

Doubly Heavy Baryon in Heavy-ion Collisions

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arXiv:1801.02652

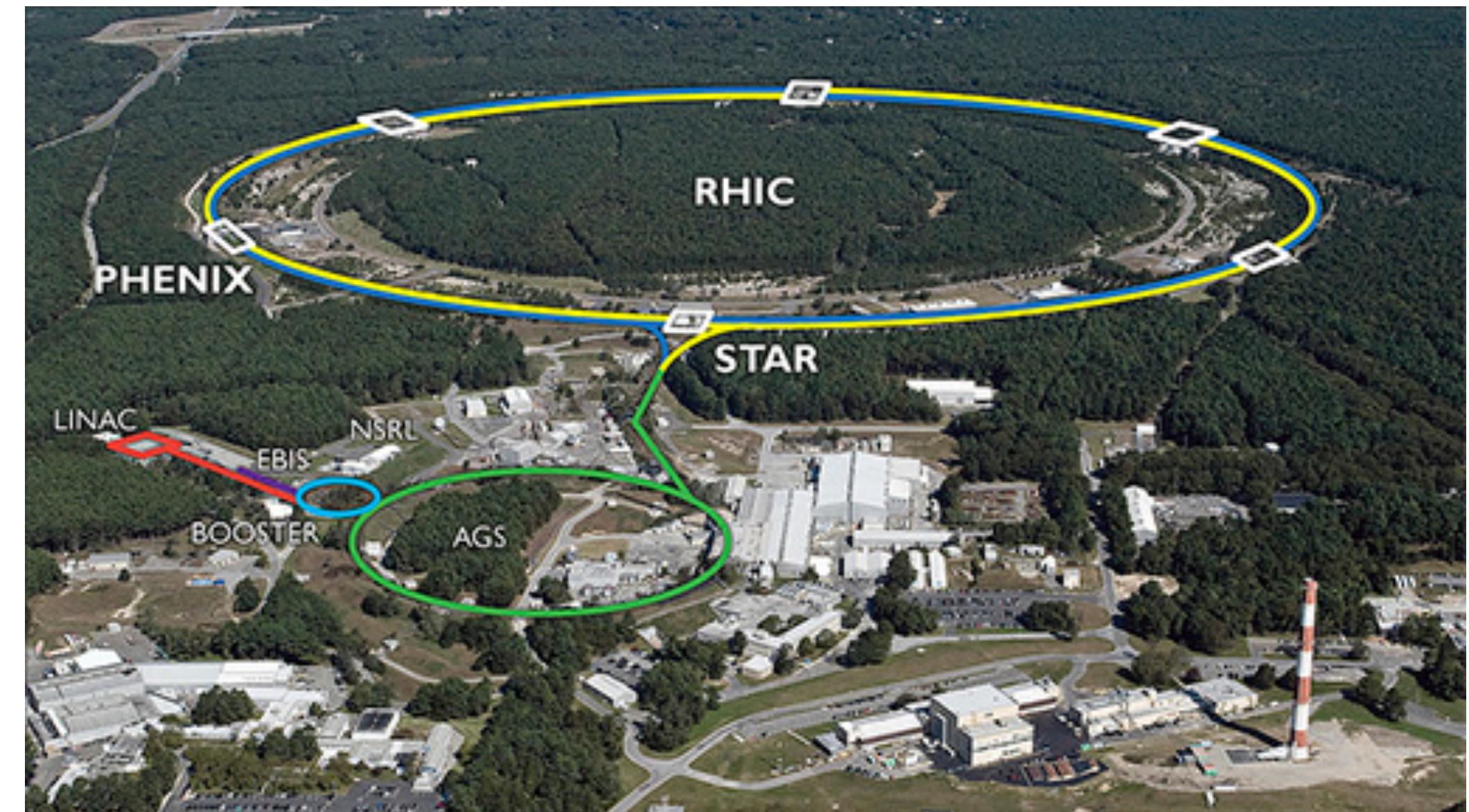
May 30 2018, SCGP
Exotic Hadrons and Flavor Physics Workshop

Contents

- Introduction: heavy-ion collision, doubly heavy baryon
- Plasma screening effect: static v.s. dynamical
- In-medium diquarks: Boltzmann equations and effective field theory
- Detailed balance, approach equilibrium
- Prediction, extension to doubly heavy tetraquarks
- Summary

Heavy-ion Collisions Quark-gluon Plasma

- High energy Au-Au, Pb-Pb collisions at RHIC and LHC
- Hot medium where free quarks and gluons exist (deconfined) — quark-gluon plasma
- QGP expands and cools, transition to confined hadronic gas at $T \sim 154$ MeV
- Phenomena: collectivity, heavy quark energy loss, quarkonium suppression, jet quenching ...



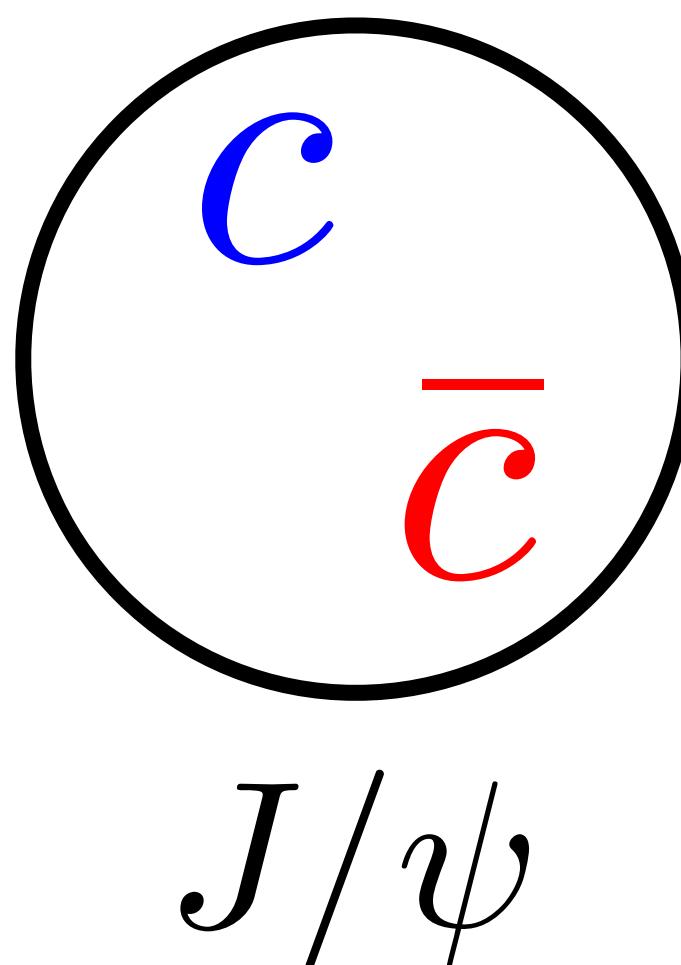
Doubly Charmed Baryon

- LHCb observed a new baryon Ξ_{cc}^{++} (ccu): u bound around cc core

LHCb, Phys. Rev. Lett. 119, no.11, 112001 (2017)

