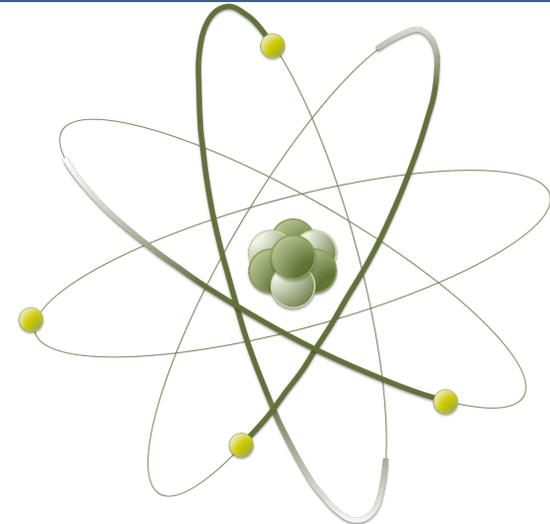


Mass modifications of singly heavy baryons in hot medium with chiral symmetry restoration

Daiki Suenaga (KMI/ Nagoya U, Japan)

References

- D. Suenaga and M. Oka, PRD 108, 014030 (2023)
- D. Suenaga and M. Oka, PRD 111, 074032 (2025)



1. Introduction

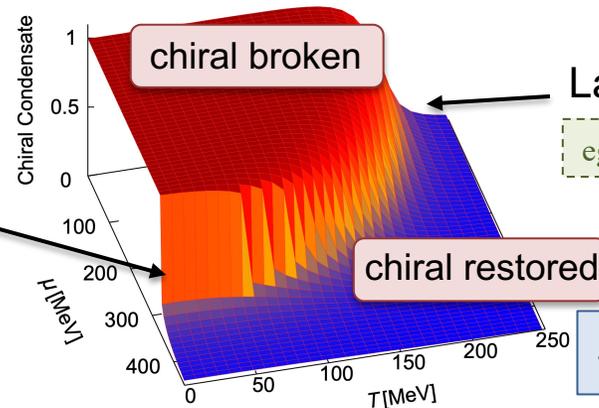
• Symmetry of QCD in medium

① $SU(3)_L \times SU(3)_R$ **chiral symmetry** restoration in medium

eg, pNJL model [Fukushima(2008)] →

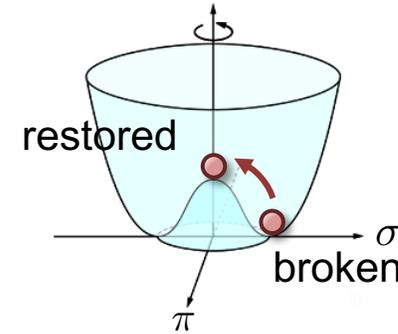
pionic atom experiment

eg, Suzuki et al (2004)



Lattice QCD

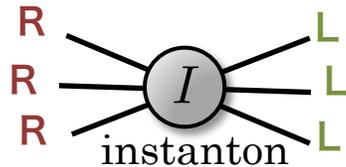
eg, Aoki et al (2008)



→ Clues to understand hadron mass generation

② Effective enhancement/restoration of $U(1)_A$ **anomaly**

eg, Gross-Pisarski-Yaffe (1981), Fejos-Hosaka(2015)



→ Clues to understand QCD topological effect to hadrons

- Examination with these symmetry aspects are inevitable to pursue systematic/comprehensive understandings of hadrons from the underlying theory: QCD

1. Introduction

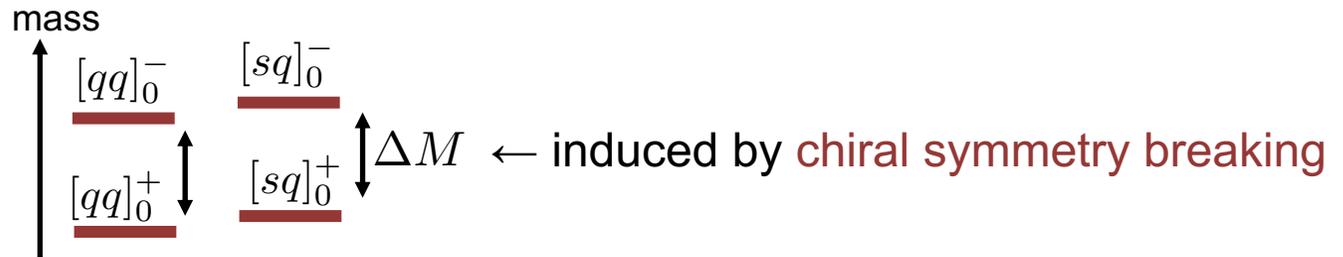
• Diquarks with QCD symmetries

eg, Hong-Sohn-Zahed (2004)

