Λ_c Enhancement from Strongly Coupled QGP

arXiv:0709.3637 [nucl-th]

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3-14 Dec. 2007

Workshop on Hadron Physics at APCTP

Contents

- Where are diquarks?
- Diquark observation in QGP
- Discussion
- Summary

Where are diquarks?

Diquarks

1. Construction of flavor multiplets of baryons

Gell-Mann, Ida-Kobayashi, Lichtenberg *et al.*

Where are diquarks?

Diquarks

1. Construction of flavor multiplets of baryons
2. Exotic structure of hadrons

   σ meson as tetraquark   Jaffe

Where are diquarks?

Diquarks

1. Construction of flavor multiplets of baryons
2. Exotic structure of hadrons
3. Dynamical description of diquark in baryons

Ebert, Feldmann, Friedlich, Reinhardt

Nagata, Hosaka, Abu-Raddad, ….

Where are diquarks?

Diquarks

1. Construction of flavor multiplets of baryons
2. Exotic structure of hadrons
3. Dynamical description of diquark in baryons
4. Lattice QCD

Alexandrou, de Forcrand, Lucini

Where are diquarks?

Diquarks

1. Construction of flavor multiplets of baryons
2. Exotic structure of hadrons
3. Dynamical description of diquark in baryons
4. Lattice QCD
5. Dense matter QCD

    Color Superconductivity

    Bose-Einstein condensate

Where are diquarks?

Diquarks

1. Construction of flavor multiplets of baryons
2. Exotic structure of hadrons
3. Dynamical description of diquark in baryons
4. Lattice QCD
5. Dense matter QCD
6. Strongly coupled QGP (sQGP)

Color non-singlet bound states Shuryak, Zahed

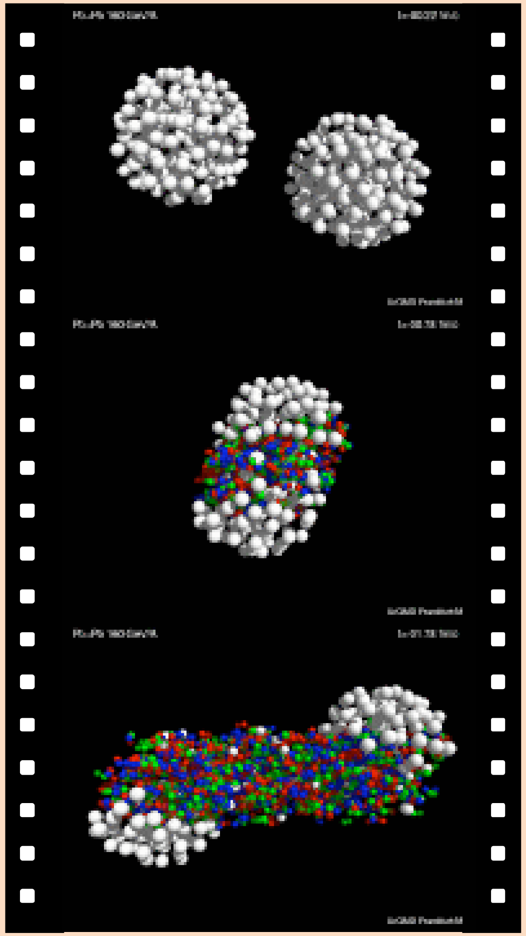
Where are diquarks?

Where are diquarks?