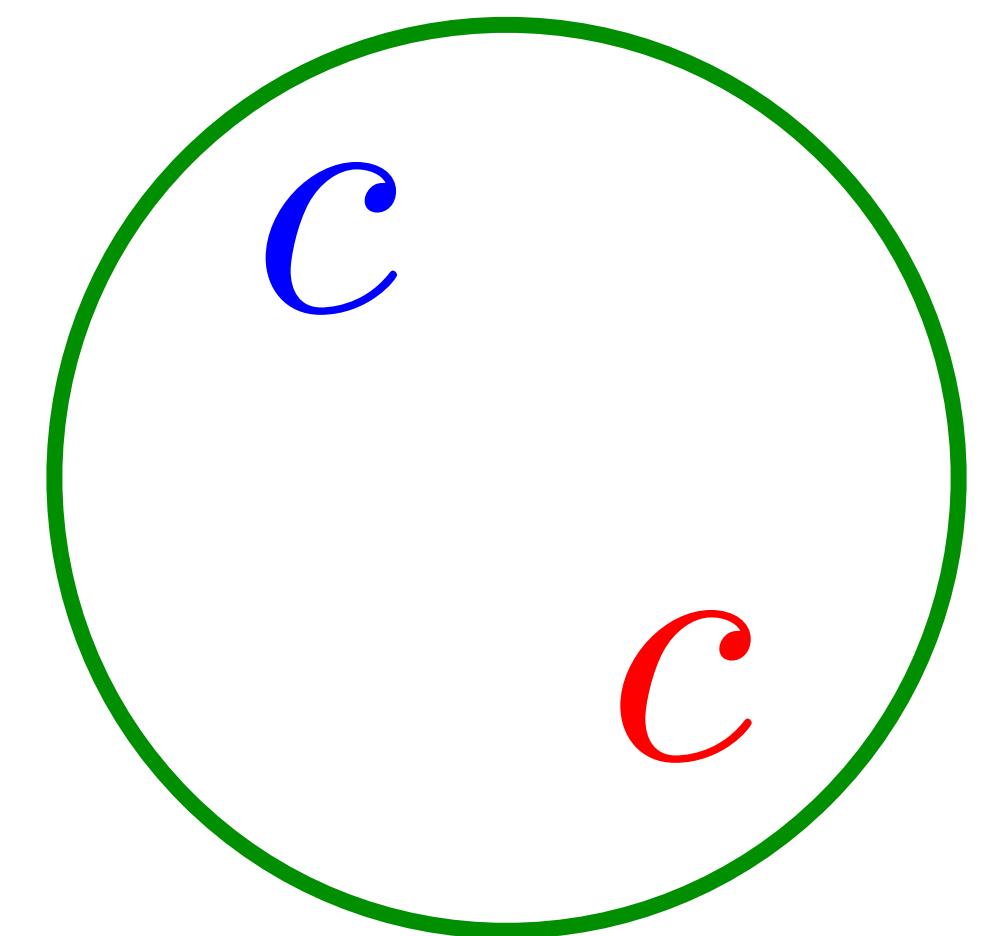
- Pair of heavy Q in anti-triplet forms bound state (diquark)

M. Karliner, J. Rosner Phys. Rev. D 90, no. 9, 094007(2014)



$Q\bar{Q}$ singlet
color neutral
exist in vacuum

J/ψ



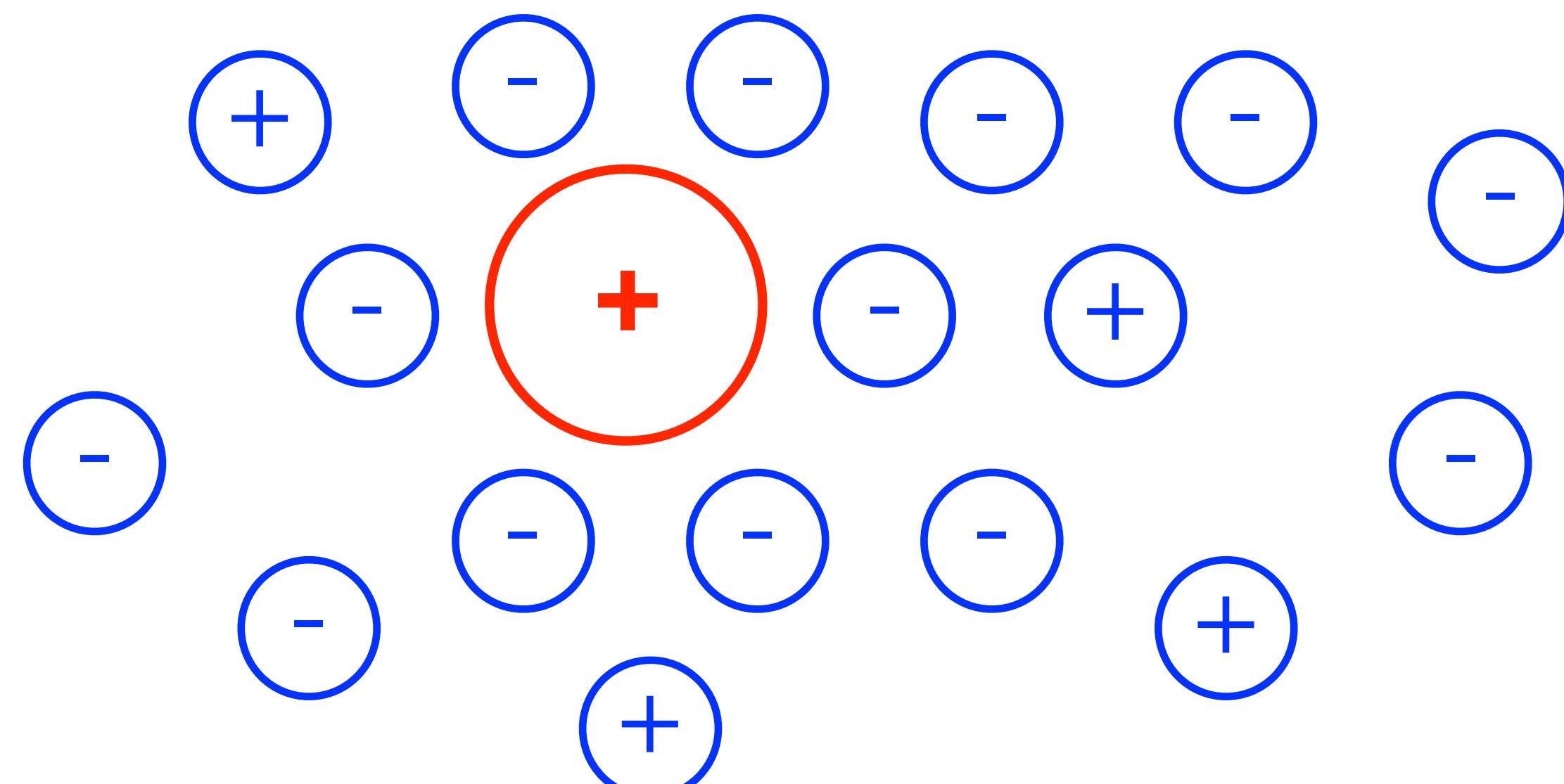
cc diquark (1S)

QQ anti-triplet
colored
not exist in vacuum
exist in QGP

- What happens to cc(1S) inside QGP ?