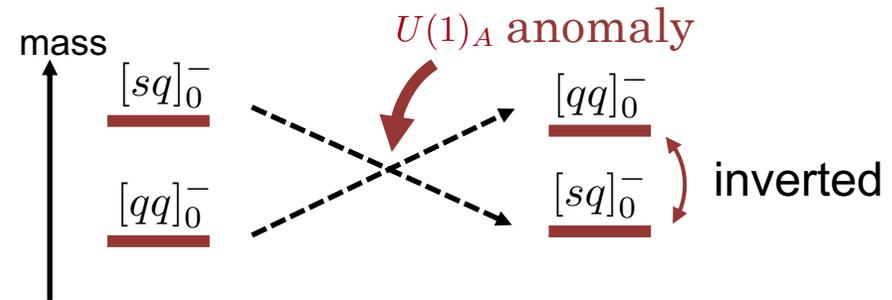
- Diquark is not “observable” but its dynamics must be governed by chiral symmetry and anomaly



i) Chiral partner structure



ii) Inverse mass hierarchy



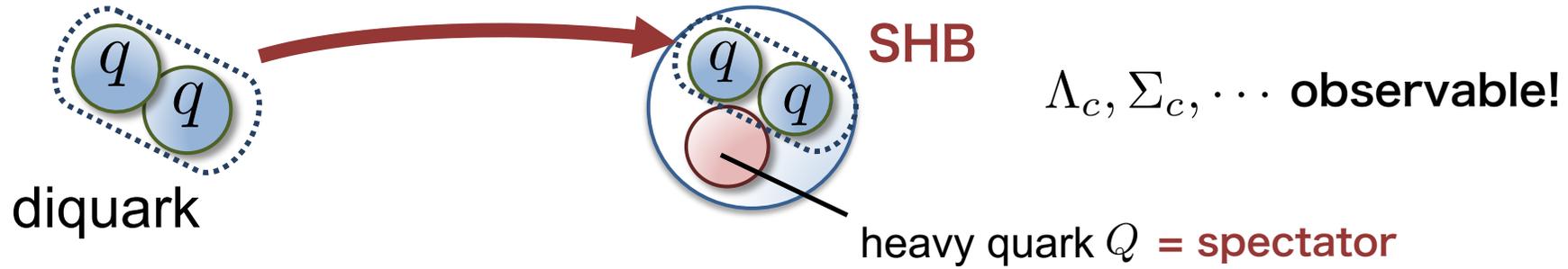
Harada-Liu-Oka-Suzuki (2020),
Suenaga-Oka (2023)

- Those properties strongly affect fate of diquark masses at high T with, eg, chiral restoration

1. Introduction

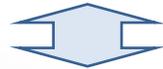
- **Singly heavy baryons**

- Diquark chiral dynamics (in our world) is reflected by **singly heavy baryons (SHBs)**

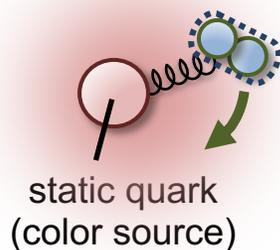
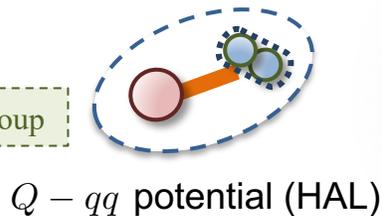


- **This work** Study masses of spin-1 diquarks and corresponding SHBs with chiral restoration, particularly focusing on $\Sigma_c \rightarrow \Lambda_c \pi$ decay at high temperature

- cf, lattice studies

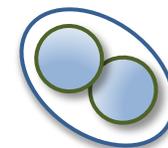


eg RCNP (Ishii-san's) group



eg, Japanese group by Iida-san, Itou-san, etc.

“Numerical experiments” in $N_c = 2$ QCD



diquark baryon (well-defined)

mass spectrum, diquark-diquark potential, etc.

• NJL model

- We start with the 3-flavor NJL model including meson and diquark channels

$$\mathcal{L}_{\text{NJL}} = \bar{\psi}(i\not{\partial} - M + \mu_q \gamma_0)\psi + \mathcal{L}_{(4)} + \mathcal{L}_{(6)}^{\text{anom.}}$$

$$\begin{cases} \mathcal{L}_{(4)} = 8G_s \text{tr}[\phi^\dagger \phi] + 2H_s(\eta_R^\dagger \eta_R + \eta_L^\dagger \eta_L) - 8H_v \text{tr}[\tilde{\eta}^\dagger \tilde{\eta}^\mu] \\ \mathcal{L}_{(6)}^{\text{anom.}} = -8K(\det \phi^\dagger + \det \phi) + K'(\eta_L^T \phi \eta_R^* + \eta_R^T \phi^\dagger \eta_L^*) \end{cases}$$

with $M = \text{diag}(m_q, m_q, m_s)$

meson/diquark fields

0^\pm meson: $\phi_{ij} = (\bar{\psi}_R)_j^a (\psi_L)_i^a$

0^\pm diquark: $\begin{cases} (\eta_L)_i^a = \epsilon_{ijk} \epsilon^{abc} (\psi_L^T)_j^b C (\psi_L)_k^c \\ (\eta_R)_i^a = \epsilon_{ijk} \epsilon^{abc} (\psi_R^T)_j^b C (\psi_R)_k^c \end{cases}$

1^\pm diquark: $(\tilde{\eta}^\mu)_{ij}^a = \epsilon^{abc} (\psi_R^T)_i^b C \gamma^\mu (\psi_L)_j^c$