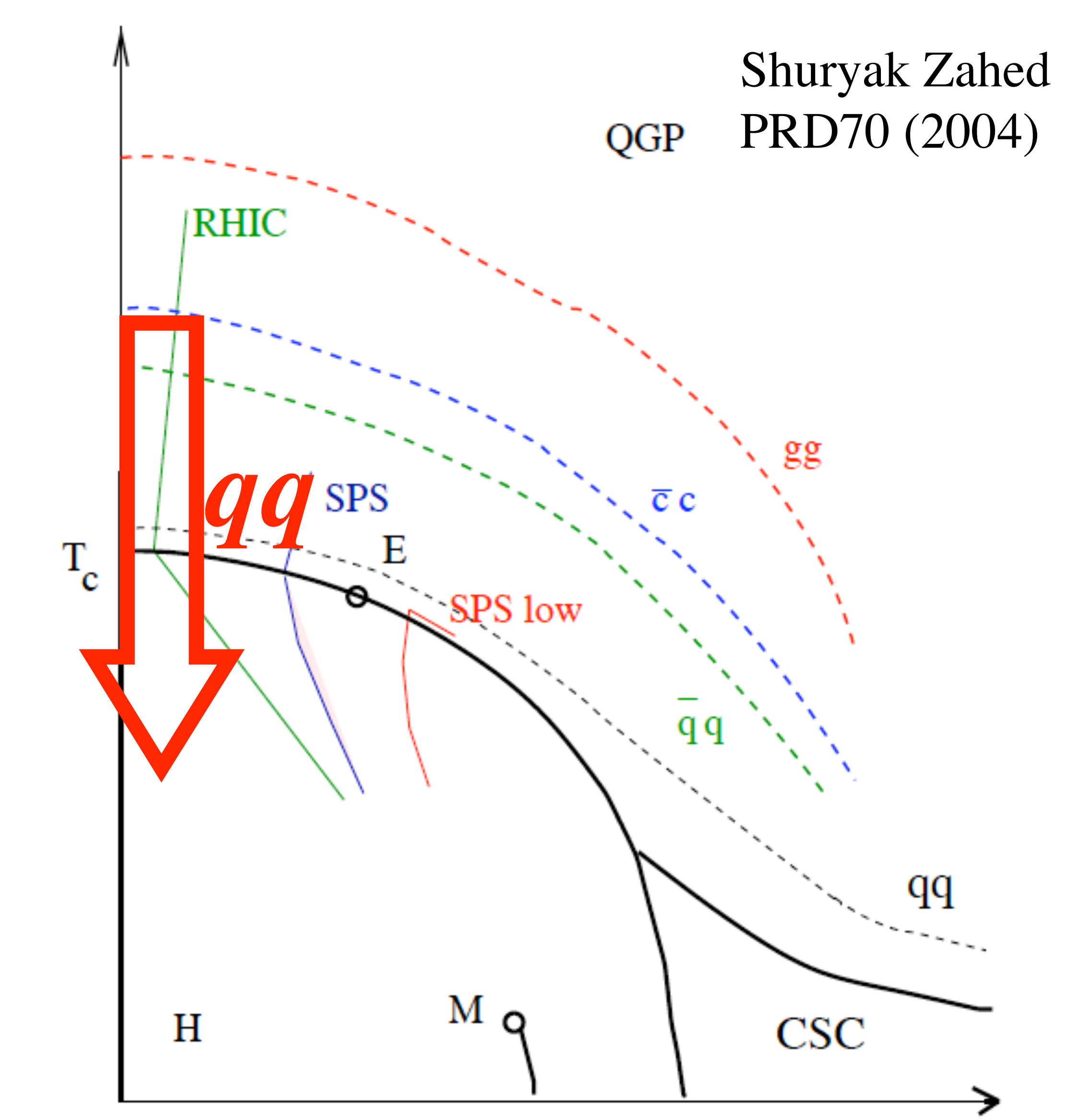
Diquarks in sQGP

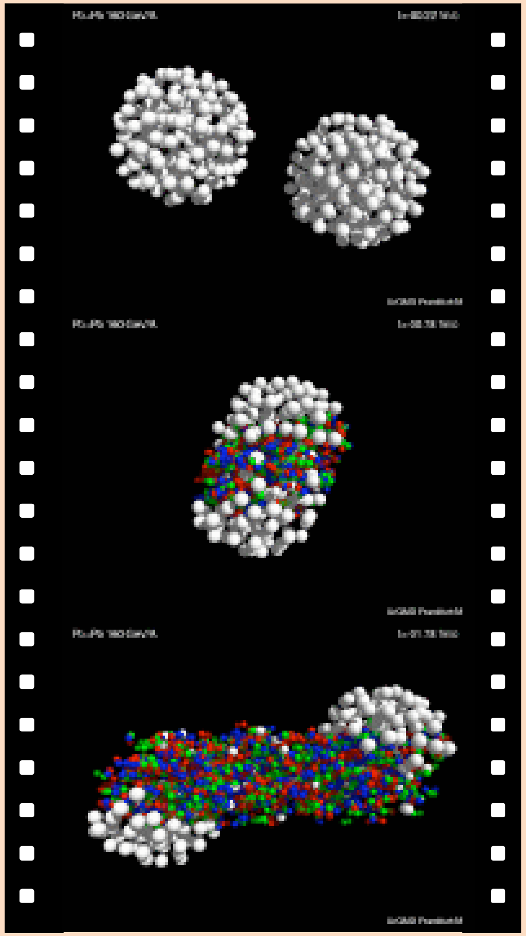
1. Perfect fluid behavior
   - ☑ Exp. Small viscosity
     Collective flow
   - ☑ Theor. Analysis from AdS/CFT

2. Strong correlations
   - ☑ $\bar{c}c$ bound state at T>> T_c
   - ☑ Variety of bound states
     $\bar{q}q$, gg, $\bar{Q}Q$
   - ☑ color non-singlet bound states ??
     $\boldsymbol{qq}$, $qq\bar{q}$



Where are diquarks?





Where are diquarks?

What is an experimental observable for diquarks in sQGP?

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Assumptions

a. Bound states of diquarks in sQGP

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Assumptions

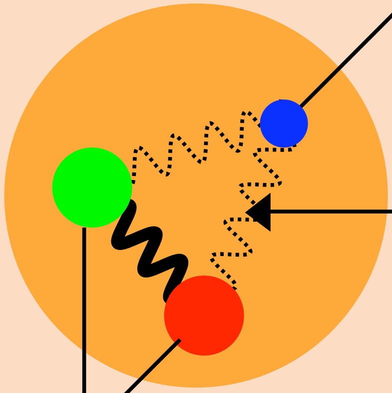
a. Bound states of diquarks in sQGP

b. Diquark picture in heavy baryons ***Qqq***

Where are diquarks?

Heavy baryons (*Qqq*)

heavy quark (*c* or *b*): color spectator



In $m_{c,b} \to \infty$, short distance forces

☑ one-gluon exchange

☑ instanton-induced interaction

are suppressed.

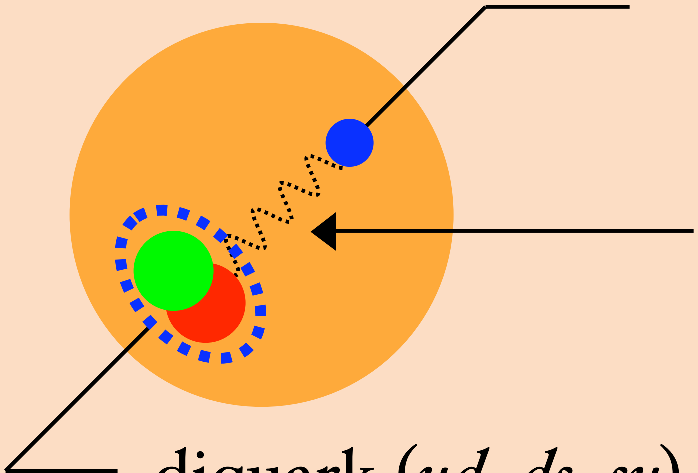
light quark (*u*, *d*, *s*)

H.J. Lipkin, PL70B, 113 (1977)
R.L.Jaffe, PRD72, 074508 (2005)

Where are diquarks?

Heavy baryons (*Qqq*)

heavy quark (*c* or *b*): color spectator



In $m_{c,b} \rightarrow \infty$, short distance forces
- ☑ one-gluon exchange
- ☑ instanton-induced interaction

are suppressed.

diquark (*ud*, *ds*, *su*)

H.J. Lipkin, PL70B, 113 (1977)
R.L.Jaffe, PRD72, 074508 (2005)

Diquarks decouple from heavy quark.

Where are diquarks?

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What is an experimental observable for diquarks in sQGP?

Assumptions

a. Bound state of diquarks in sQGP

b. Diquark picture in heavy baryons ***Qqq***

Diquark observation in QGP

Diquarks in QGP

Diquark observation in QGP

Diquarks in QGP

1. Stability of diquark

color-spin interaction

6_f $(6_c, S=0)$

6_f $(3_c^*, S=1)$

Threshold

3_f^* $(6_c, S=1)$

3_f^* $(3_c^*, S=0)$

bound state

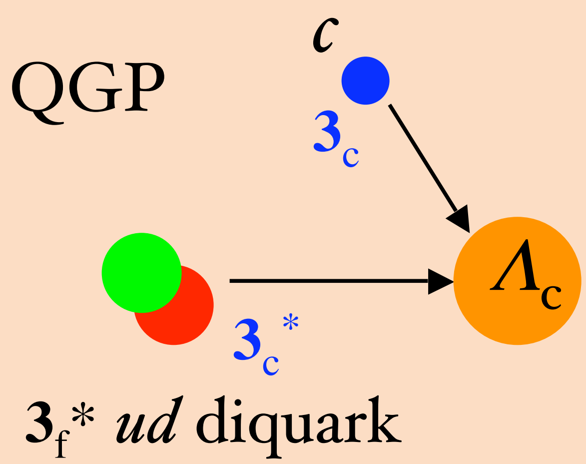
Diquark observation in QGP

Diquarks in QGP

1. Stability of diquark

☑ $\mathbf{3}_f^*$ diquark is a bound state.

2. Color neutralization of diquark



Diquark observation in QGP

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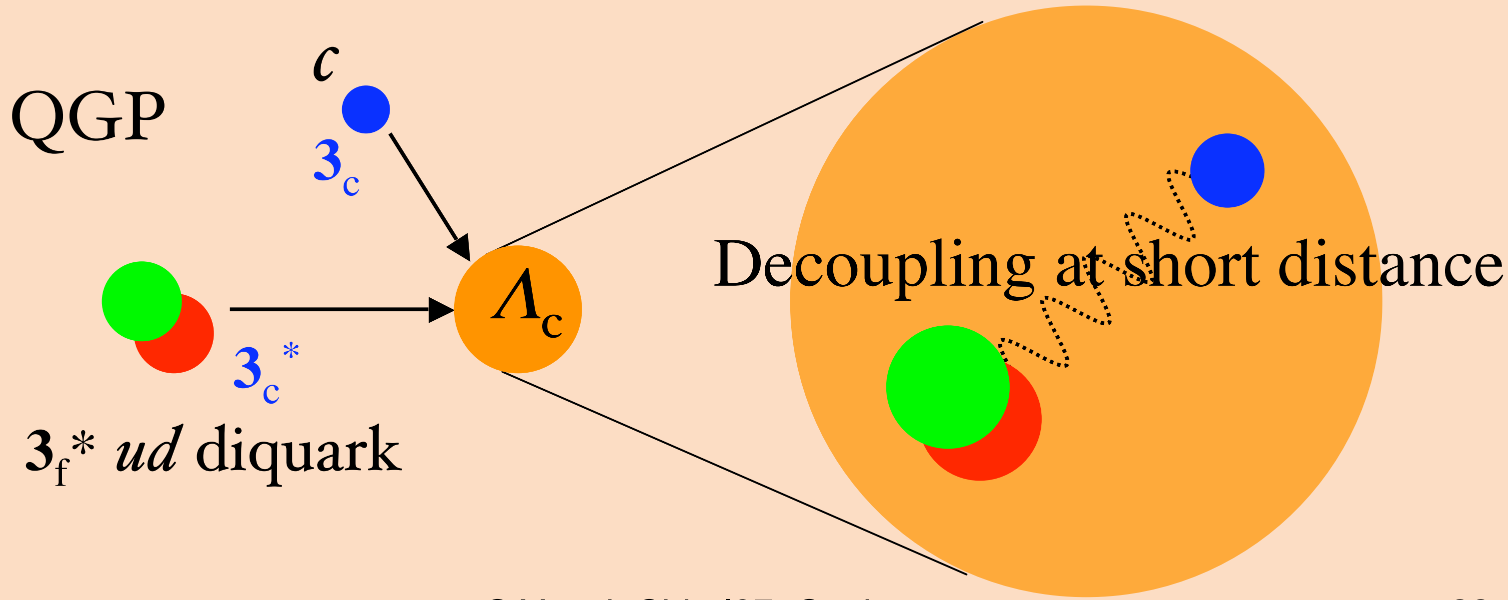