Plasma Screening Effect

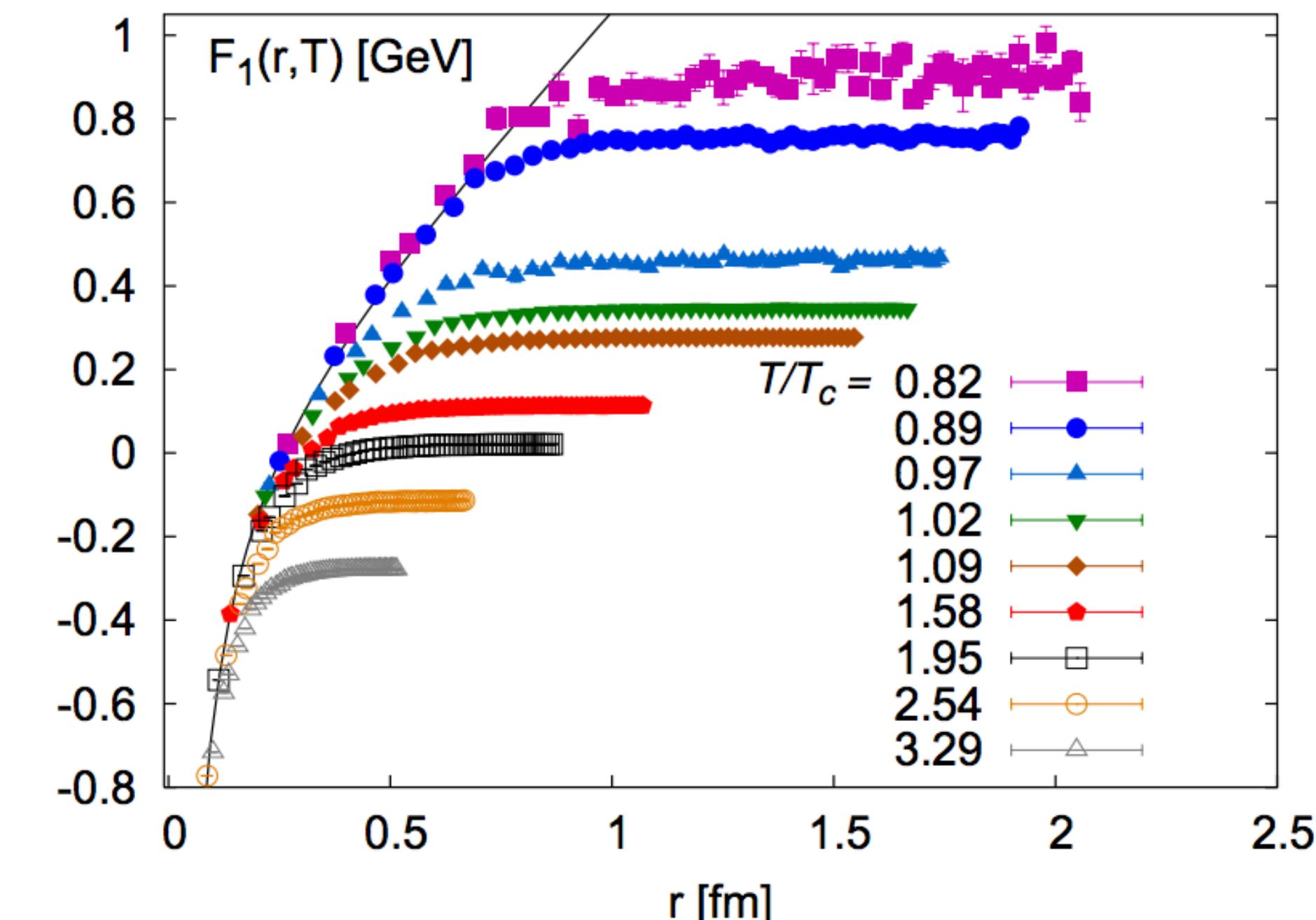
First view in QED:



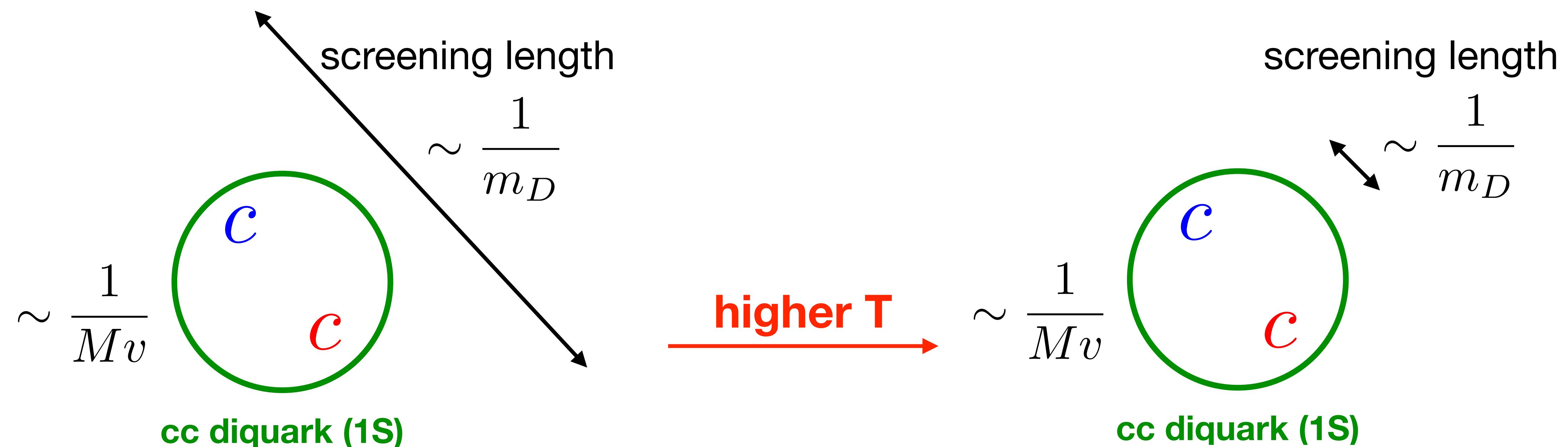
For QCD at finite temperature
lattice studies show string breaking

Second view: thermal field theory
at one loop \rightarrow Debye mass

$$V(r) = \frac{\alpha}{r} \longrightarrow \frac{\alpha}{r} e^{-m_D r}$$



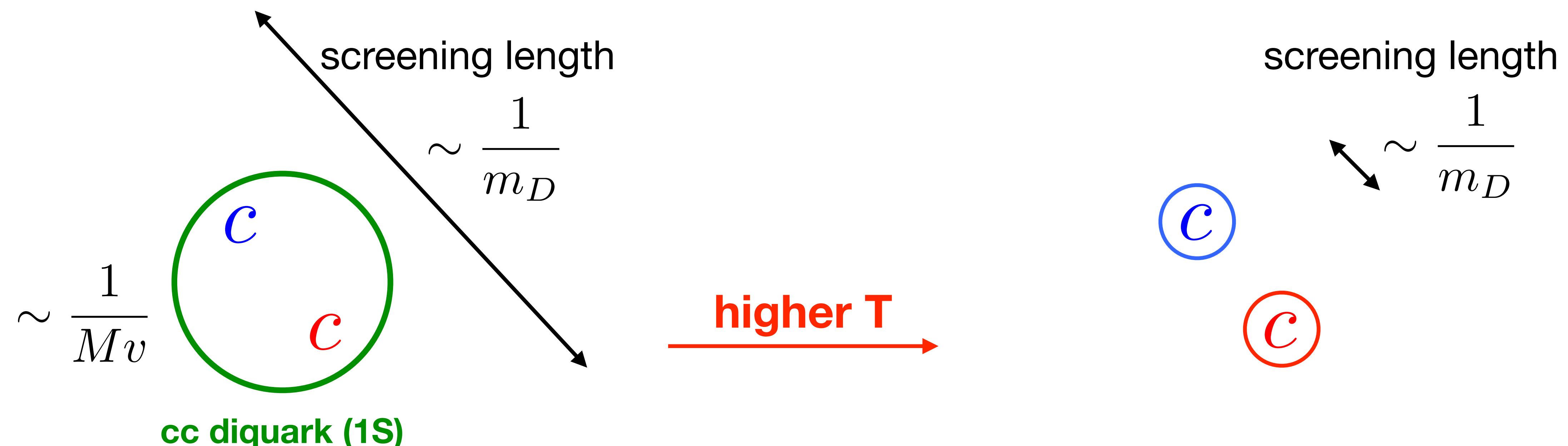
Heavy Diquark inside QGP: Static Screening