- Interactions respect $SU(3)_L \times SU(3)_R$ **chiral symmetry**
- $\mathcal{L}_{(6)}^{\text{anom.}}$ is responsible for the $U(1)_A$ **anomaly effects**

- With mean field approximation, dynamical quark masses read

$$\begin{cases} (u, d \text{ quark}) & M_q = m_q - 4G_s \langle \bar{q}q \rangle + 2K \langle \bar{q}q \rangle \langle \bar{s}s \rangle \\ (s \text{ quark}) & M_s = m_s - 4G_s \langle \bar{s}s \rangle + 2K \langle \bar{q}q \rangle^2 \end{cases}$$

Anomalous K term generates s (q) contributions to M_q (M_s)

$\langle \phi \rangle = \text{diag}(\langle \bar{q}q \rangle, \langle \bar{q}q \rangle, \langle \bar{s}s \rangle)$

• One loop approximation

- Chiral condensates, diquark masses, etc. are evaluated at quark one loops

eg diquark fluc.

$$T = \frac{1}{K^{-1} - J} \propto (\text{propagator})$$

- The loop function J of, eg, $[ud]_0^+$ diquark at $q = 0$ reads

$$J_{[ud]_0^+}^{ab}(q_0) = 8i\delta^{ab} \int \frac{d^3p}{(2\pi)^3} \left\{ \frac{\mathcal{R}(q_0 - 2\epsilon_p^{(q)})}{q_0 - 2\epsilon_p^{(q)}} [1 - 2f_F(\epsilon_p^{(q)})] - \frac{\mathcal{R}(q_0 + 2\epsilon_a^{(q)})}{q_0 + 2\epsilon_a^{(q)}} [1 - 2f_F(\epsilon_a^{(q)})] \right\}$$

$$E_p^{(f)} = \sqrt{\mathbf{p}^2 + M_f^2}$$

$$\epsilon_{p/a}^{(f)} = E_p^{(p)} \mp \mu_q$$

$$f_F(\epsilon) = \frac{1}{e^{\epsilon/T} + 1}$$

proper-time regulator with UV and IR cutoffs: $\mathcal{R}(x) = e^{-\frac{|x|}{\Lambda_{UV}}} - e^{-\frac{|x|}{\mu_{IR}}}$



$$\frac{\mathcal{R}(q_0 - 2\epsilon_p^{(q)})}{q_0 - 2\epsilon_p^{(q)} + i0} \stackrel{\text{Im}}{=} -i\pi\delta(q_0 - 2\epsilon_p^{(q)}) \left(\underbrace{e^{-\frac{|q_0 - 2\epsilon_p^{(q)}|}{\Lambda_{UV}}}}_{\rightarrow 1} - \underbrace{e^{-\frac{|q_0 - 2\epsilon_p^{(q)}|}{\mu_{IR}}}}_{\rightarrow 1} \right) \rightarrow 0 \text{ (imaginary parts vanish!)}$$

Ebert-Feldmann-Reinhardt (1996)
Suenaga-Oka (2023)

→ No ambiguity from imaginary part to define diquark mass

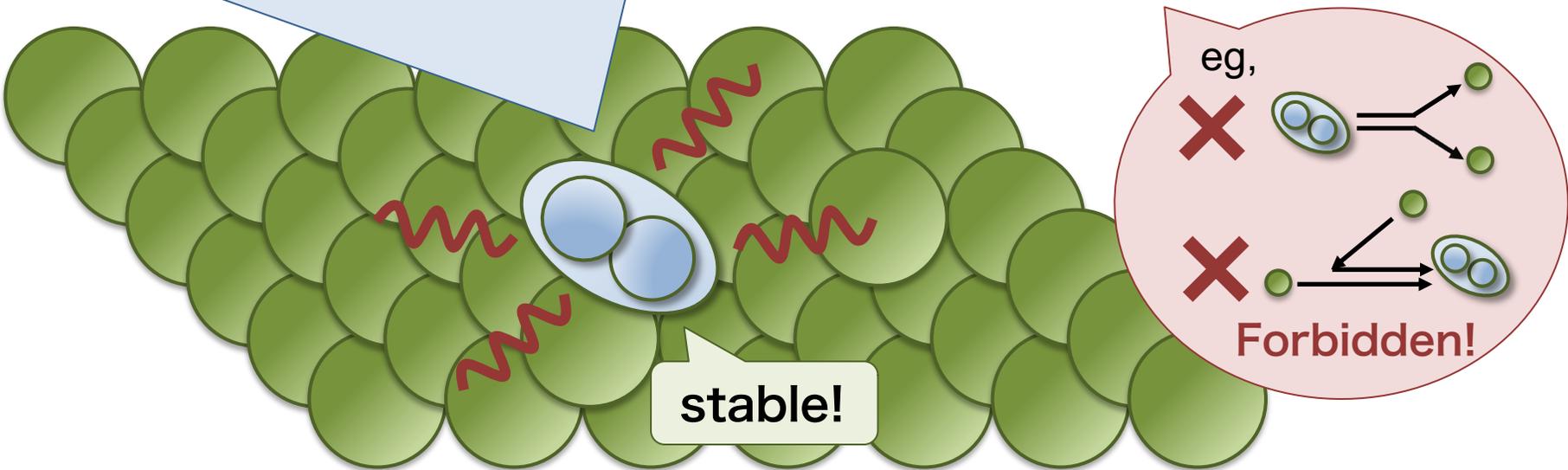
- IR cutoff is suggested by, eg, gluon mass