Diquark observation in QGP

Diquarks in QGP

1. Stability of diquark
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   - ☑ $\mathbf{3}_f^*$ diquark (ud) $\Longleftrightarrow$ heavy baryon (Λ_c)

Diquark observation in QGP

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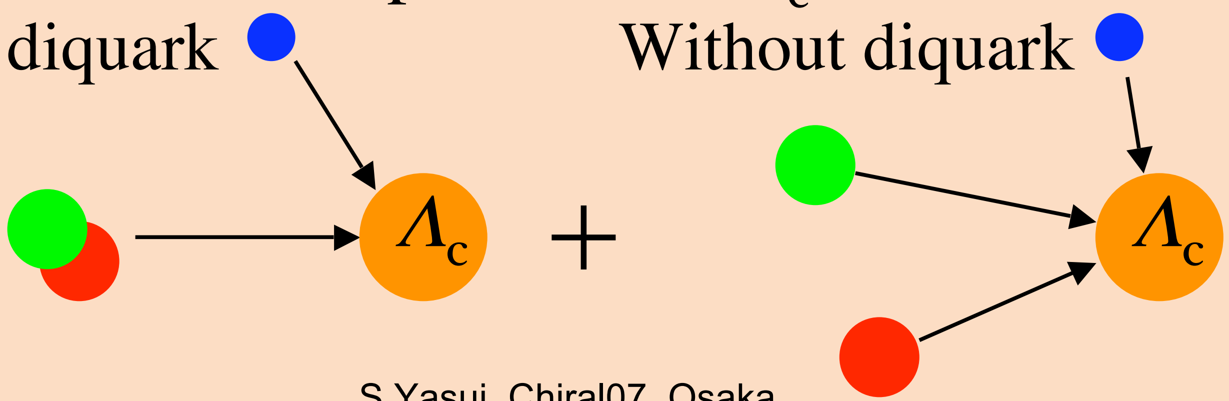
3. Hadronization process for Λ_c

With diquark + Without diquark



Diquark observation in QGP

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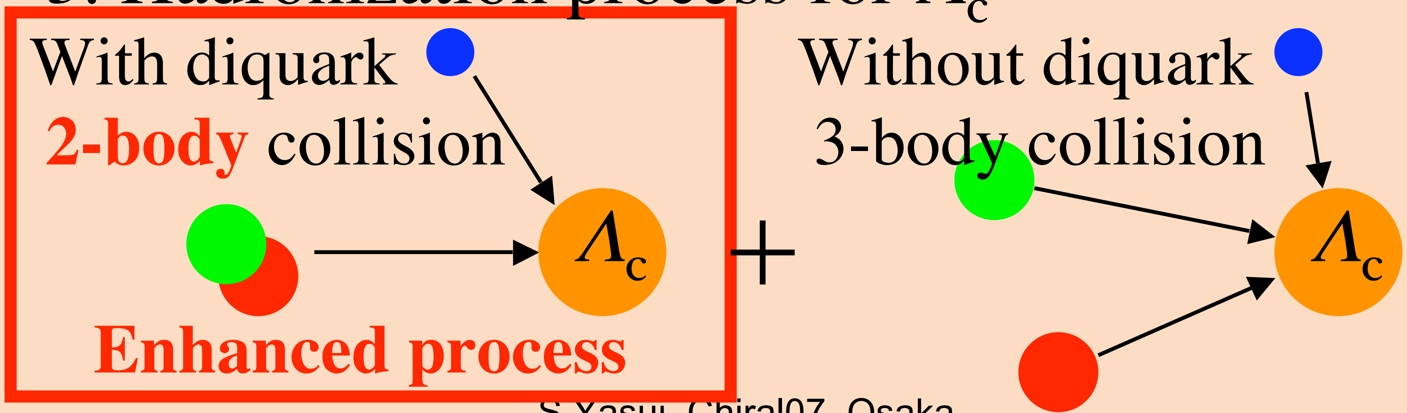

Diquark observation in QGP

Diquarks in QGP

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   ☑ $\mathbf{3}_f^*$ diquark is a bound state.
2. Color neutralization of diquark
   ☑ $\mathbf{3}_f^*$ diquark (ud) $\Leftrightarrow$ heavy baryon (Λ_c)
3. Hadronization process for Λ_c
   ☑ 2-body $(ud)c$ collision > 3-body udc collision

Diquark observation in QGP

Diquarks in QGP

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   ☑ $\mathbf{3}_f^*$ diquark (ud) $\Leftrightarrow$ heavy baryon (Λ_c)

3. Hadronization process for Λ_c

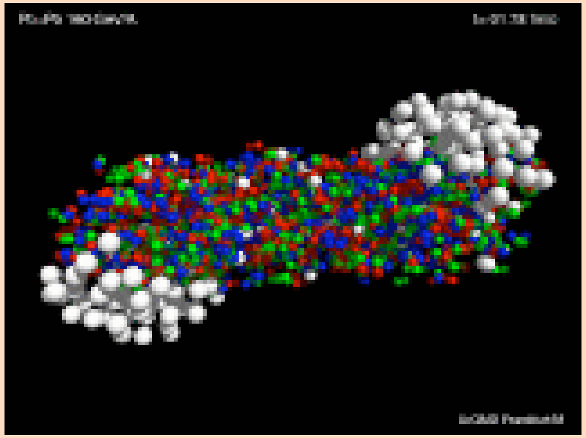
   ☑ 2-body $(ud)c$ collision > 3-body udc collision