no significant screening
respond as a whole (anti-triplet)

significant screening
no more bound state
respond individually as free quarks

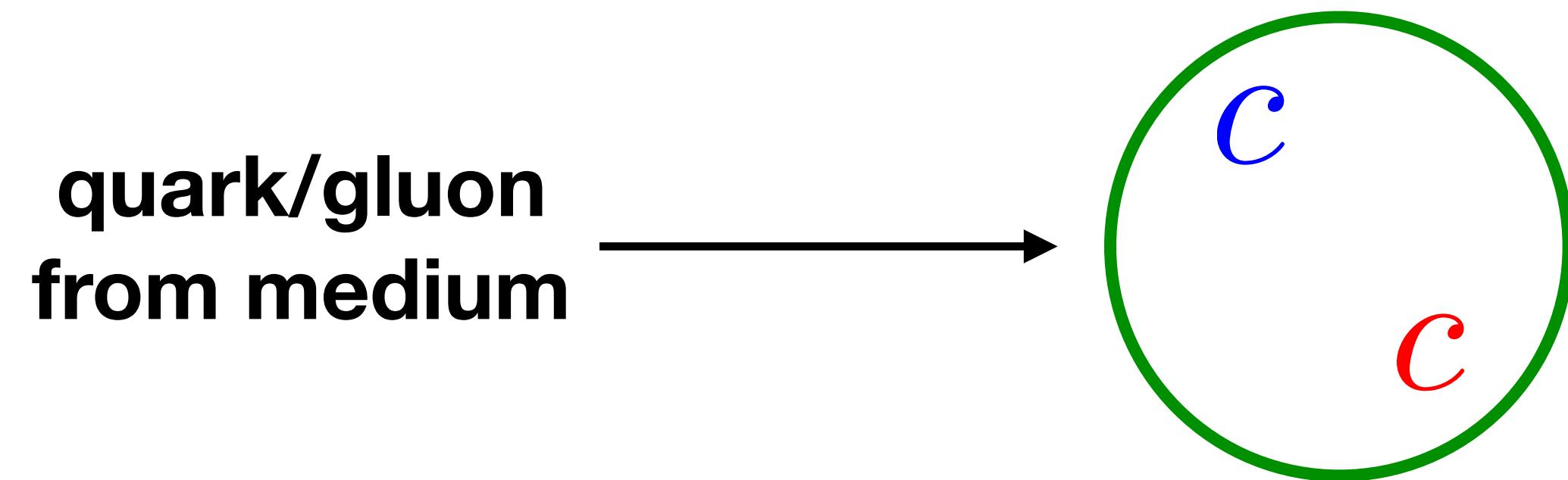
Heavy Diquark inside QGP: Static Screening



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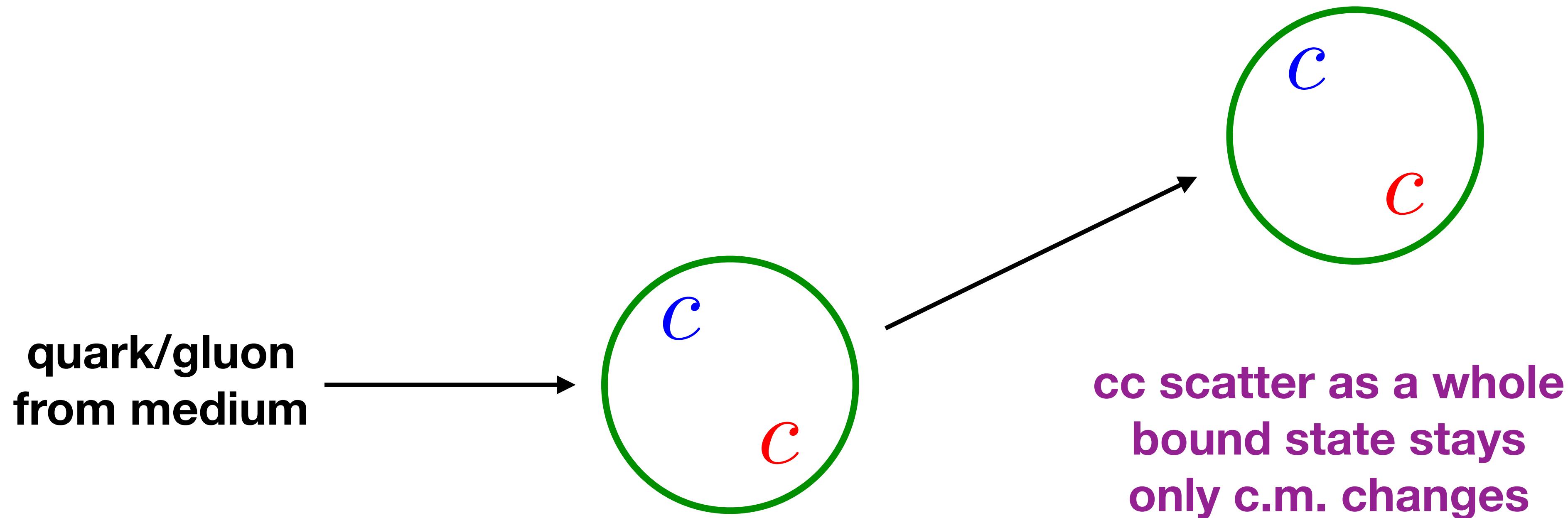
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Heavy Diquark inside QGP: Dynamical Screening



