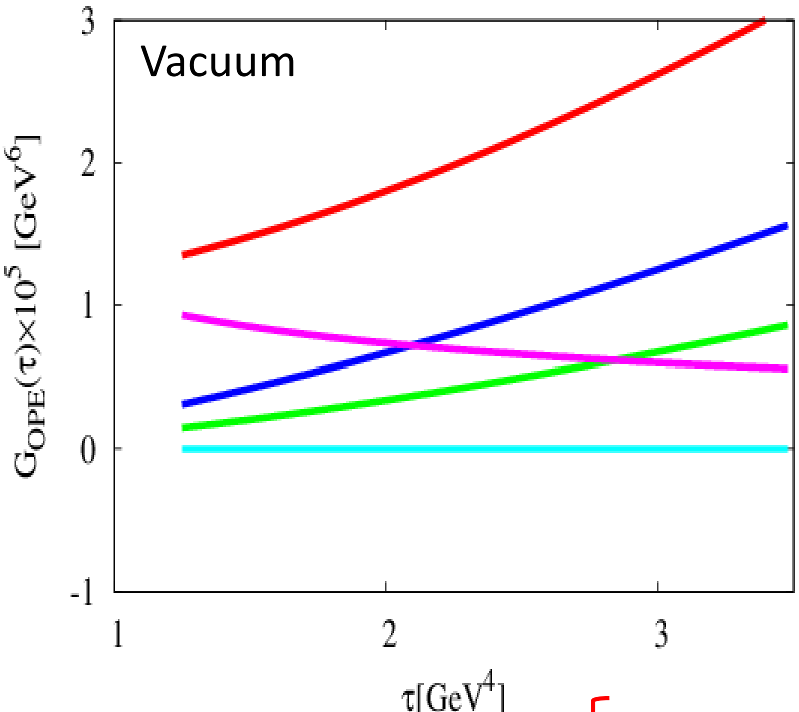

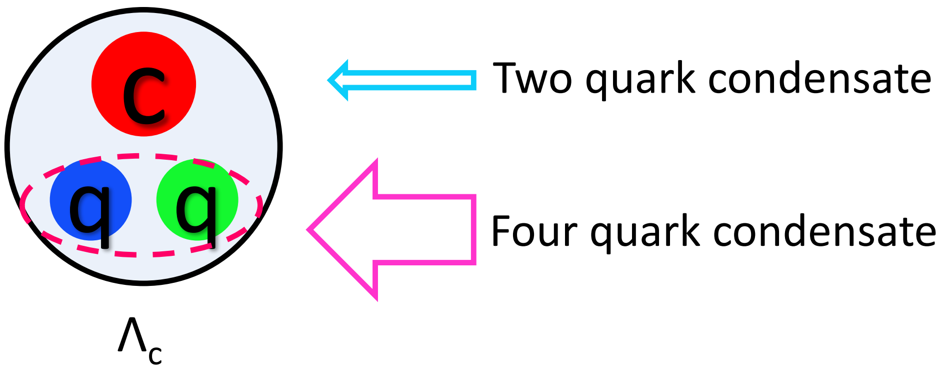

- The relation between the four quark condensate and the spontaneous breaking of the chiral symmetry
- The density dependence of the four quark condensate.

Structure of the four quark condensate

The structure of the four quark condensate "$\langle \overline{q} q \overline{q} q \rangle_m$" in Λ_c interpolating operator:

$$
\begin{aligned}
\text{“}\langle \overline{q} q \overline{q} q \rangle_m\text{”} = & \langle (\epsilon^{abc} u^a C \gamma_5 d^b) \cdot (\epsilon^{efc} \overline{d}^f \gamma_5 C \overline{u}^e) \rangle_m \\
& = -\tfrac{1}{4} \big[\langle \overline{d}^f d^b \overline{u}^e u^a \rangle_m + \langle \overline{d}^f \gamma_5 d^b \overline{u}^e \gamma_5 u^a \rangle_m \\
& \quad - \tfrac{1}{2} \langle \overline{d}^f \sigma_{\mu\nu} d^b \overline{u}^e \sigma^{\mu\nu} u^a \rangle_m + \langle \overline{d}^f \gamma_\mu d^b \overline{u}^e \gamma^\mu u^a \rangle_m \\
& \quad + \langle \overline{d}^f \gamma_5 \gamma_\mu d^b \overline{u}^e \gamma_5 \gamma^\mu u^a \rangle_m \big] \epsilon^{abc} \epsilon^{efc}.
\end{aligned}
$$

decomposed into the independent four-quark condensates.

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The structure of the four quark condensate "$\langle\overline{q}q\overline{q}q\rangle_m$" in Λ_c interpolating operator:

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& = -\tfrac{1}{4}\big[\langle\overline{d}^f d^b\overline{u}^e u^a\rangle_m + \langle\overline{d}^f\gamma_5 d^b\overline{u}^e\gamma_5 u^a\rangle_m \\
& \quad - \tfrac{1}{2}\langle\overline{d}^f\sigma_{\mu\nu}d^b\overline{u}^e\sigma^{\mu\nu}u^a\rangle_m + \langle\overline{d}^f\gamma_\mu d^b\overline{u}^e\gamma^\mu u^a\rangle_m \\
& \quad + \langle\overline{d}^f\gamma_5\gamma_\mu d^b\overline{u}^e\gamma_5\gamma^\mu u^a\rangle_m\big]\epsilon^{abc}\epsilon^{efc}.
\end{aligned}
$$

decomposed into the independent four-quark condensates.

⇨ The four-quark condensate is singlet under the chiral transformation.

Its in-medium modification is not directly related to the partial restoration of chiral symmetry.