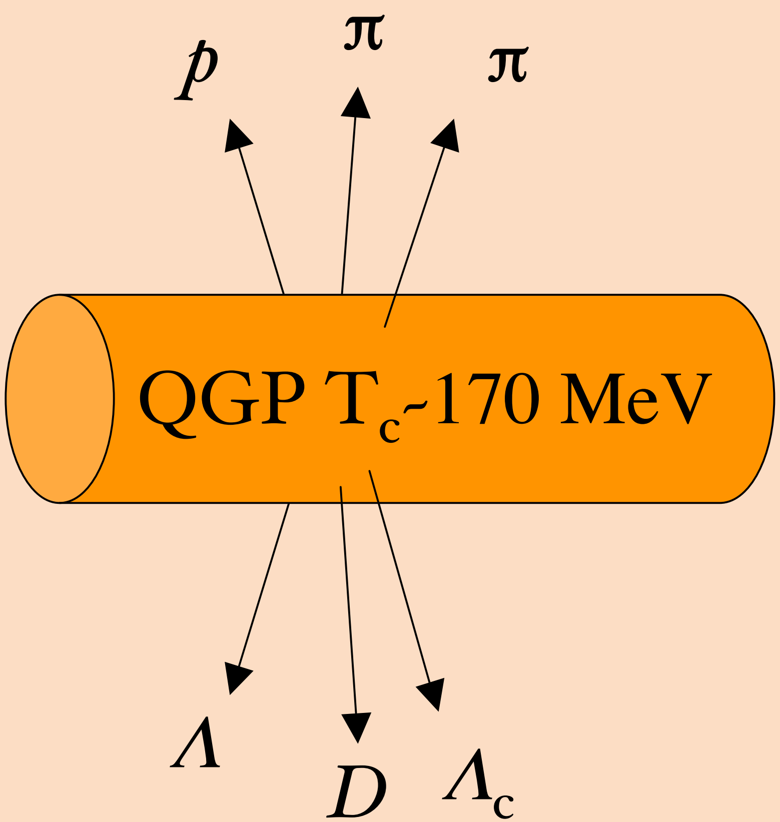
Diquark (ud) enhances heavy baryon (Λ_c) yield.

Diquark observation in QGP

Numerical estimate

1. fire-cylinder model





Diquark observation in QGP

Numerical estimate

1. fire-cylinder model (thermal distribution T_c~170 MeV)
2. quark/diqaurk mass at T_c

☑ quark $m_u = m_d$ ~ 300 MeV

☑ diquark m_{ud} = ???

Diquark observation in QGP

Numerical estimate

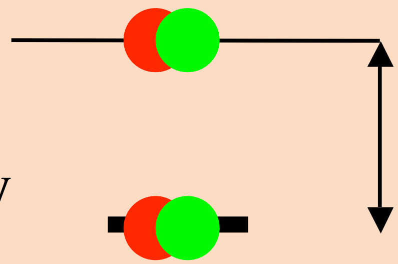
1. fire-cylinder model (thermal distribution T_c~170 MeV)
2. quark/diqaurk mass at T_c

☑ quark $m_u = m_d$ ~ 300 MeV

☑ diquark $m_{ud} = m_u + m_d - \Delta E_{color\text{-}spin}$

a. Threshold

b. Most deeply binding



$\Delta E_{color\text{-}spin}$ ~0 MeV

$\Delta E_{color\text{-}spin}$ ~150 MeV

Diquark observation in QGP

Numerical estimate

1. fire-cylinder model (thermal distribution T_c~170 MeV)
2. quark/diqaurk mass at T_c

☑ quark $m_u = m_d$ ~ 300 MeV

☑ diquark $m_{ud} = m_u + m_d - \Delta E_{color\text{-}spin}$ ~ 450-600 MeV

a. Threshold

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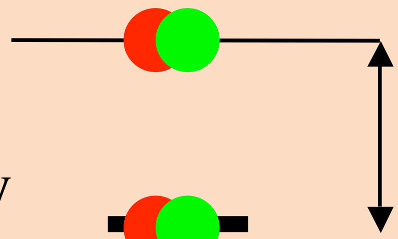

$\Delta E_{color\text{-}spin}$ ~0 MeV

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Diquark observation in QGP

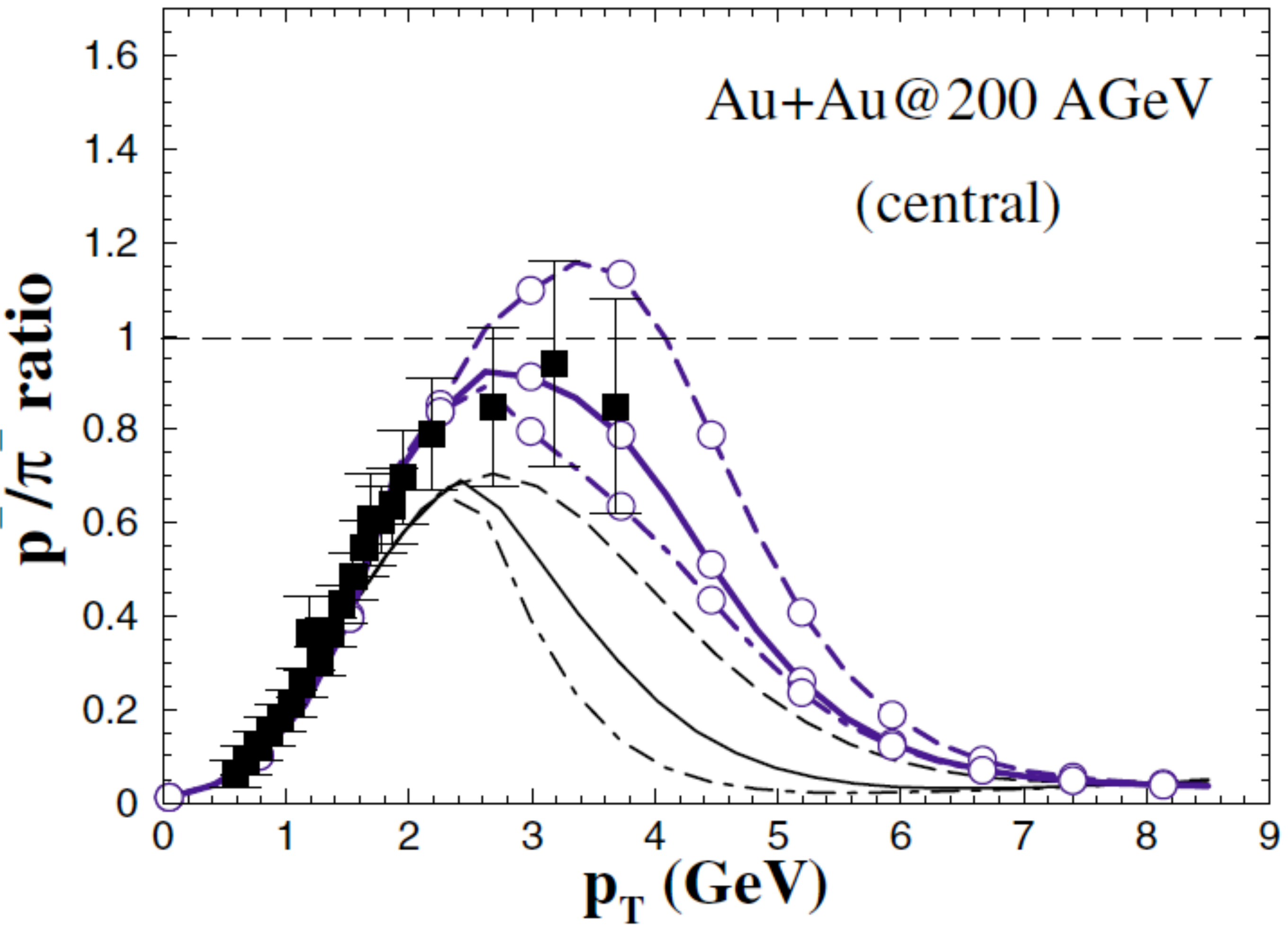
Numerical estimate

1. fire-cylinder model (thermal distribution T_c~170 MeV)
2. quark/diqaurk mass at T_c
 ☑ quark $m_u = m_d \sim 300$ MeV
 ☑ diquark $m_{ud} = m_u + m_d - \Delta E_{color\text{-}spin} \sim 450\text{-}600$ MeV
3. the coalescence model
 ☑ hadron yield ∝ (quark thermal distribution in QGP) ×(Wigner function of hadron)