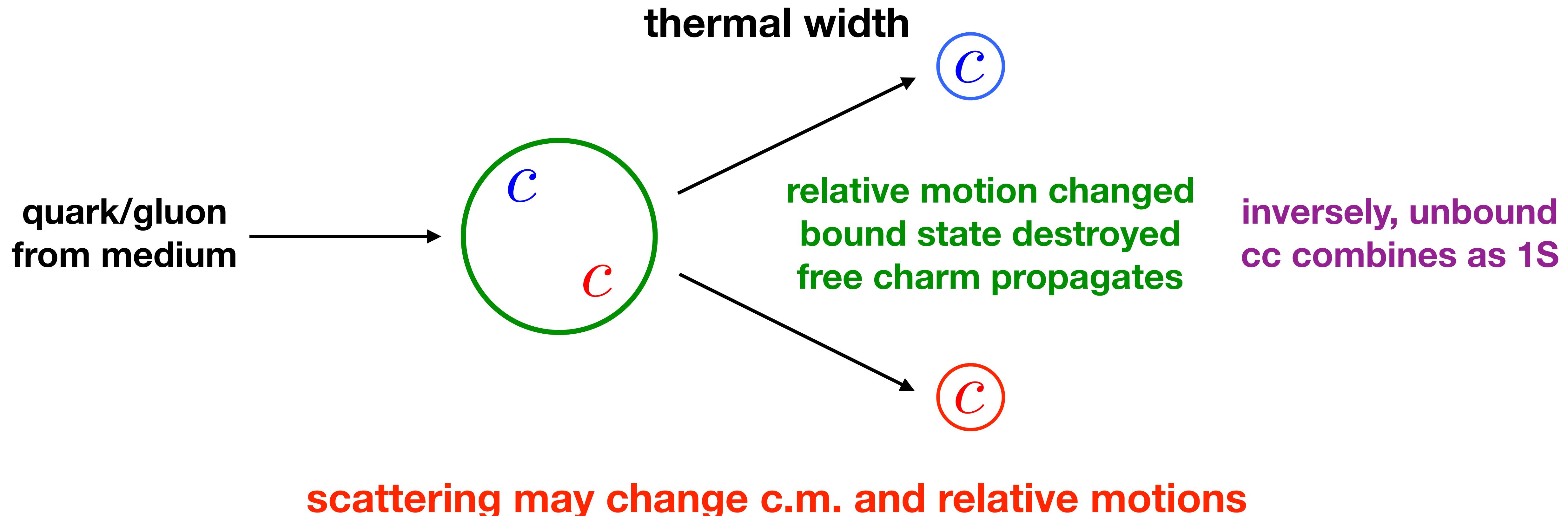
scattering may change c.m. and relative motions