Density dependence of the four quark condensate

Two approaches for evaluating in-medium four quark condensate

Factorization hypothesis:
(Justified in large N_c limit)

$$“\langle\overline{q}q\overline{q}q\rangle_m” = -\frac{1}{6}\left(\langle\overline{q}q\rangle_m^2 + \langle q^\dagger q\rangle_m^2\right)$$
$$= -\frac{1}{6}\left(\langle\overline{q}q\rangle_0^2 + \rho\frac{\sigma_N}{m_q}\langle\overline{q}q\rangle_0 + \left(\frac{\sigma_N^2}{4m_q^2} + \frac{9}{4}\right)\rho^2\right)$$

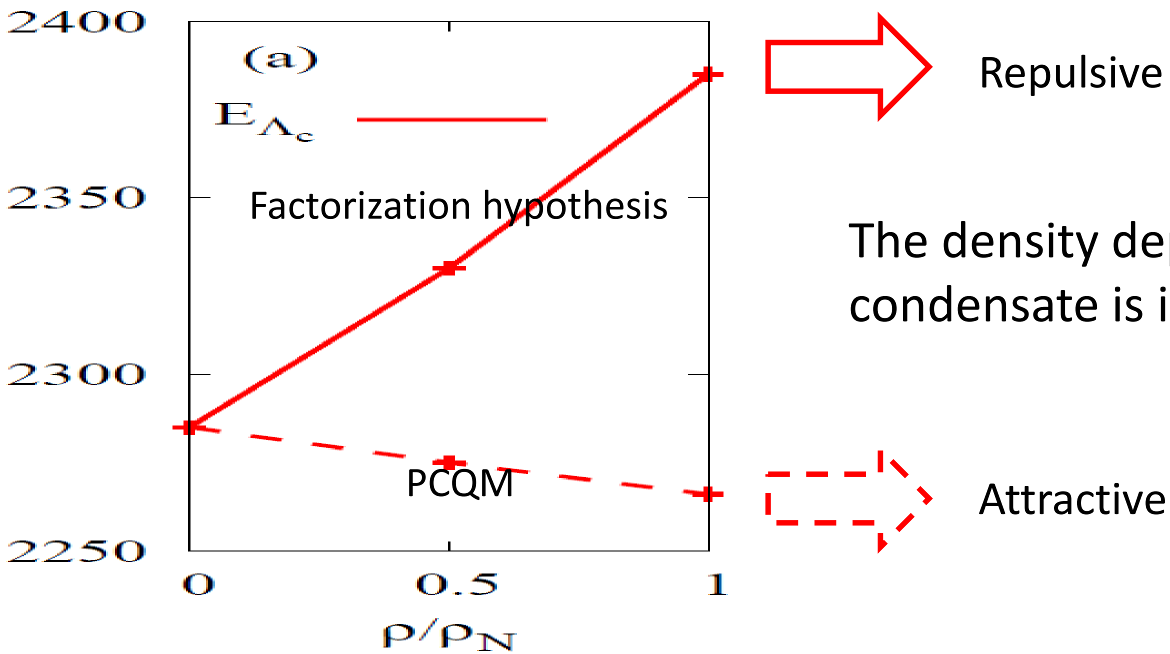
Perturbative chiral quark model (PCQM):

E.G. Drukarev, et al., Phys. Rev. D **68** 054021 (2003).
R. Thomas, T. Hilger, and B. Kampfer, Nucl. Phys. **A795**, 19 (2007).

$$“\langle\overline{q}q\overline{q}q\rangle_m” = -\frac{1}{6}\langle\overline{q}q\rangle_0^2 - \rho\frac{1}{4}0.935\langle\overline{q}q\rangle_0 + \mathcal{O}(\rho^2)$$

Using the two methods, we investigate the property of Λ_c baryon in nuclear matter.

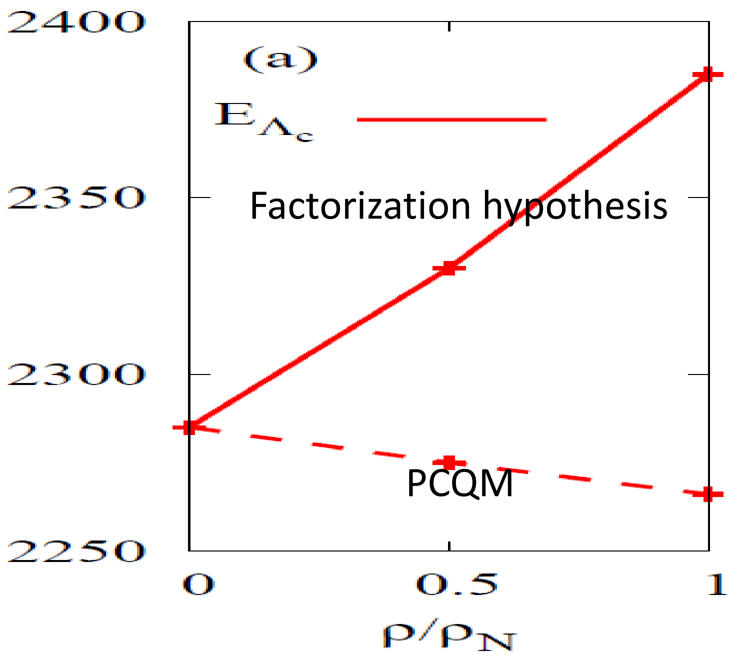
Results



The density dependence of four quark condensate is important.

The density dependence of the mass of Λ_c

Results



Repulsive

The density dependence of four quark condensate is important.