Diquark observation in QGP

1.
2.
☑
☑
3.
☑ GP)

Greco Ko Levai PRL90 (2003)



Diquark observation in QGP

Numerical estimate

Λ_c yield from the coalescence model

$$N^{\rm coal}_{\Lambda_c({\rm cud})} = g_{\Lambda_c({\rm cud})} \int_{\sigma_{\rm C}} \prod_{i=1}^{n=3} \frac{p_i \cdot {\rm d}\sigma_i {\rm d}^3\mathbf{p}_i}{(2\pi)^3 E_i} f_{\rm q}(x_i, p_i)$$

$$\times f^{\rm W}_{\Lambda_c}(x_1..x_n; p_1..p_n),$$

quark thermal distribution
× Wigner function of hadron

3-body collision (without diquark)

$$f^{\rm W}_{\Lambda_c({\rm cud})}(x;p) = 8^2 \exp\left(-\sum_{i=1}^{2} \frac{\mathbf{y}_i^2}{\sigma_i^2} - \sum_{i=1}^{2} \mathbf{k}_i^2 \sigma_i^2 \right)$$

2-body collision (with diquark)

$$f^{\rm W}_{\Lambda_c({\rm c[ud]})}(x;p) = 8 \exp\left(-\frac{\mathbf{y}^2}{\sigma^2_{\rm c[ud]}} - \mathbf{k}^2 \sigma^2_{\rm c[ud]} \right)$$

Diquark observation in QGP

Numerical estimate

Λ_c yield from the coalescence model

$$N^{\mathrm{coal}}_{\Lambda_c(\mathrm{cud})} = g_{\Lambda_c(\mathrm{cud})} \int_{\sigma_C} \prod_{i=1}^{n=3} \frac{p_i \cdot \mathrm{d}\sigma_i \mathrm{d}^3\mathbf{p}_i}{(2\pi)^3 E_i} f_{\mathrm{q}}(x_i, p_i) \times f^{\mathrm{W}}_{\Lambda_c}(x_1..x_n; p_1..p_n),$$

quark thermal distribution
× Wigner function of hadron

3-body collision (without diquark)

$$N^{\mathrm{coal}}_{\Lambda_c(\mathrm{cud})} \simeq g_{\Lambda_c(\mathrm{cud})} N_{\mathrm{c}} N_{\mathrm{u}} N_{\mathrm{d}} \prod_{i=1}^{2} \frac{(4\pi\sigma_i^2)^{3/2}}{V_{\mathrm{c}}(1+2\mu_i T_{\mathrm{C}} \sigma_i^2)}$$

2-body collision (with diquark)

$$N^{\mathrm{coal}}_{\Lambda_c(\mathrm{c[ud]})} \simeq g_{\Lambda_c(\mathrm{c[ud]})} N_{\mathrm{c}} N_{[\mathrm{ud}]} \frac{(4\pi\sigma^2_{\mathrm{c[ud]}})^{3/2}}{V_{\mathrm{c}}(1+2\mu_{\mathrm{c[ud]}} T_{\mathrm{C}} \sigma^2_{\mathrm{c[ud]}})}$$

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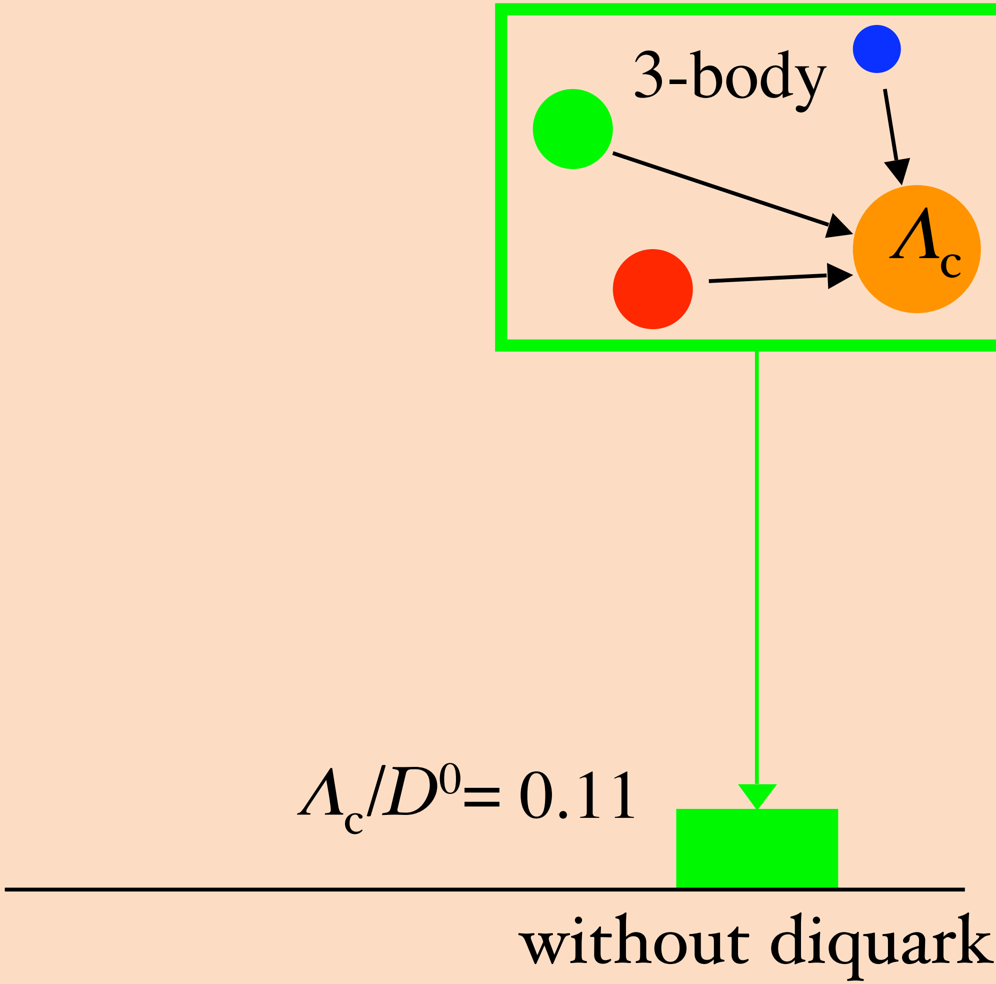
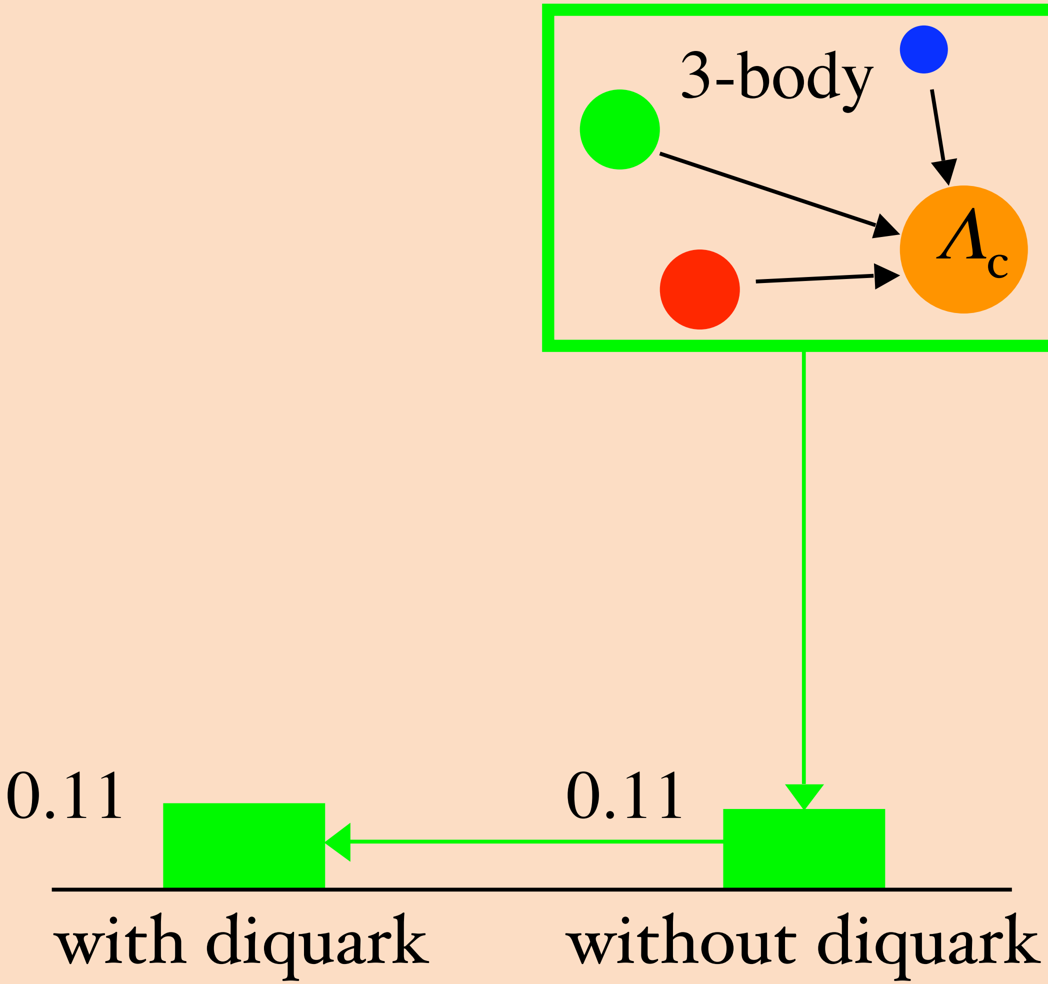
   - ☑ quark $m_u = m_d$ ~ 300 MeV
   - ☑ diquark $m_{ud} = m_u + m_d - \Delta E_{color\text{-}spin}$ ~ 450-600 MeV
3. the coalescence model
   - ☑ hadron yield ∝ (quark thermal distribution in QGP) ×(Wigner function of hadron)
4. normalization by Λ_c/D^0
   - ☑ D^0 is not affected by diquark correlation in QGP.