Heavy Diquark inside QGP: Dynamical Screening

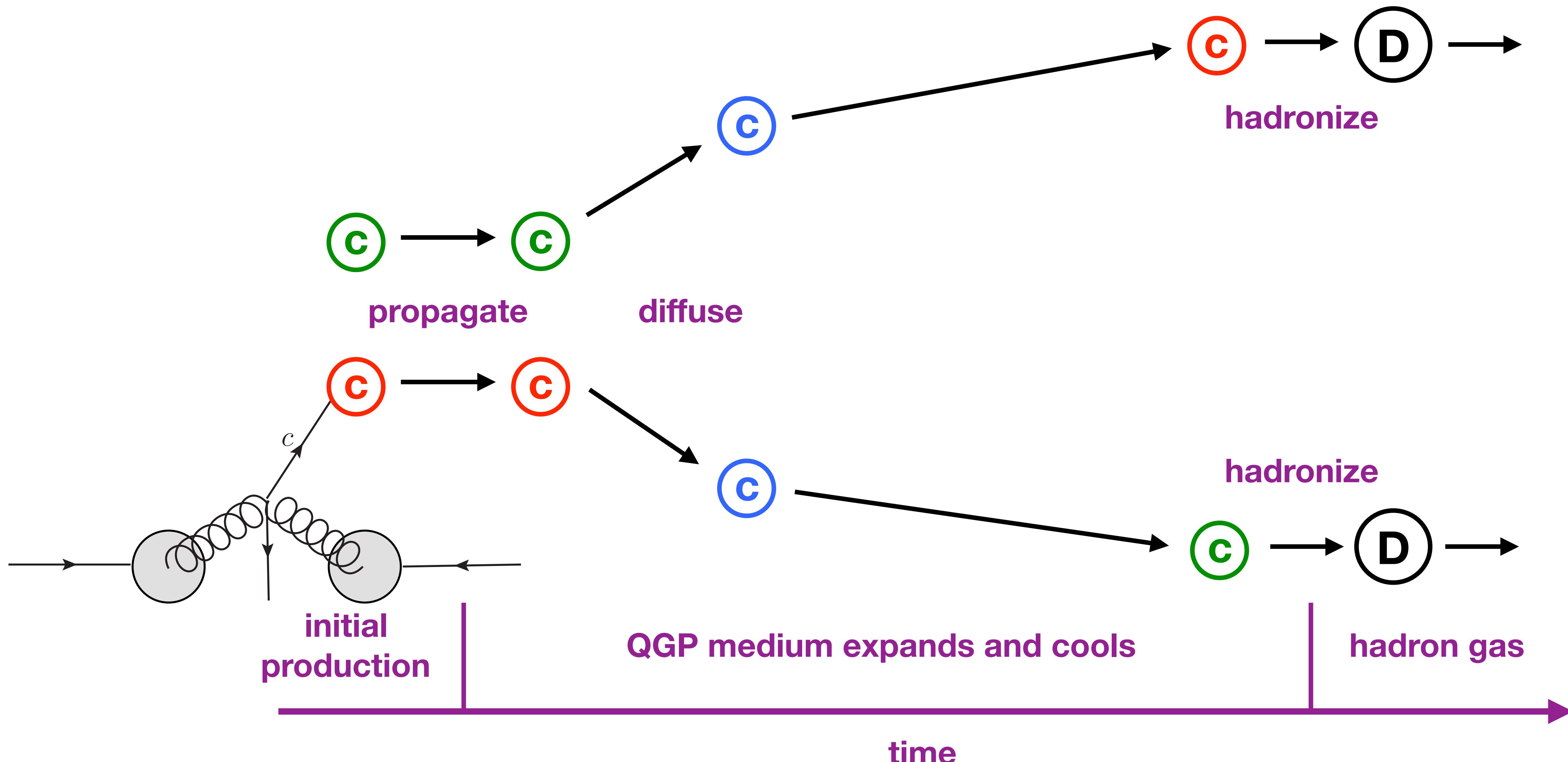


scattering may change c.m. and relative motions

Heavy Diquark inside QGP: Dynamical Screening



Dynamical Evolution inside QGP

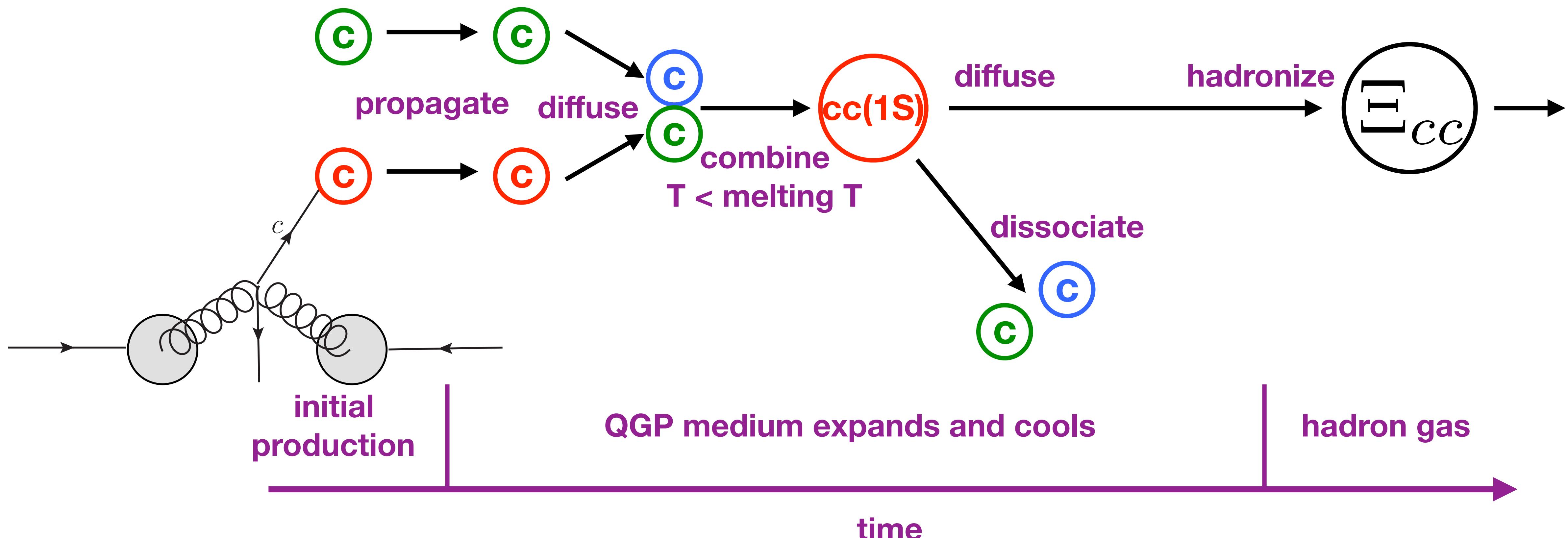


Dynamical Evolution inside QGP

melting temperature: above which a specific bound state

1) ill defined (thermal width too large)

2) not exists (potential not supports bound state)



Coupled Boltzmann Equations

charm quark	$\left(\frac{\partial}{\partial t} + \dot{x} \cdot \nabla_x \right) f_c(x, p, t) = \mathcal{C}_c - \mathcal{C}_c^+ + \mathcal{C}_c^-$
cc diquark (1S)	$\left(\frac{\partial}{\partial t} + \dot{x} \cdot \nabla_x \right) f_{cc}(x, p, t) = \mathcal{C}_{cc} + \mathcal{C}_{cc}^+ - \mathcal{C}_{cc}^-$

Coupled Boltzmann Equations

phase space evolution
of distribution function

charm quark

$$\left(\frac{\partial}{\partial t} + \dot{x} \cdot \nabla_x \right) f_c(x, p, t)$$

cc diquark (1S)

$$\left(\frac{\partial}{\partial t} + \dot{x} \cdot \nabla_x \right) f_{cc}(x, p, t)$$

energy loss (diffusion)

$$= \mathcal{C}_c - \mathcal{C}_c^+ + \mathcal{C}_c^-$$
$$= \mathcal{C}_{cc} + \mathcal{C}_{cc}^+ - \mathcal{C}_{cc}^-$$

combination dissociation
diquark gain diquark loss
charm quark loss charm quark gain

Heavy Quark Energy Loss: Linearized Boltzmann

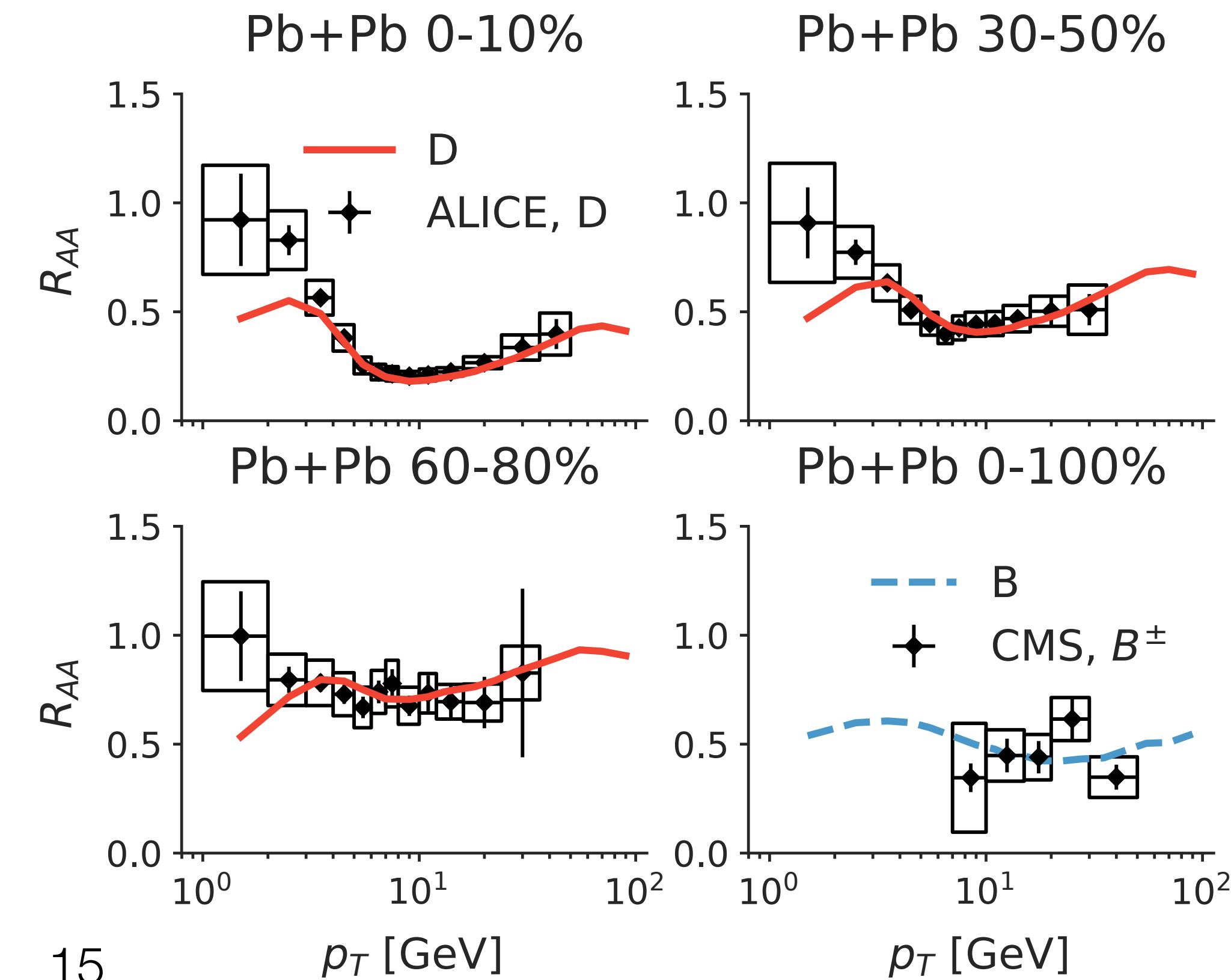
- Collision terms: $gQ \rightarrow gQ$, $qQ \rightarrow qQ$, $gQ \rightarrow gQg$, $qQ \rightarrow qQg$, $gQg \rightarrow gQ$, $qQg \rightarrow qQ$
(Landau-Pomeranchuk-Migdal effect)

Gossiaux, Aichelin Phys.Rev.C78,014904(2008)

Gossiaux, Bierkandt, Aichelin Phys.Rev.C79,044906(2009)

Uphoff, Fochler, Xu, Greiner J.Phys.G42,no.11,115106(2015)

- Specific implementation: Duke LBT
describe open heavy R_{AA} and v_2
developed by Weiyao Ke, Yingru Xu,
Steffen Bass (Duke)