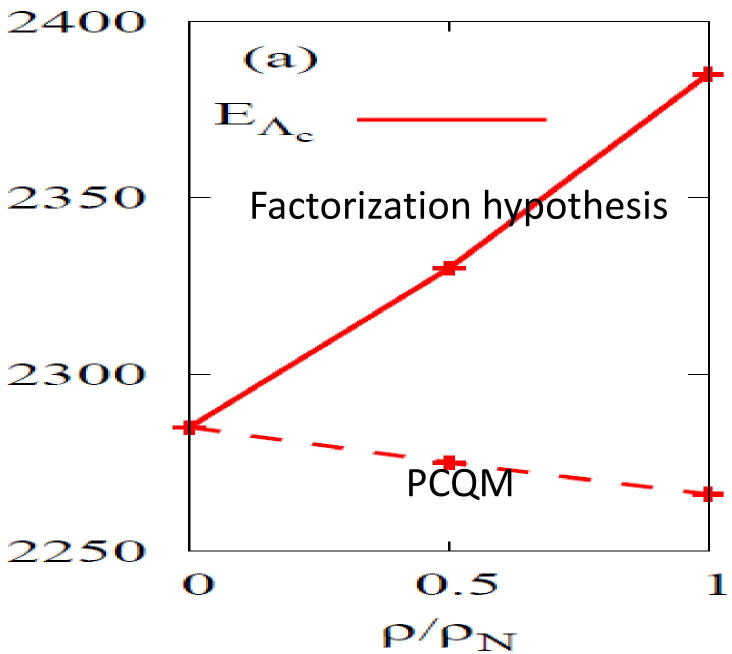
Which cases are more realistic?

Attractive

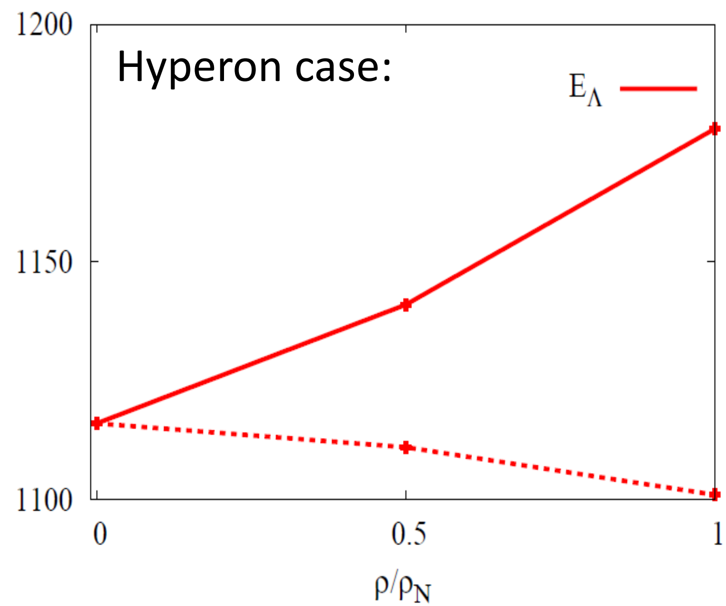
The density dependence of the mass of Λ_c

Results

Which cases are more realistic?



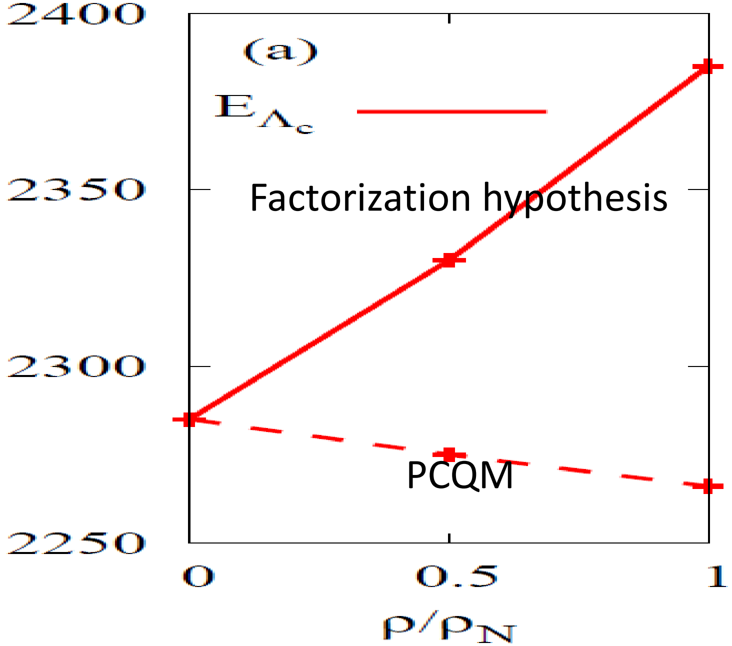
The density dependence of the mass of Λ_c



The density dependence of the mass of Λ

⇨ PCQM type (Weak density dependence of the four quark condensate) is more realistic

Results



The density dependence of the mass of Λ_c

PCQM type (Weak density dependence of the four quark condensate) is more realistic

In the case of the PCQM type,
Λ_c in nuclear matter feels weak attraction.
At normal nuclear matter density, the mass decreases about 20 MeV.

Summary

- We construct the parity projected Λ_c QCD sum rule and investigate the density dependence of the mass of Λ_c.

- The four quark condensate is important in the Λ_c QCD sum rule.