Tissier-Wschebor (2010), Suenaga-Kojo (2019)

2. Model

- Intuitive picture of vanishing imaginary parts

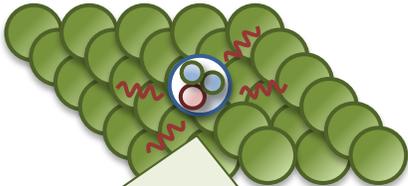
diquark is affected by matter but **does not discriminate single quark in medium**



stable!



convenient for SHB study in medium



more-or-less **stable** due to confinement

NOTE: deconfinement is crossover
SHB structure would survive at T

3. Results

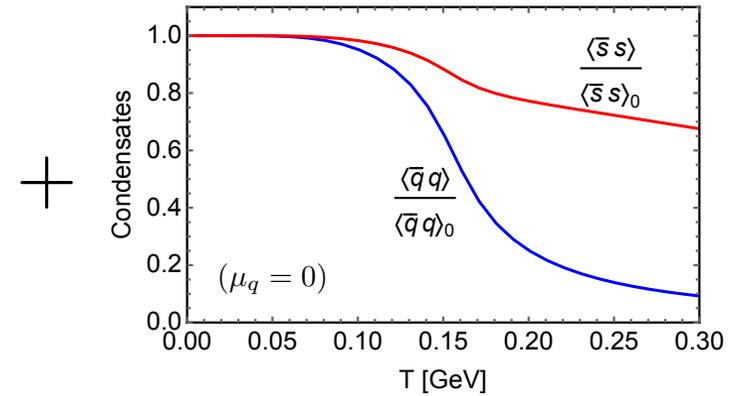
• Parameter determination

- Our model has 9 parameters: $m_q, m_s, G_s, \underline{H}_s, \underline{H}_v, K, \underline{K}', \Lambda_{UV}, \mu_{IR}$

$$\begin{aligned}
 m_q &= 0.00258 \text{ GeV} \\
 m_s &= 0.0761 \text{ GeV} & \Lambda_{UV} &= 1.6 \text{ GeV} \\
 G_s &= 1.15 \text{ GeV}^{-2} & \mu_{IR} &= 0.45 \text{ GeV} \\
 K &= 10.3 \text{ GeV}^{-5}
 \end{aligned}$$

for diquarks

$$\begin{aligned}
 f_\pi &= 0.092 \text{ GeV} \\
 f_K &= 0.110 \text{ GeV} \\
 m_\pi &= 0.138 \text{ GeV} \\
 m_K &= 0.496 \text{ GeV}
 \end{aligned}$$

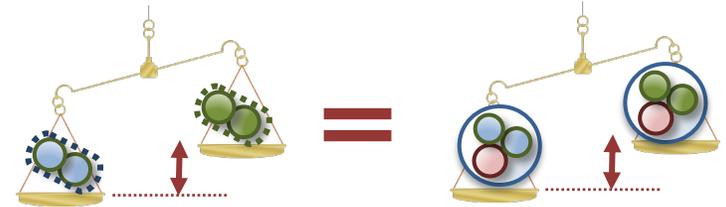


- Fix H_s and H_v for a given K' as follows

additional inputs

$$\left\{ \begin{aligned}
 \Delta m_1 &\equiv m_{[su]_0^+}^{\text{vac}} - m_{[ud]_0^+}^{\text{vac}} = M_{\Xi_c}^{\text{vac}} - M_{\Lambda_c}^{\text{vac}} = 0.183 \text{ GeV} \quad (\leftarrow \text{exp. value}) \\
 \Delta m_2 &\equiv m_{\{ud\}_1^+}^{\text{vac}} - m_{[ud]_0^+}^{\text{vac}} = M_{\Sigma_c}^{\text{vac}} - M_{\Lambda_c}^{\text{vac}} = 0.215 \text{ GeV} \quad (\leftarrow \text{exp. value with spin average taken})
 \end{aligned} \right.$$

simple assumption
(cf, HQET)



• Determined diquark masses

in units of GeV

positive party diquarks

K' [GeV ⁻⁵]	H_s [GeV ⁻²]	H_v [GeV ⁻²]	$m_{[ud]_0^+}$	$m_{[su]_0^+}$	$m_{\{ud\}_1^+}$	$m_{\{su\}_1^+}$	$m_{\{ss\}_1^+}$	Δm_1	Δm_2
-5	2.3	3.06	0.119	0.302	0.333	0.418	0.472	0.184	0.215
0	2.2	3.0	0.187	0.374	0.387	0.463	0.514	0.187	0.200
5	2.08	2.86	0.277	0.461	0.495	0.560	0.606	0.183	0.218
10	1.95	2.75	0.360	0.547	0.577	0.629	0.671	0.187	0.216
15	1.77	2.6	0.490	0.674	0.703	0.726	0.757	0.184	0.213

negative party diquarks

K' [GeV ⁻⁵]	H_s [GeV ⁻²]	H_v [GeV ⁻²]	$m_{[ud]_0^-}$	$m_{[su]_0^-}$	$m_{[ud]_1^-}$	$m_{[su]_1^-}$
-5	2.3	3.06	0.134	0.421	0.581	0.700
0	2.2	3.0	0.421	0.570	0.618	0.732
5	2.08	2.86	0.617	0.715	0.705	0.808
10	1.95	2.75	0.817	0.868	0.776	0.871
15	1.77	2.6	1.10	1.09	0.88	0.961