Diquark observation in QGP



Diquark observation in QGP



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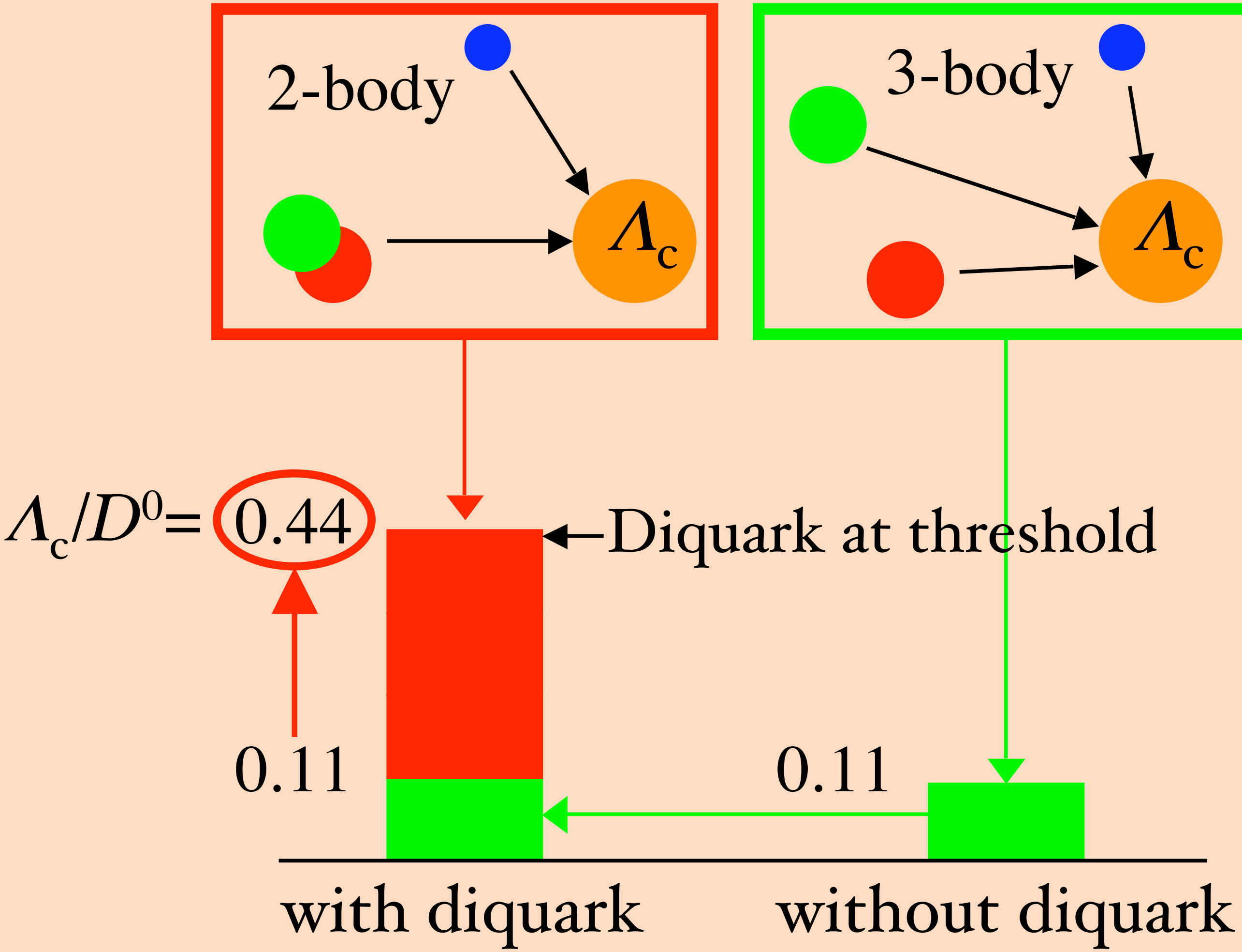