- Weak density dependence of the four quark condensate is more realistic

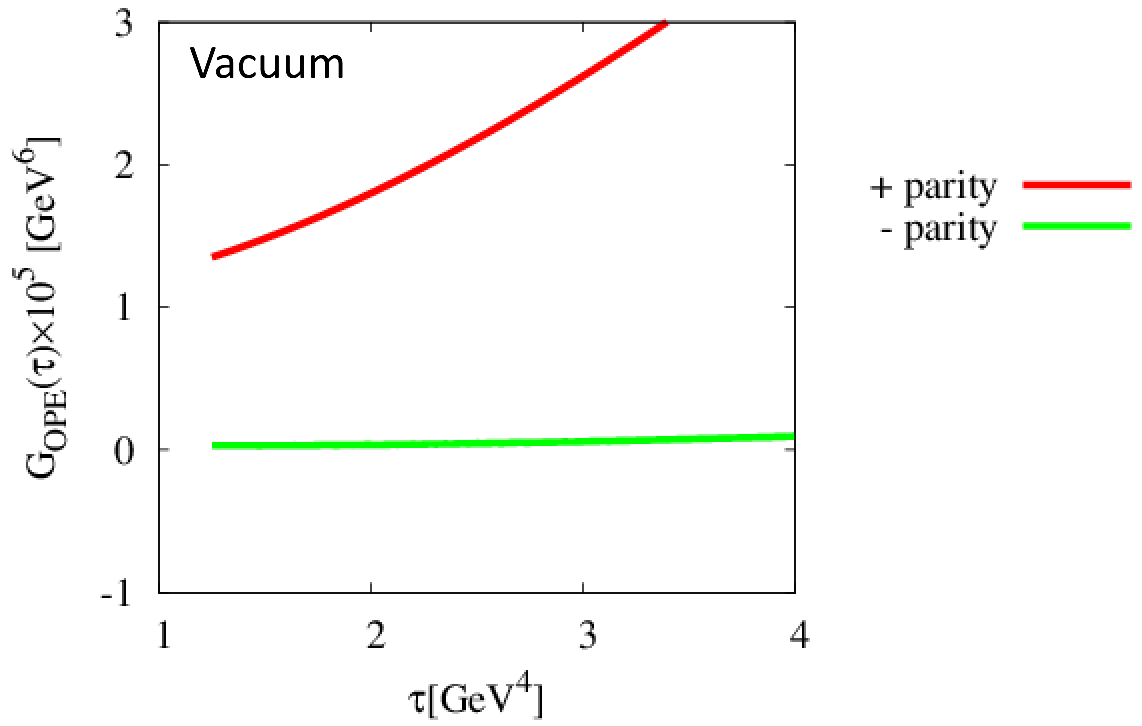
- In the case of the weak density dependence of the four quark condensate, the Λ_c baryon feels weak attraction in nuclear matter.

Future plan

- We will investigate the Σ_c baryon and Λ_c excited states.

Backup slides

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

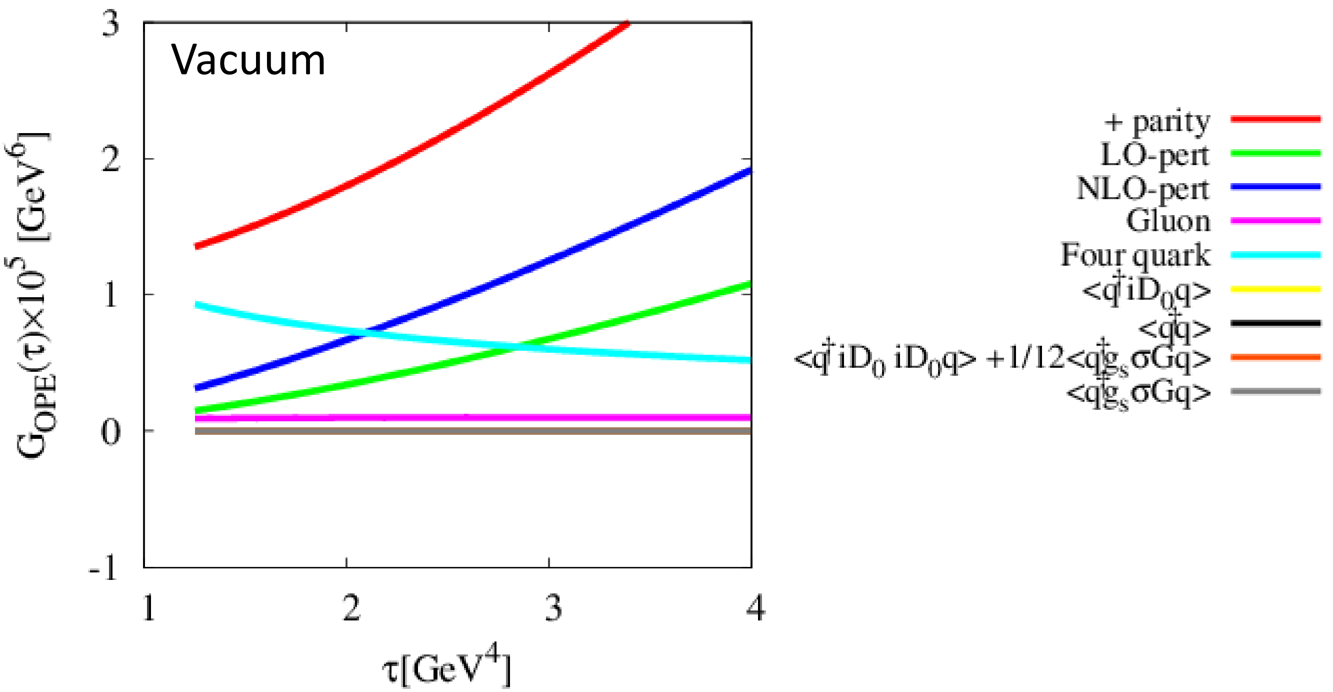


The positive parity states strongly couple to the interpolating operator J_{Λ_Q} .