- For smaller K' , all the diquark masses become small
- When $K' \lesssim 0$, $[ud]_0^+$ mass becomes negative at $T \rightarrow$ **unstable (excluded)**

• Determined diquark masses

in units of GeV

positive party diquarks

K' [GeV ⁻⁵]	H_s [GeV ⁻²]	H_v [GeV ⁻²]	$m_{[ud]_0^+}$	$m_{[su]_0^+}$	$m_{\{ud\}_1^+}$	$m_{\{su\}_1^+}$	$m_{\{ss\}_1^+}$	Δm_1	Δm_2
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negative party diquarks

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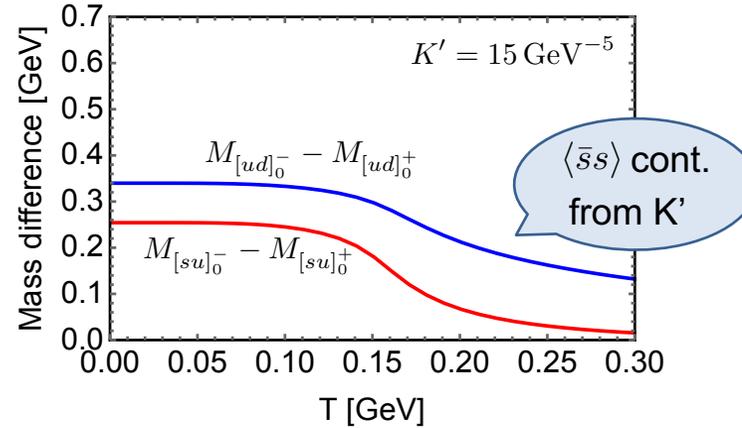
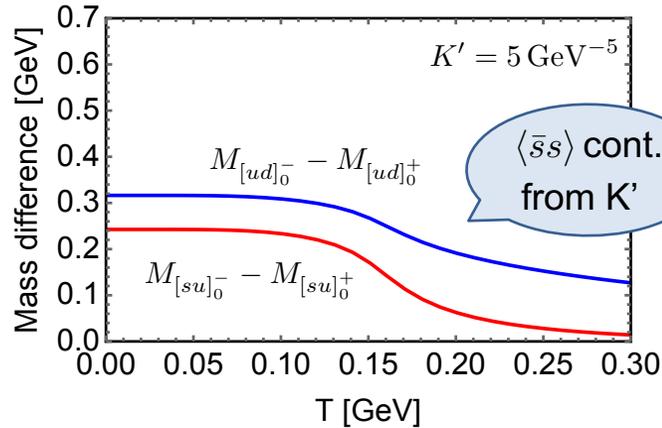
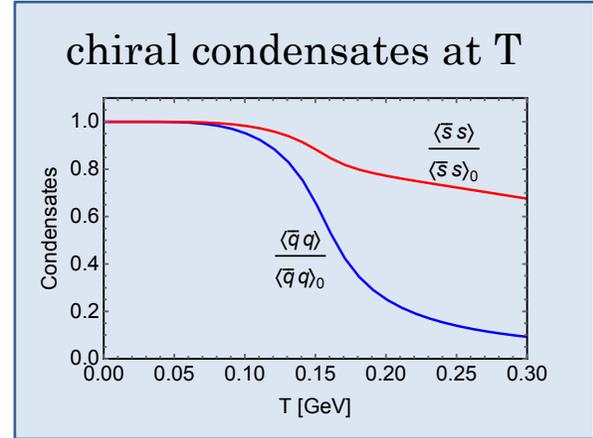
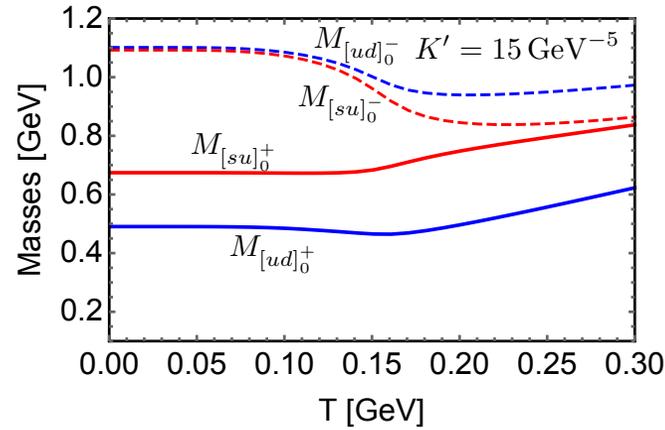
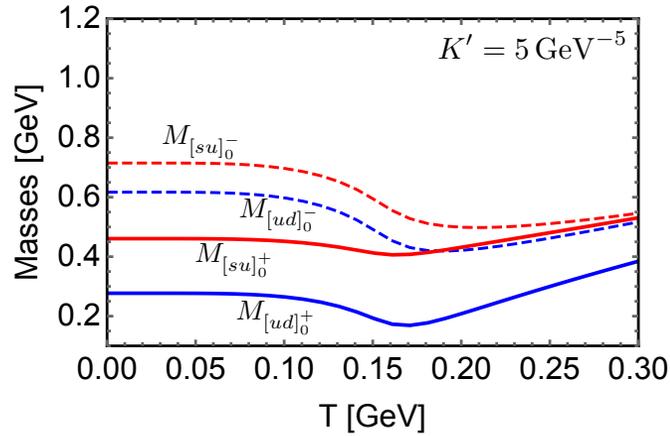
Let me show results with