Separating C.M. and Relative Motions

non-relativistic heavy quark

$$\mathcal{L}_{NRQCD} = Q^\dagger \left(iD_0 + \frac{D^2}{2m} + \dots \right) Q$$

pair of heavy quarks

$$Q_i(\mathbf{x}_1, t) Q_j(\mathbf{x}_2, t) \sim t_{ij}^l T^l(\mathbf{R}, \mathbf{r}, t) + \sigma_{ij}^\nu \Sigma^\nu(\mathbf{R}, \mathbf{r}, t)$$

anti-triplet field

sextet field

$$Q_i(\mathbf{x}_1, t) Q_j(\mathbf{x}_2, t) = U_{ii'}(\mathbf{x}_1, \mathbf{R}, t) U_{jj'}(\mathbf{x}_2, \mathbf{R}, t) \left[t_{ij}^l T^l(\mathbf{R}, \mathbf{r}, t) + \sigma_{ij}^\nu \Sigma^\nu(\mathbf{R}, \mathbf{r}, t) \right]$$

gauge links

$$t_{ij}^l = \frac{1}{\sqrt{2}} \epsilon_{ijl}$$

$$\sigma_{11}^1 = \sigma_{22}^4 = \sigma_{33}^6 = 1$$

NR and multipole expansion

$$\sigma_{12}^2 = \sigma_{21}^2 = \sigma_{13}^3 = \sigma_{31}^3 = \sigma_{23}^5 = \sigma_{32}^5 = \frac{1}{\sqrt{2}}$$

Effective Field Theory: pNRQCD

$$\mathcal{L}_{\text{pNRQCD}} = \int d^3r \text{ Tr} \left\{ T^\dagger (iD_0 - H_T) T + \Sigma^\dagger (iD_0 - H_\Sigma) \Sigma + \boxed{T^\dagger \mathbf{r} \cdot gE \Sigma + \Sigma^\dagger \mathbf{r} \cdot gE T} + \dots \right\}$$

Degrees of freedom: anti-triplet and sextet

$$T = t^l T^l$$

$$\Sigma = \sigma^\nu \Sigma^\nu$$

**multipole expansion
color dipole interaction**

Free field EoM: Schrodinger equation

N. Brambilla, A. Vairo and T. Rosch, Phys. Rev. D 72, 034021 (2005)

S. Fleming and T. Mehen, Phys. Rev. D 73, 034502 (2006)

Non-relativistic expansion in $1/M$

$$H_{T,\Sigma} = -\frac{D_R^2}{4M} \boxed{-\frac{\nabla_r^2}{M} + V_{T,\Sigma}^{(0)}} + \frac{V_{T,\Sigma}^{(1)}}{M} + \frac{V_{T,\Sigma}^{(2)}}{M^2} + \dots$$

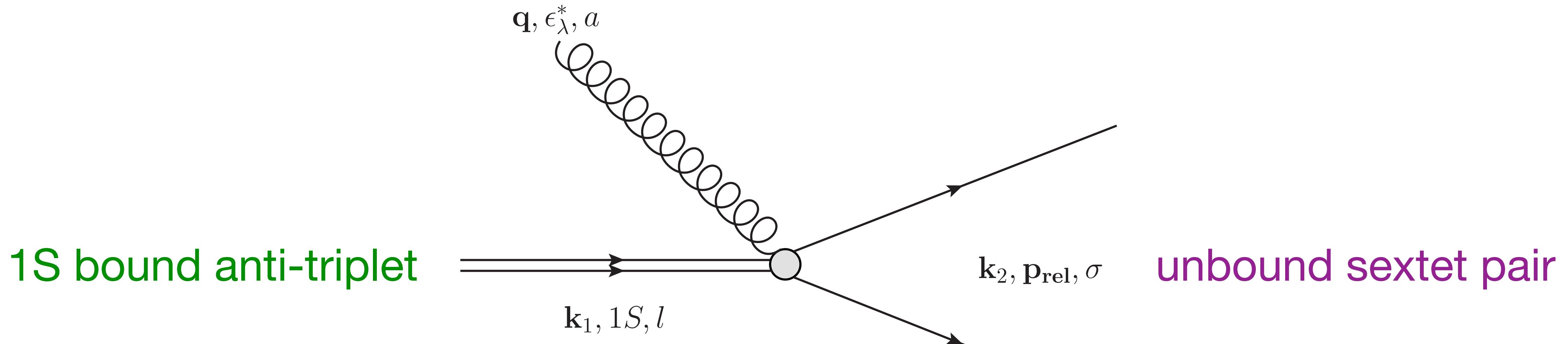
$$V_T^{(0)} = -\frac{2}{3} \frac{\alpha_s}{r}$$

$$V_\Sigma^{(0)} = \frac{1}{3} \frac{\alpha_s}{r}$$

virial theorem: same order

Separation of scales: $M \gg Mv \gg Mv^2, T, m_D$

LO Scattering Amplitude



$$\mathcal{T}_\lambda^{\nu la} = (2\pi)^4 \delta^3(\mathbf{k}_1 + \mathbf{q} - \mathbf{k}_2) \delta\left(\frac{k_1^2}{4M} + E_{1S} + q - \frac{k_2^2}{4M} - \frac{p_{\text{rel}}^2}{M}\right) \mathcal{M}_\lambda^{\nu la}$$

$$\mathcal{M}_\lambda^{\nu la} = -igq \text{Tr}(\sigma^\nu t_F^a t^l)(\epsilon_\lambda^*)_i \langle \psi_{1S} | r_i | \Psi_{\mathbf{p}_{\text{rel}}} \rangle \quad \text{LO in } 1/M$$

$$|\mathcal{M}|^2 \equiv \sum_{a=1}^8 \sum_{l=1}^3 \sum_{\nu=1}^6 \sum_{\lambda=\pm}^6 |\mathcal{M}_\lambda^{\nu la}|^2 = 2g^2 q^2 |\langle \Psi_{\mathbf{p}_{\text{rel}}} | \mathbf{r} | \psi_{1S} \rangle|^2$$