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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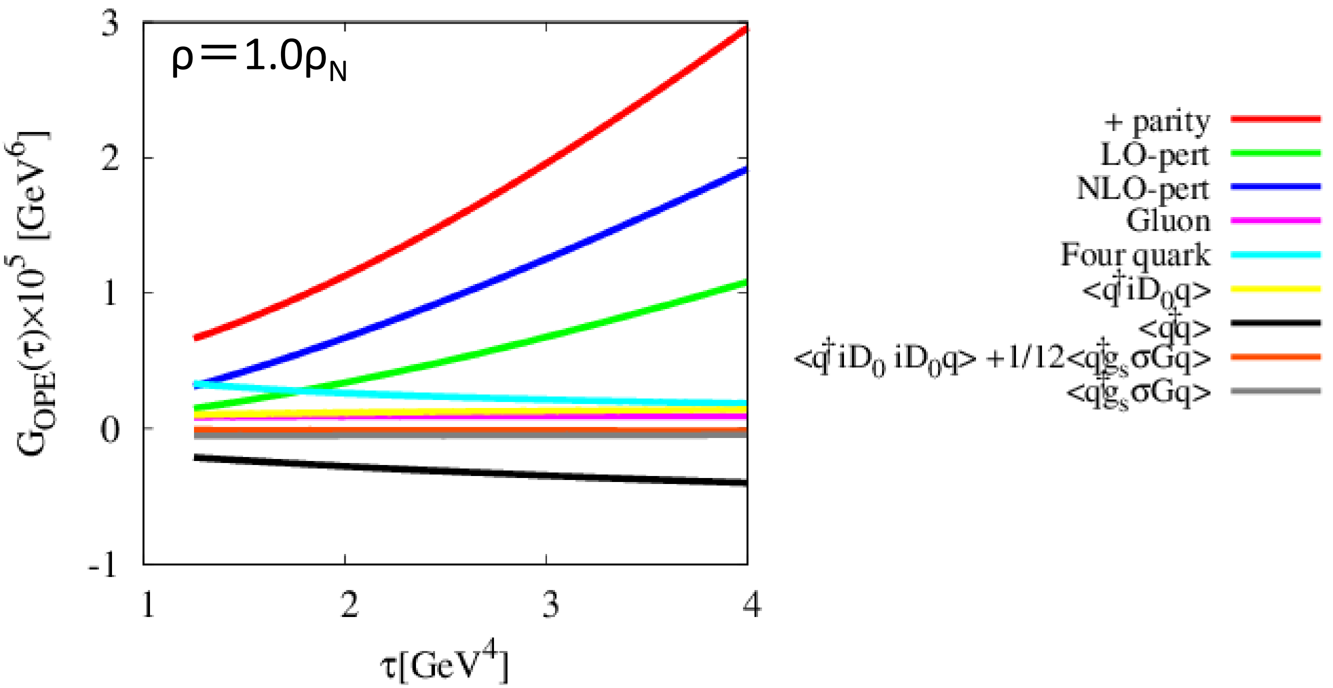

Backup slides

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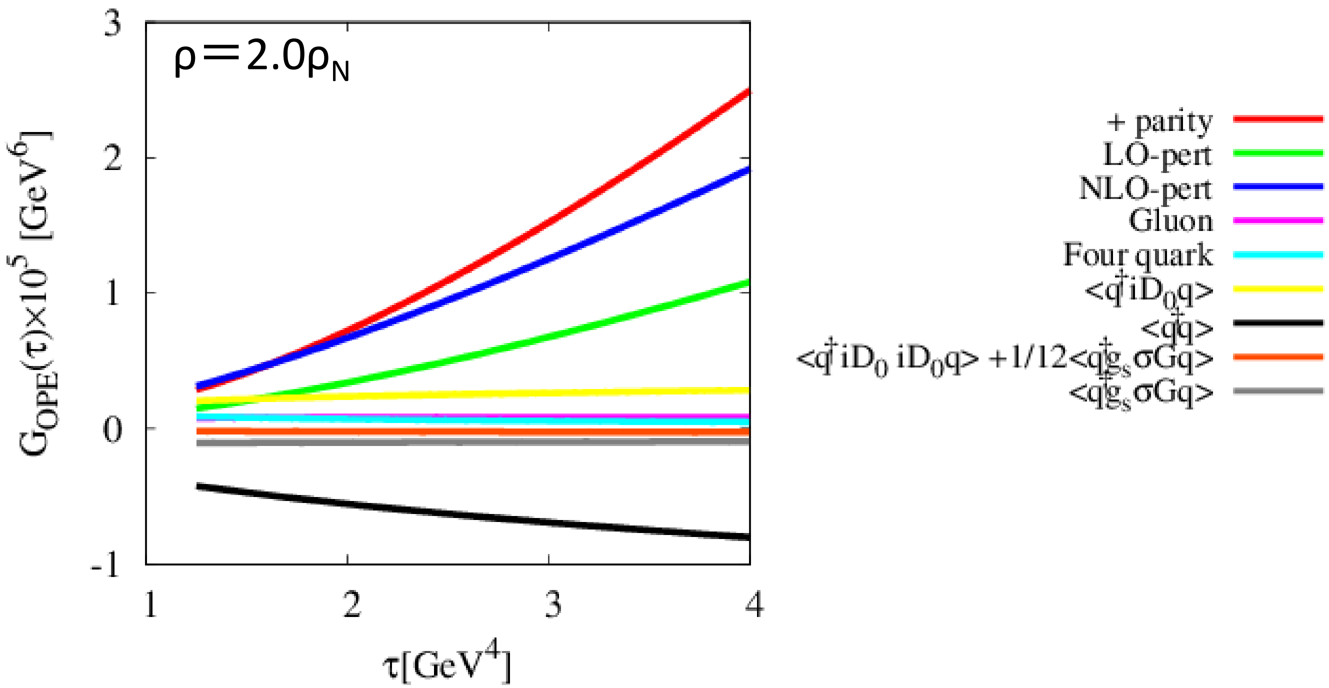