$$\begin{cases} K' = 5 \text{ GeV}^{-5} \\ K' = 15 \text{ GeV}^{-5} \end{cases}$$

- For smaller K' , all the diquark masses become small
- When $K' \lesssim 0$, $[ud]_0^+$ mass becomes negative at $T \rightarrow$ **unstable (excluded)**

3. Results

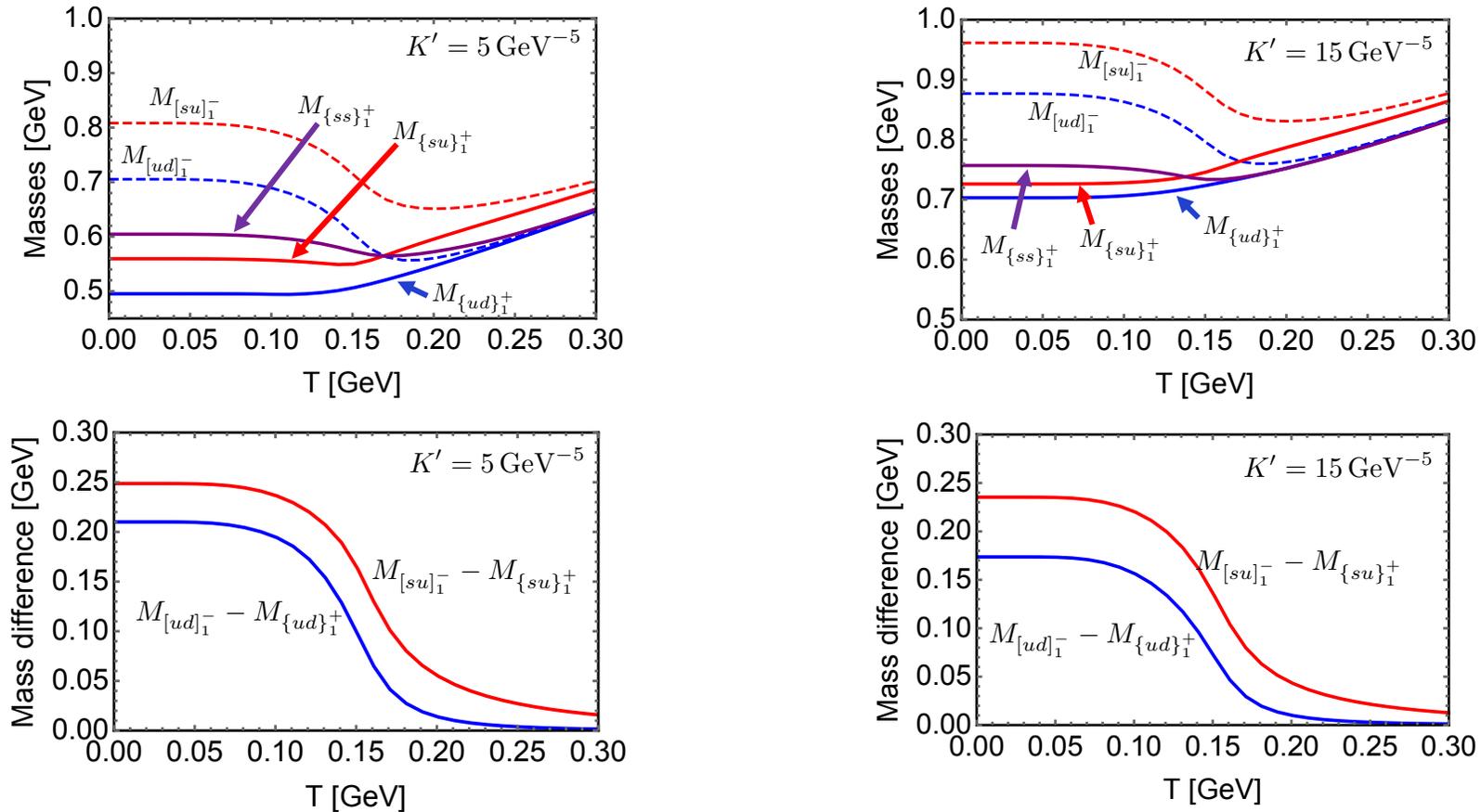
• Results of spin-0 diquarks ($\mu_q = 0$)



- Chiral-partner mass degeneracies are not well realized for [ud] sector
- Weak inverse mass hierarchy $M_{[ud]_0^-} > M_{[su]_0^-}$ for larger anomaly effect ($K' = 15 \text{ GeV}^{-5}$)