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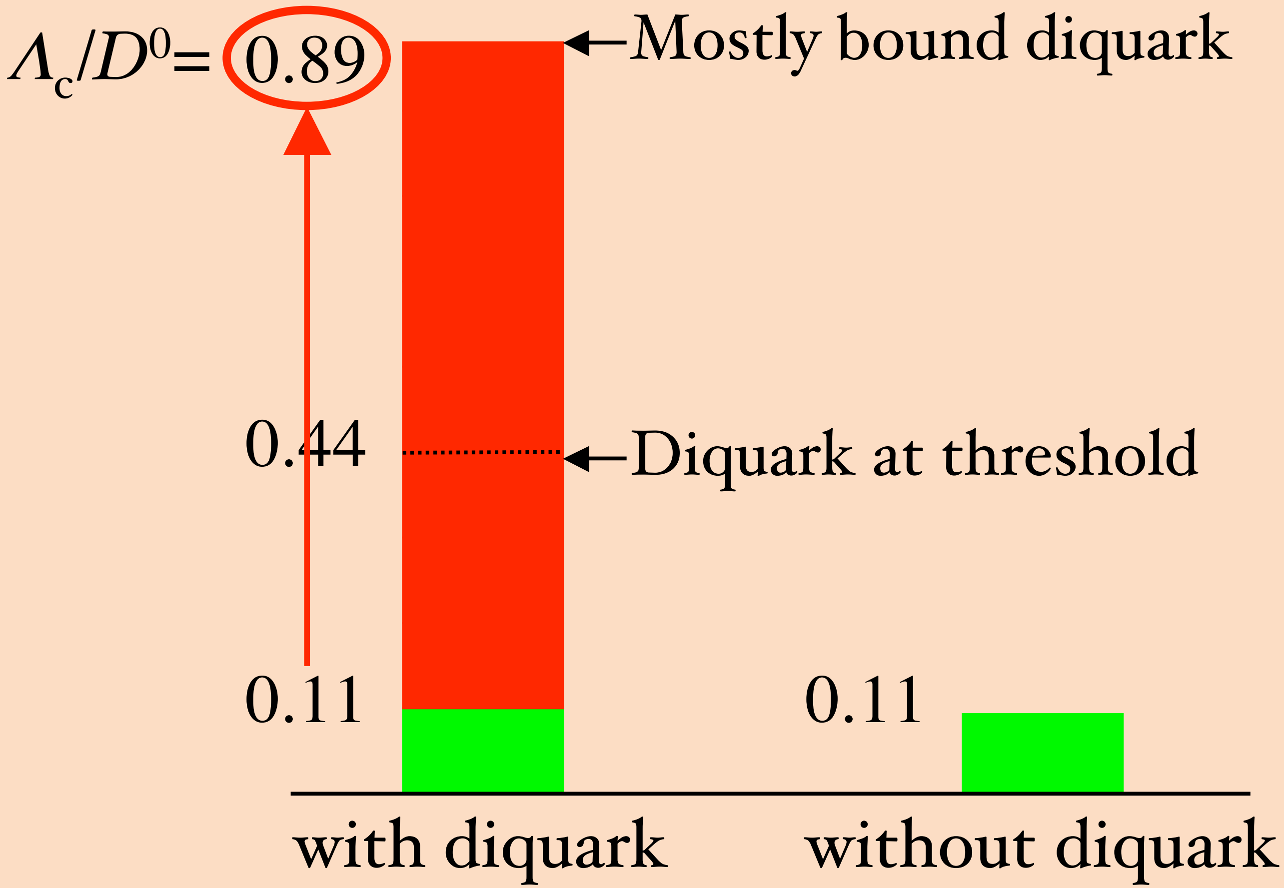

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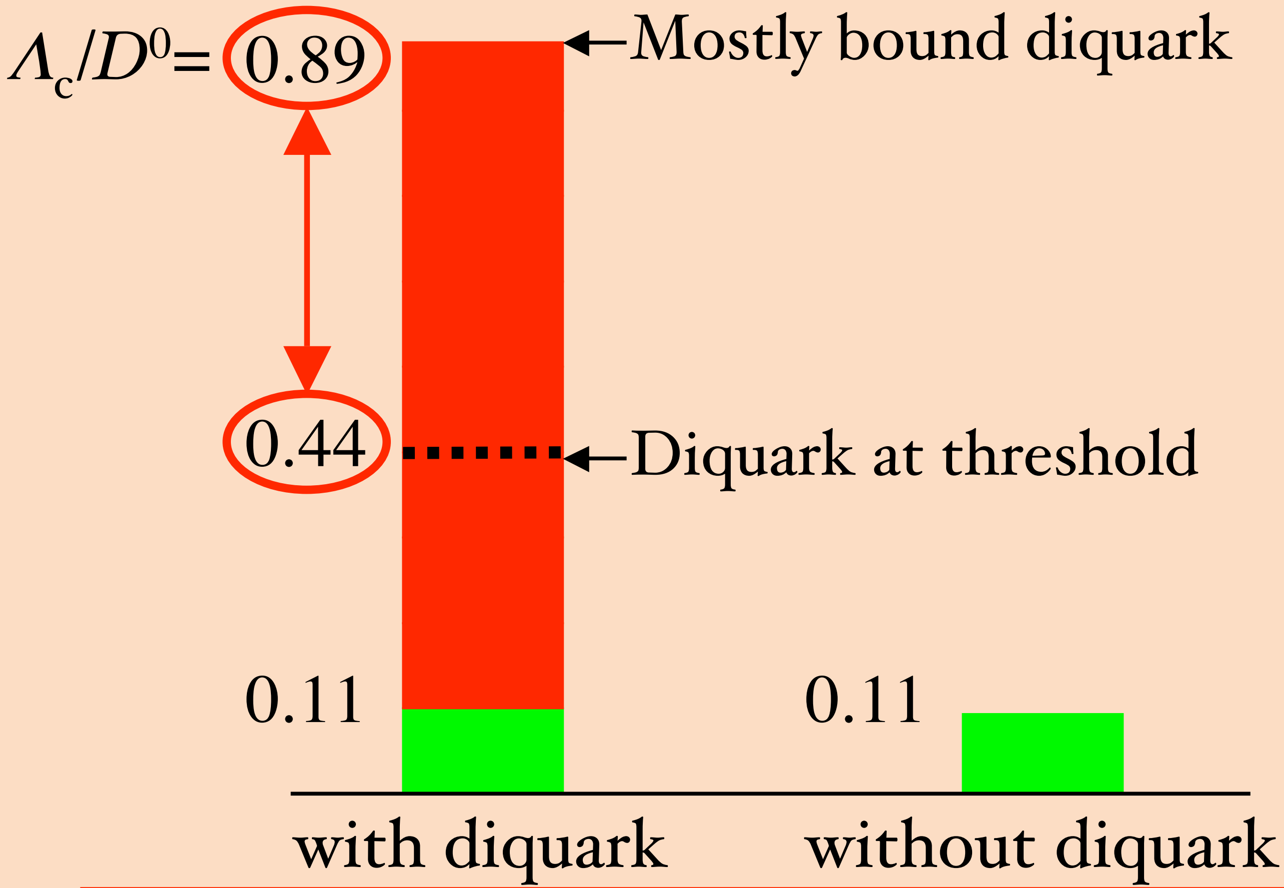


Substantial increase of Λ_c/D^0 by diquark !!

Discussions

Comparison with another phenomena

<u>Without</u> diquark correlation

1. statistical model : $\Lambda_c/D^0 = 0.09$

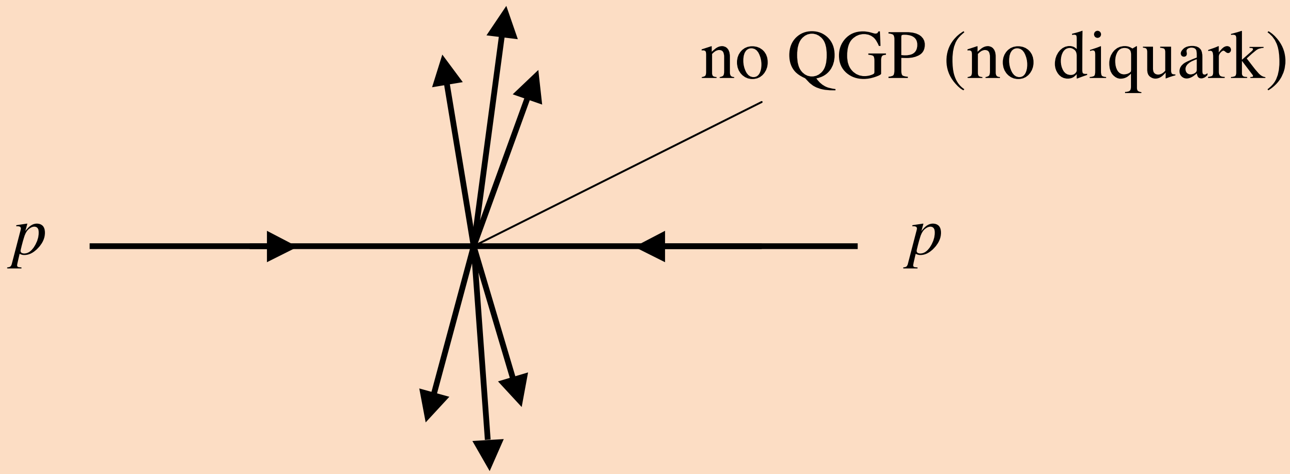
$$\exp(-(m_{\Lambda_c} - m_{D^0})/T_{\mathrm{C}}) \simeq 0.09$$