Backup slides

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

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

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

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

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

Backup slides

$$q_0\ \rho^q_{old}(q^2)|_{\vec{q}=0} = \rho^{q\ pert}_{old}(q_0) + \rho^{q\ cond}_{old}(q_0)$$

$$q_0\rho^{q\ pert}_{old}(q_0) = \frac{q_0^5}{128\pi^4}\left\{\rho^q_0(s)\left(1+\frac{\alpha_s}{\pi}\ln\frac{\mu^2}{m^2}\right)+\frac{\alpha_s}{\pi}\rho^q_1(s)\right\}\theta(q_0-m),$$

$$\rho^q_0(s) = \frac{1}{4} - 2z + 2z^3 - \frac{1}{4}z^4 - 3z^2\ln z,$$

$$\begin{aligned}\rho^q_1(s) = {} & \frac{71}{48} - \frac{565}{36}z - \frac{7}{8}z^2 + \frac{625}{36}z^3 - \frac{109}{48}z^4 \\ & - \left(\frac{49}{36} - \frac{116}{9}z + \frac{116}{9}z^3 - \frac{49}{36}z^4\right)\ln(1-z) \\ & + \left(\frac{1}{4} - \frac{17}{3}z - 11z^2 + \frac{113}{9}z^3 - \frac{49}{36}z^4\right)\ln z \\ & + \frac{2}{3}\left(1 - 8z + 8z^3 - z^4\right)\left(\mathrm{Li}_2(z) + \frac{1}{2}\ln(1-z)\ln z\right) \\ & - \frac{1}{3}z^2\left(54 + 8z - z^2\right)\left(\mathrm{Li}_2(z) - \zeta(2) + \frac{1}{2}\ln^2 z\right) \\ & - 12z^2\left(\mathrm{Li}_3(z) - \zeta(3) - \frac{1}{3}\mathrm{Li}_2(z)\ln(z)\right)\end{aligned}$$

$z = m^2 / q_0^2$

Backup slides

$$q_0\ \rho^q_{old}(q^2)|_{\vec{q}=0} = \rho^{q\ pert}_{old}(q_0) + \rho^{q\ cond}_{old}(q_0)$$

$$\begin{aligned}
q_0\rho^{q\ cond}_{old}(q_0) = &- \frac{m_Q^2}{768\pi^2}\langle\frac{\alpha_s GG}{\pi}\rangle \int_\Lambda^1 d\alpha \frac{(1-\alpha)^2}{\alpha^2}\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}}) \\
&+ \frac{q_0}{128\pi^2}\langle\frac{\alpha_s GG}{\pi}\rangle \int_\Lambda^1 d\alpha\alpha\theta(q_0 - m_Q) \\
&- q_0\frac{\langle q^\dagger iD_0 q\rangle_{\rho_N}}{6\pi^2}\int_\Lambda^1 \alpha d\alpha\theta(q_0 - m_Q) \\
&+ \frac{\langle q^\dagger iD_0 q\rangle_{\rho_N}}{3\pi^2}\int_\Lambda^1 d\alpha\alpha(1-\alpha)\left[q_0\theta(q_0 - m_Q) + q_0^2\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}})\right] \\
&+ \frac{\langle\bar{q}q\rangle^2 + \langle q^\dagger q\rangle^2}{12}\delta(q_0 - m_Q) \\
&+ \frac{1}{2^3\cdot 3}\langle\overline{q}g\sigma Gq\rangle\langle\overline{q}q\rangle \\
&\times \left(\frac{1}{8}\left(\delta''(q_0 - m_Q) - \frac{7}{m_Q}\delta'(q_0 - m_Q) + \frac{6}{m_Q^2}\delta(q_0 - m_Q)\right)\right) \\
&- q_0\left[\frac{q_0\langle q^\dagger q\rangle_{\rho_N}}{4\pi^2}\int_\Lambda^1 d\alpha\alpha(1-\alpha)\theta(q_0 - m_Q)\right. \\
&- \frac{1}{4\pi^2}\left(\langle q^\dagger iD_0 iD_0 q\rangle_{\rho_N} + \frac{1}{12}\langle q^\dagger g_s\sigma Gq\rangle_{\rho_N}\right)\int_\Lambda^1 \alpha\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}})d\alpha \\
&+ \frac{1}{4\pi^2}\left(\langle q^\dagger iD_0 iD_0 q\rangle_{\rho_N} + \frac{1}{12}\langle q^\dagger g_s\sigma Gq\rangle_{\rho_N}\right) \\
&\quad\times \int_\Lambda^1 \alpha(1-\alpha)\left(4\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}}) + q_0\delta'(q_0 - \frac{m_Q}{\sqrt{\alpha}})\right)d\alpha \\
&\left.+ \frac{\langle q^\dagger g_s\sigma Gq\rangle}{96\pi^2}\int_\Lambda^1 \alpha\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}})d\alpha\right]
\end{aligned}$$

$$\Lambda = \frac{m_Q^2}{q_0^2}$$

Backup slides

$$m\ \rho^m_{old}(q^2)|_{\vec{q}=0} = \rho^{m\ pert}_{old}(q_0) + \rho^{m\ cond}_{old}(q_0)$$

$$\rho^{m\ pert}_{old}(q_0) = \frac{m q_0^4}{128\pi^4}\left\{\rho^m_0(s)\left(1+\frac{\alpha_s}{\pi}\ln\frac{\mu^2}{m^2}\right)+\frac{\alpha_s}{\pi}\rho^m_1(s)\right\}\theta(q_0-m),$$

$$\rho^m_0(s) = 1 + 9z - 9z^2 - z^3 + 6z(1+z)\ln z$$

$$\begin{aligned}
\rho^m_1(s) = {} & 9 + \frac{665}{9}z - \frac{665}{9}z^2 - 9z^3 \\
& - \left(\frac{58}{9} + 42z - 42z^2 - \frac{58}{9}z^3\right)\ln(1-z) \\
& + \left(2 + \frac{154}{3}z - \frac{22}{3}z^2 - \frac{58}{9}z^3\right)\ln z \\
& + \frac{8}{3}(1 + 9z - 9z^2 - z^3)\left(\mathrm{Li}_2(z) + \frac{1}{2}\ln(1-z)\ln z\right) \\
& + z\left(24 + 36z + \frac{4}{3}z^2\right)\left(\mathrm{Li}_2(z) - \zeta(2) + \frac{1}{2}\ln^2 z\right) \\
& + 24z(1+z)\left(\mathrm{Li}_3(z) - \zeta(3) - \frac{1}{3}\mathrm{Li}_2(z)\ln z\right)
\end{aligned}$$