3. Results

- Results of spin-1 diquarks ($\mu_q = 0$)

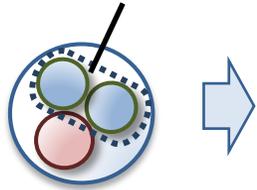


- Chiral-partner mass degeneracies are well realized for all sectors
- The mass hierarchy seems to be reasonable

3. Results

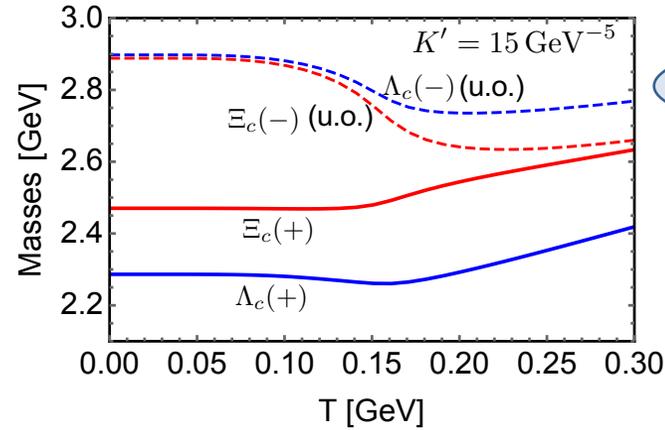
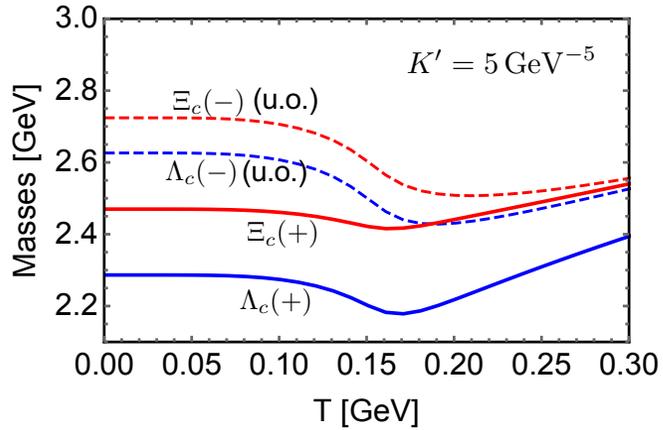
• Mass spectrum of SHBs

spin-0 diquark

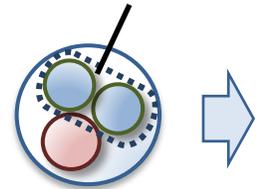


$1/2^\pm$

HQS-singlet

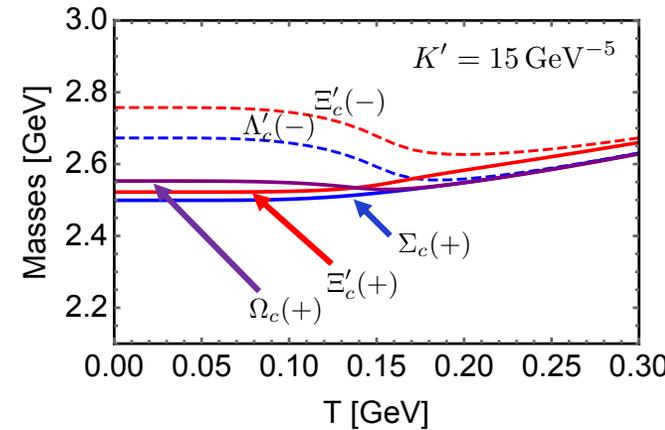
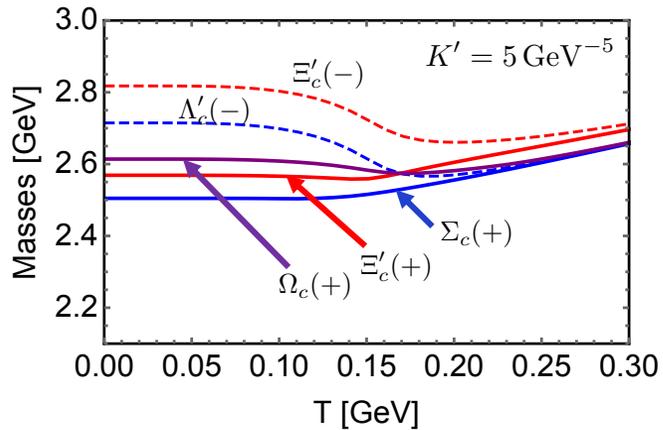


spin-1 diquark



$(1/2^\pm, 3/2^\pm)$

HQS-doublet



NOTE

$\{\Lambda_c(2595), \Lambda_c(2625)\}$ is HQS-doublet

u.o. = unobserved SHBs

- assumption:

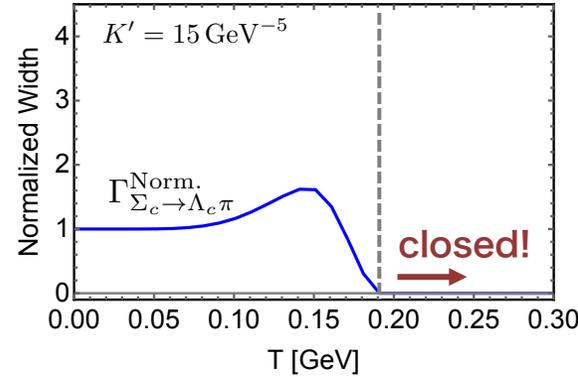
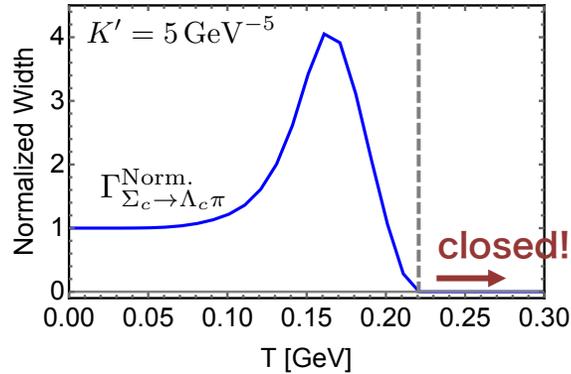
$$M_{\text{SHB}} = m_Q + m_{\text{diquark}}$$

- spin average taken

3. Results

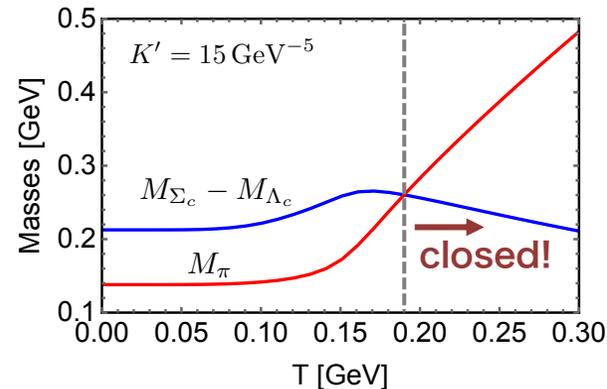
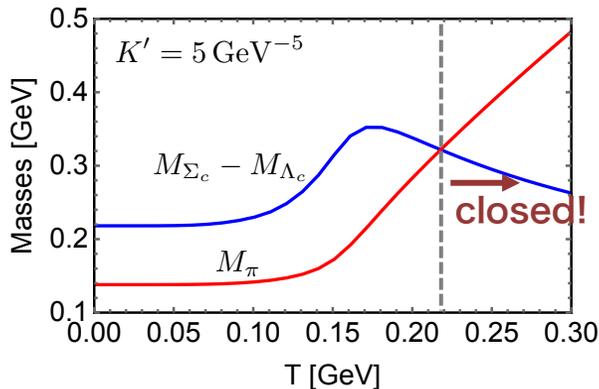
- Decay width of Σ_c : $\Gamma_{\Sigma_c \rightarrow \Lambda_c \pi}^{\text{Norm.}} \equiv \Gamma_{\Sigma_c \rightarrow \Lambda_c \pi} / \Gamma_{\Sigma_c \rightarrow \Lambda_c \pi}^{\text{vac}}$

Decay width \Rightarrow



threshold information \Rightarrow

$M_{\Sigma_c} - M_{\Lambda_c}$ vs M_π



always $M_{\Sigma_c} > M_{\Lambda_c}$

- Mass inversion of M_{Λ_c} and M_{Σ_c} does not occur, but **the width is closed!**
 \rightarrow one distinguishing phenomena by chiral restoration at T on SHBs

4. Conclusions

15/15

- We investigated spin-0 and spin-1 diquark masses at T with NJL model

➡ delineation from chiral restoration and $U(1)_A$ anomaly effects

- $U(1)_A$ anomaly effect on spin-0 diquark would be sizable (K' is finite)

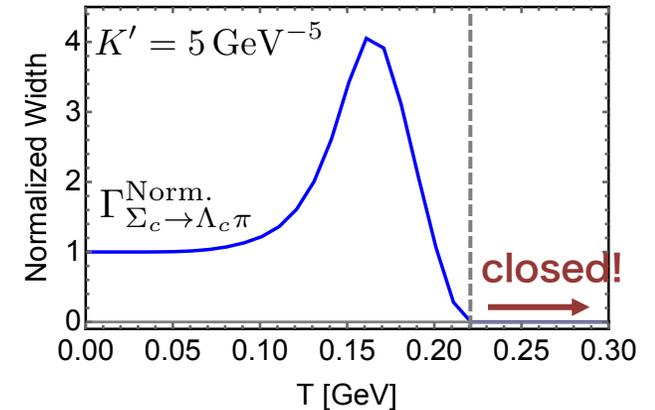
↔ otherwise tachyonic mode appeared

- The decay width of $\Sigma_c \rightarrow \Lambda_c \pi$ is closed at $T \sim 0.2 \text{ GeV}$

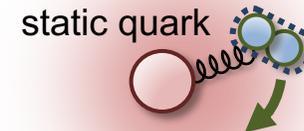
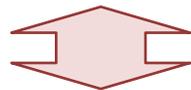
= distinguishing phenomena with chiral restoration

➡ challenging issue for future HIC experiments, etc.

needs more phenomenological investigation



- Lattice studies are also welcome!



“Numerical experiment” with $N_c=2$