Discussions

Comparison with another phenomena

<u>Without</u> diquark correlation

1. statistical model : $\Lambda_c/D^0 = 0.09$
2. pp collisions : $\Lambda_c/D^0 = 0.159$ (SELEX)

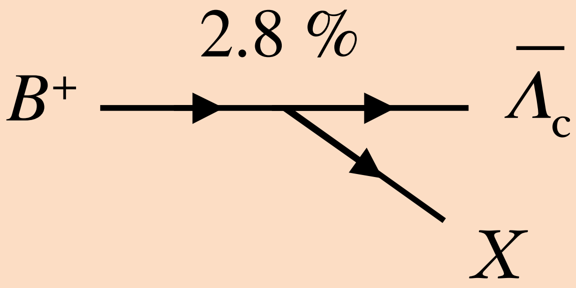


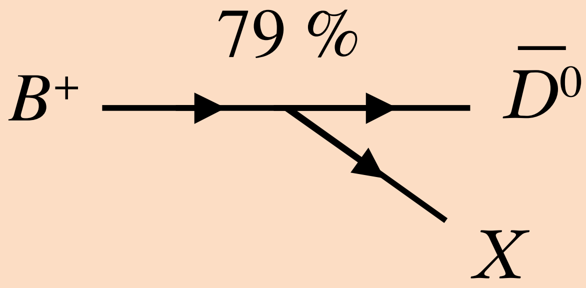
Discussions

Comparison with another phenomena

<u>Without</u> diquark correlation

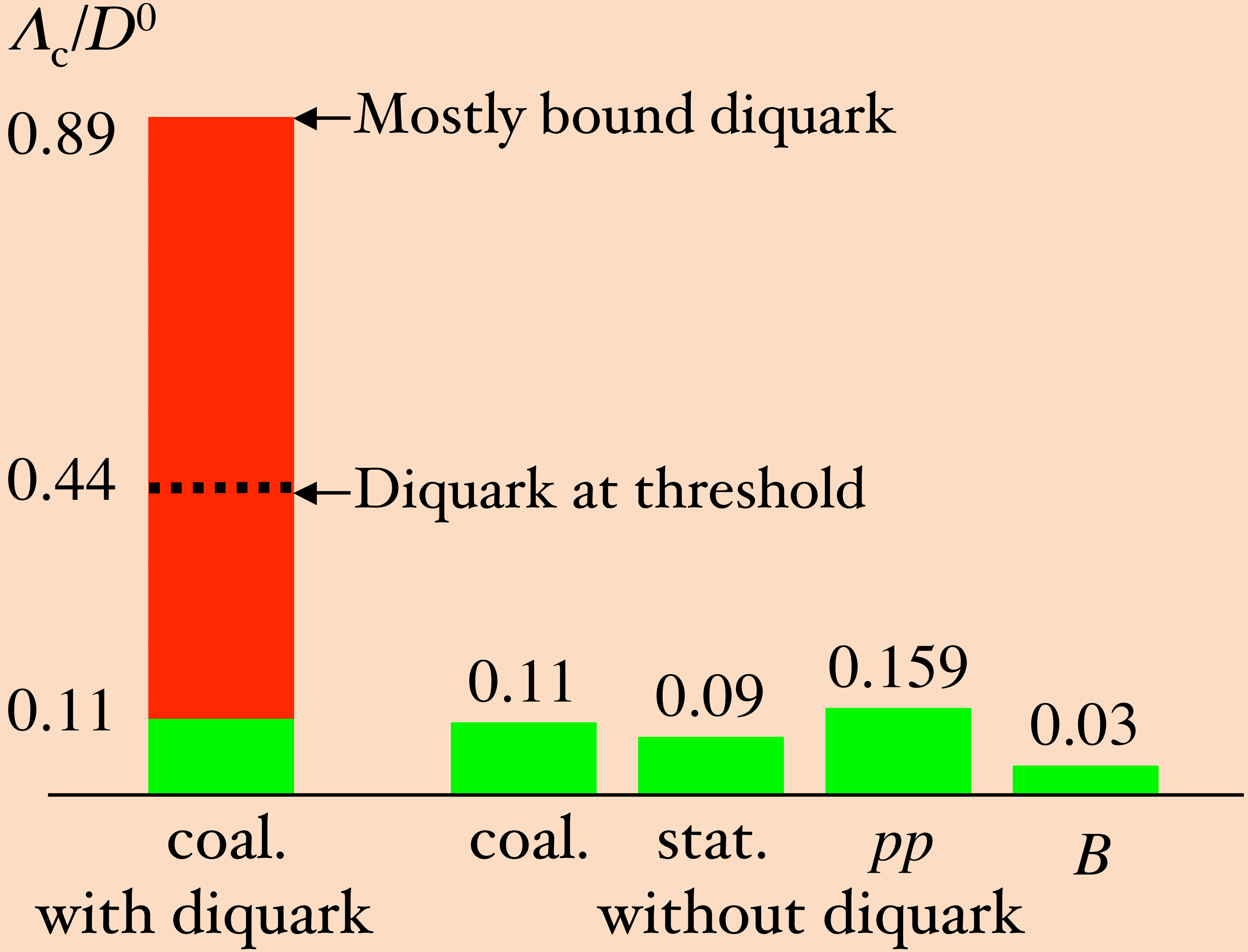
1. statistical model : $\Lambda_c/D^0 = 0.09$
2. *pp* collisions : $\Lambda_c/D^0 = 0.159$ (SELEX)
3. *B* decay : $\Lambda_c/D^0 = 0.03$





PDG2006

Discussions



Discussions

Experiments

1. much abundance of c quarks in heavy ion collisions

    1.1. estimate by initial hard scattering of nucleons

    $N_c = 3$ by Au+Au collisions at $s_{\mathrm{NN}}^{1/2} = 200$ GeV

    $N_c = 20$ by Pb+Pb collisions at $s_{\mathrm{NN}}^{1/2} = 5.5$ TeV

Discussions

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   1.2. free c quarks in QGP

   $\bar{c}c$ pairs are resolved as J/ψ suppression

Discussions

Experiments

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    1.2. free c quarks in QGP
        $\bar{c}c$ pairs are resolved as J/ψ suppression
2. enhanced tracking system for charmed hadrons
    sensitivity to short lifetime (cτ~60mm)
        ALICE at LHC
        STAR and PHENIX at RHIC

Summary

Diquarks in QGP enhance $\Lambda_{c,b}$ yield from heavy ion collisions.

We propose to measure Λ_c/D^0 in LHC and RHIC.

- ☑ New way to observe the existence of QGP.
- ☑ Experimental approach to study diquark correlation.
- ☑ Diquark structure in heavy baryons with single heavy quark.