$z = m^2/s$ かつ $s = q_0^2$

Backup slides

$$m\ \rho^{m}_{old}(q^2)|_{\vec{q}=0} = \rho^{m\ pert}_{old}(q_0) + \rho^{m\ cond}_{old}(q_0)$$

$$\begin{aligned}
m\rho^{m\ cond}_{old}(q_0) = &- \frac{m_Q}{768\pi^2}\langle\frac{\alpha_s GG}{\pi}\rangle \int_{\Lambda}^{1} d\alpha \frac{(1-\alpha)^2}{\alpha}\frac{m_Q}{\sqrt{\alpha}}\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}}) \\
&+ \frac{m_Q}{192\pi^2}\langle\frac{\alpha_s GG}{\pi}\rangle \int_{\Lambda}^{1} d\alpha \frac{(1-\alpha)^3}{\alpha^2}\theta(q_0 - m_Q) \\
&+ \frac{m_Q}{128\pi^2}\langle\frac{\alpha_s GG}{\pi}\rangle \int_{\Lambda}^{1} d\alpha\theta(q_0 - m_Q) \\
&- \frac{m_Q\langle q^\dagger iD_0 q\rangle_{\rho_N}}{6\pi^2} \int_{\Lambda}^{1} d\alpha\theta(q_0 - m_Q) \\
&+ \frac{m_Q\langle q^\dagger iD_0 q\rangle_{\rho_N}}{3\pi^2} \int_{\Lambda}^{1} (1-\alpha)\left[\theta(q_0 - m_Q) + q_0\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}})\right] d\alpha \\
&+ \frac{\langle\bar{q}q\rangle^2 + \langle q^\dagger q\rangle^2}{12}\delta(q_0 - m_Q) \\
&+ \frac{1}{2^3\cdot 3}\langle\bar{q}g\sigma Gq\rangle\langle\bar{q}q\rangle \\
&\times \left(\frac{1}{8}\left(\delta''(q_0 - m_Q) - \frac{3}{m_Q}\delta'(q_0 - m_Q) + \frac{3}{m_Q^2}\delta(q_0 - m_Q)\right)\right) \\
&- q_0\left[m_Q\frac{\langle q^\dagger q\rangle_{\rho_N}}{4\pi^2} \int_{\Lambda}^{1} (1-\alpha)d\alpha\theta(q_0 - m_Q)\right. \\
&- \frac{1}{4\pi^2}\left(\langle\langle q^\dagger iD_0 iD_0 q\rangle_{\rho_N} + \frac{1}{12}\langle q^\dagger g_s\sigma Gq\rangle_{\rho_N}\right) \int_{\Lambda}^{1} \sqrt{\alpha}\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}})d\alpha \\
&+ \frac{1}{4\pi^2}\left(\langle q^\dagger iD_0 iD_0 q\rangle_{\rho_N} + \frac{1}{12}\langle q^\dagger g_s\sigma Gq\rangle_{\rho_N}\right) \\
&\quad \times \int_{\Lambda}^{1} (1-\alpha)\left(4\sqrt{\alpha}\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}}) + m_Q\delta'(q_0 - \frac{m_Q}{\sqrt{\alpha}})\right) d\alpha \\
&\left. + \frac{\langle q^\dagger g_s\sigma Gq\rangle}{96\pi^2} \int_{\Lambda}^{1} \sqrt{\alpha}\delta(q_0 - \frac{m_Q}{\sqrt{\alpha}})d\alpha\right]
\end{aligned}$$

$$\Lambda = \frac{m_Q^2}{q_0^2}$$

Backup slides

$$
\begin{aligned}
\rho^u_{old}(q_0,|\vec{q}|)|_{\vec{q}=0} = & -\frac{\langle q^\dagger q\rangle_{\rho_N}}{8\pi^2}\int_\Lambda^1 \alpha(1-\alpha)^2(q_0^2-\frac{m_Q^2}{\alpha})d\alpha\theta(q_0-m_Q) \\
& +\frac{1}{4\pi^2}\left(\langle\langle q^\dagger iD_0 iD_0 q\rangle_{\rho_N}+\frac{1}{12}\langle q^\dagger g_s\sigma G q\rangle_{\rho_N}\right)\int_\Lambda^1 \alpha d\alpha\theta(q_0-m_Q) \\
& -\frac{3}{4\pi^2}\left(\langle q^\dagger iD_0 iD_0 q\rangle_{\rho_N}+\frac{1}{12}\langle q^\dagger g_s\sigma G q\rangle_{\rho_N}\right) \\
& \times\int_\Lambda^1 \alpha(1-\alpha)\left[\theta(q_0-m_Q)+q_0\delta(q_0-\frac{m_Q}{\sqrt{\alpha}})\right]d\alpha \\
& +\frac{\langle q^\dagger g_s\sigma G q\rangle}{48\pi^2}\int_\Lambda^1 \alpha d\alpha\theta(q_0-m_Q) \\
& -q_0\left[-\frac{2\langle q^\dagger iD_0 q\rangle_{\rho_N}}{3\pi^2}\int_\Lambda^1 \alpha(1-\alpha)d\alpha\theta(q_0-m_Q)\right]
\end{aligned}
$$

$$\Lambda = \frac{m_Q^2}{q_0^2}$$

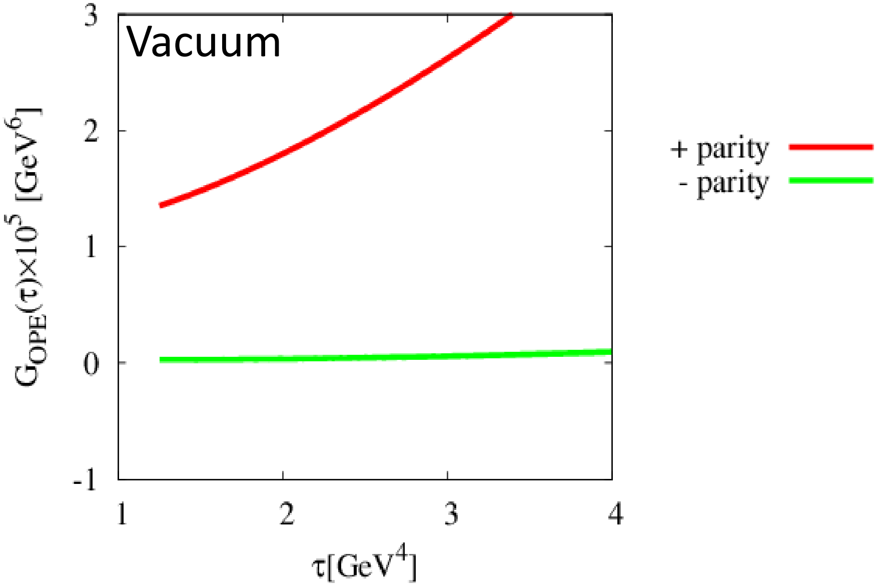
Backup slides

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

Λ_Q interpolating operator:

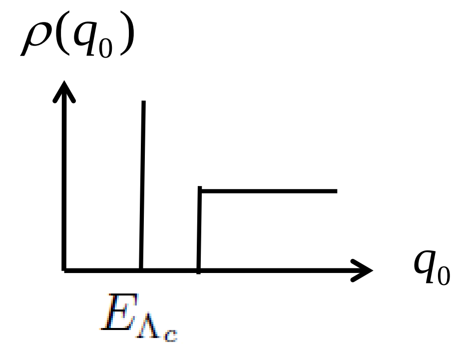
$$J^1_{\Lambda_Q} = \epsilon^{abc}(q^{T\,a} C q^b)\gamma_5 Q^c,$$

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

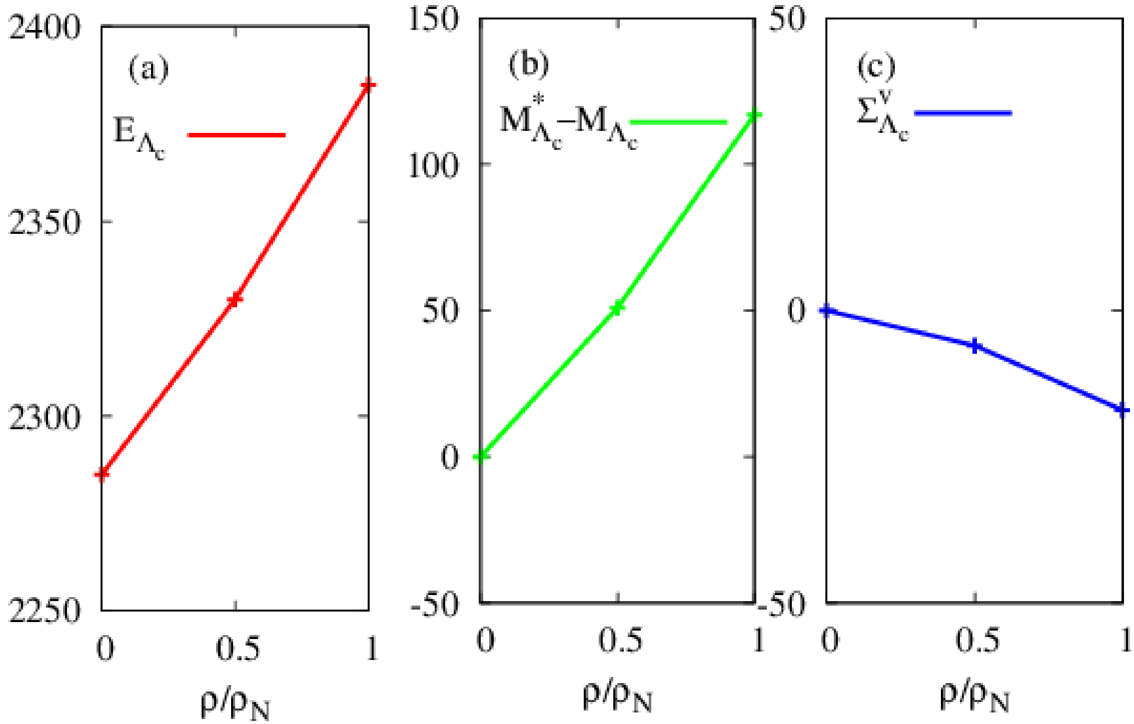
$$J^3_{\Lambda_Q} = \epsilon^{abc}(q^{T\,a} C \gamma_5 \gamma_\mu q^b)\gamma_\mu Q^c$$

Backup slides

Λ_c propagator: $$\frac{\not{q} - \not{u}\Sigma_v + M^*_{\Lambda_c}}{(q_0 - E_{\Lambda_c} + i\epsilon)(q_0 + \overline{E}_{\Lambda_c} - i\epsilon)}$$



$$E_{\Lambda_c} = \Sigma_v + \sqrt{M^{*2}_{\Lambda_c} + \vec{q}^2}$$



Backup slides

Results of Λ_b baryon