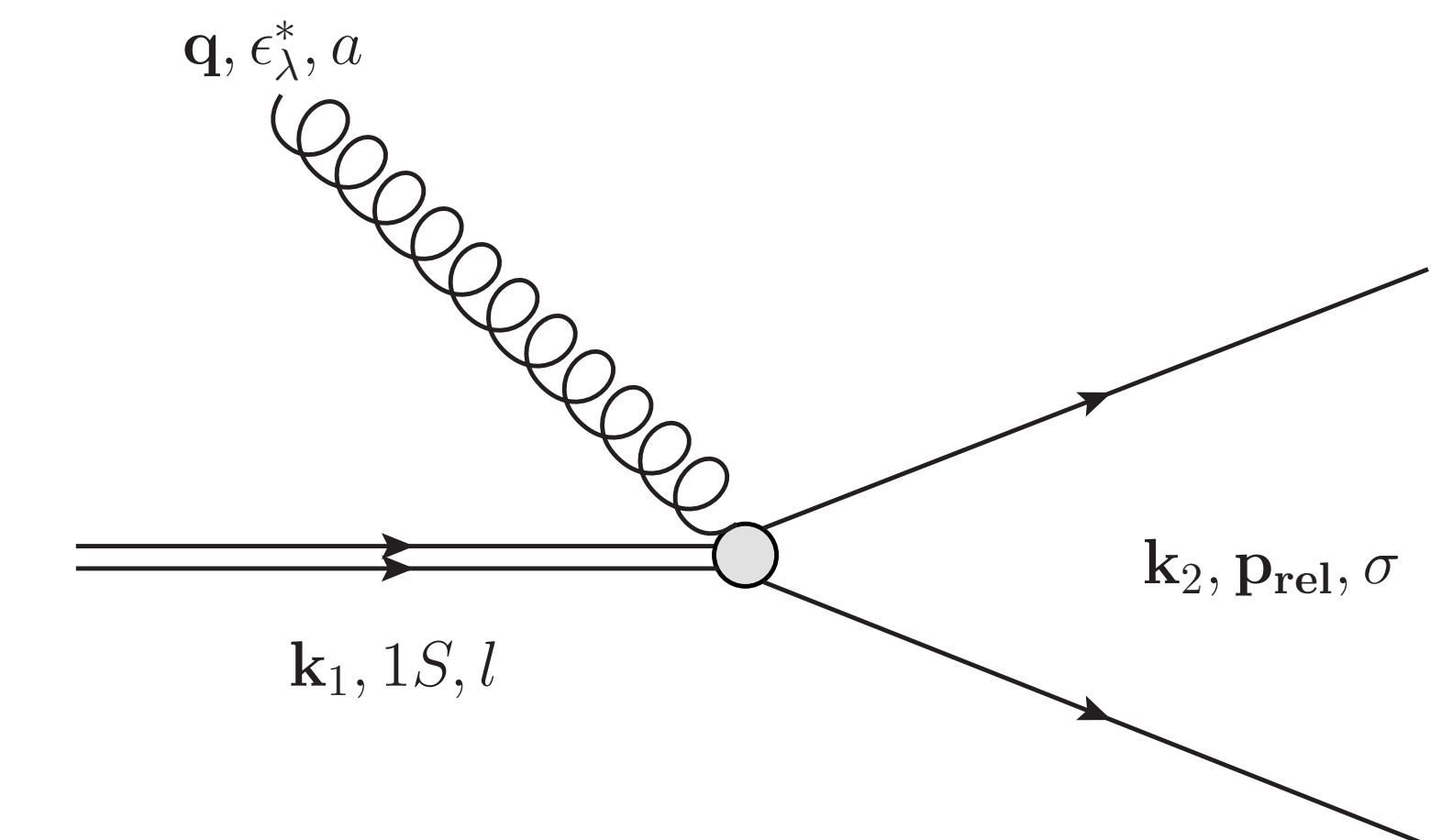
Coulomb wave
function (scattering)

Hydrogen-like
wave function (bound)

Dissociation and Combination

$$\left(\frac{\partial}{\partial t} + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} \right) f_c(\mathbf{x}, \mathbf{p}, t) = \mathcal{C}_c \boxed{- \mathcal{C}_c^+ + \mathcal{C}_c^-}$$

$$\left(\frac{\partial}{\partial t} + \dot{\mathbf{x}} \cdot \nabla_{\mathbf{x}} \right) f_{cc}(\mathbf{x}, \mathbf{p}, t) = \mathcal{C}_{cc} \boxed{+ \mathcal{C}_{cc}^+ - \mathcal{C}_{cc}^-}$$



$$\mathcal{F}^+ \equiv \frac{1}{2} g_+ \int \frac{d^3 p_1}{(2\pi)^3} \frac{d^3 p_2}{(2\pi)^3} \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 q}{(2\pi)^3 2q} (1 + n_B^{(q)}) f_c(\mathbf{x}, \mathbf{p}_1, t) f_c(\mathbf{x}, \mathbf{p}_2, t) (2\pi)^4 \delta^3(\mathbf{k}_1 + \mathbf{q} - \mathbf{k}_2) \delta(\Delta E) |\mathcal{M}|^2$$

$$\mathcal{F}^- \equiv \frac{1}{2} g_- \int \frac{d^3 k_1}{(2\pi)^3} \frac{d^3 k_2}{(2\pi)^3} \frac{d^3 p_{\text{rel}}}{(2\pi)^3} \frac{d^3 q}{(2\pi)^3 2q} n_B^{(q)} f_{cc}(\mathbf{x}, \mathbf{k}_1, t) (2\pi)^4 \delta^3(\mathbf{k}_1 + \mathbf{q} - \mathbf{k}_2) \delta(\Delta E) |\mathcal{M}|^2$$

$$g_+ = \frac{3}{4} \frac{d_6}{N_c^2} \frac{1}{d_6} = \frac{1}{12}$$

$$\begin{aligned} \frac{\delta}{\delta \mathbf{p}_i} \int \prod_{j=1}^n \frac{d^3 p_j}{(2\pi)^3} h(\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_n) \Big|_{\mathbf{p}_i=\mathbf{p}} &\equiv \frac{\delta}{\delta a(\mathbf{p})} \int \prod_{j=1}^n \frac{d^3 p_j}{(2\pi)^3} h(\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_n) a(\mathbf{p}_i) \\ &= \int \prod_{j=1, j \neq i}^n \frac{d^3 p_j}{(2\pi)^3} h(\mathbf{p}_1, \mathbf{p}_2, \dots, \mathbf{p}_{i-1}, \mathbf{p}, \mathbf{p}_{i+1}, \dots, \mathbf{p}_n) \end{aligned}$$

$$\mathcal{C}_c^\pm = \frac{\delta \mathcal{F}^\pm}{\delta \mathbf{p}_1} \Big|_{\mathbf{p}_1=\mathbf{p}} + \frac{\delta \mathcal{F}^\pm}{\delta \mathbf{p}_2} \Big|_{\mathbf{p}_2=\mathbf{p}}$$

$$\mathcal{C}_{cc}^\pm = \frac{\delta \mathcal{F}^\pm}{\delta \mathbf{k}_1} \Big|_{\mathbf{k}_1=\mathbf{p}}$$

formation rate

dissociation rate

$$\mathcal{C}_c^+ \equiv \Gamma_f(\mathbf{x}, \mathbf{p}, t) f_c(\mathbf{x}, \mathbf{p}, t)$$

$$\mathcal{C}_{cc}^- \equiv \Gamma_d(\mathbf{x}, \mathbf{p}, t) f_{cc}(\mathbf{x}, \mathbf{p}, t)$$

Solve Boltzmann Equations

- Test particle Monte Carlo $f(x, p, t) = \sum_i \delta^3(x - \mathbf{y}_i(t)) \delta^3(p - \mathbf{k}_i(t))$
- Each time step: consider diffusion, dissociation, combination (boost to rest frame)
- If specific process occurs (probability = rate times step size), sample incoming medium particles and outgoing particles conserving energy momentum
- Combination term contains $f_c(x, p_1, t) f_c(x, p_2, t)$

Two delta at same x ill-defined, almost never at same point

Enhance sampling for combination, search pairs within a sphere

$$f_c(x, p_1, t) f_c(x, p_2, t) \rightarrow \sum_{i,j} \frac{e^{-(\mathbf{y}_i - \mathbf{y}_j)^2 / 2a_B^2}}{(2\pi a_B^2)^{3/2}} \delta^3 \left(x - \frac{\mathbf{y}_i + \mathbf{y}_j}{2} \right) \delta^3(\mathbf{p}_1 - \tilde{\mathbf{p}}_i) \delta^3(\mathbf{p}_2 - \tilde{\mathbf{p}}_j)$$

Approach Equilibrium

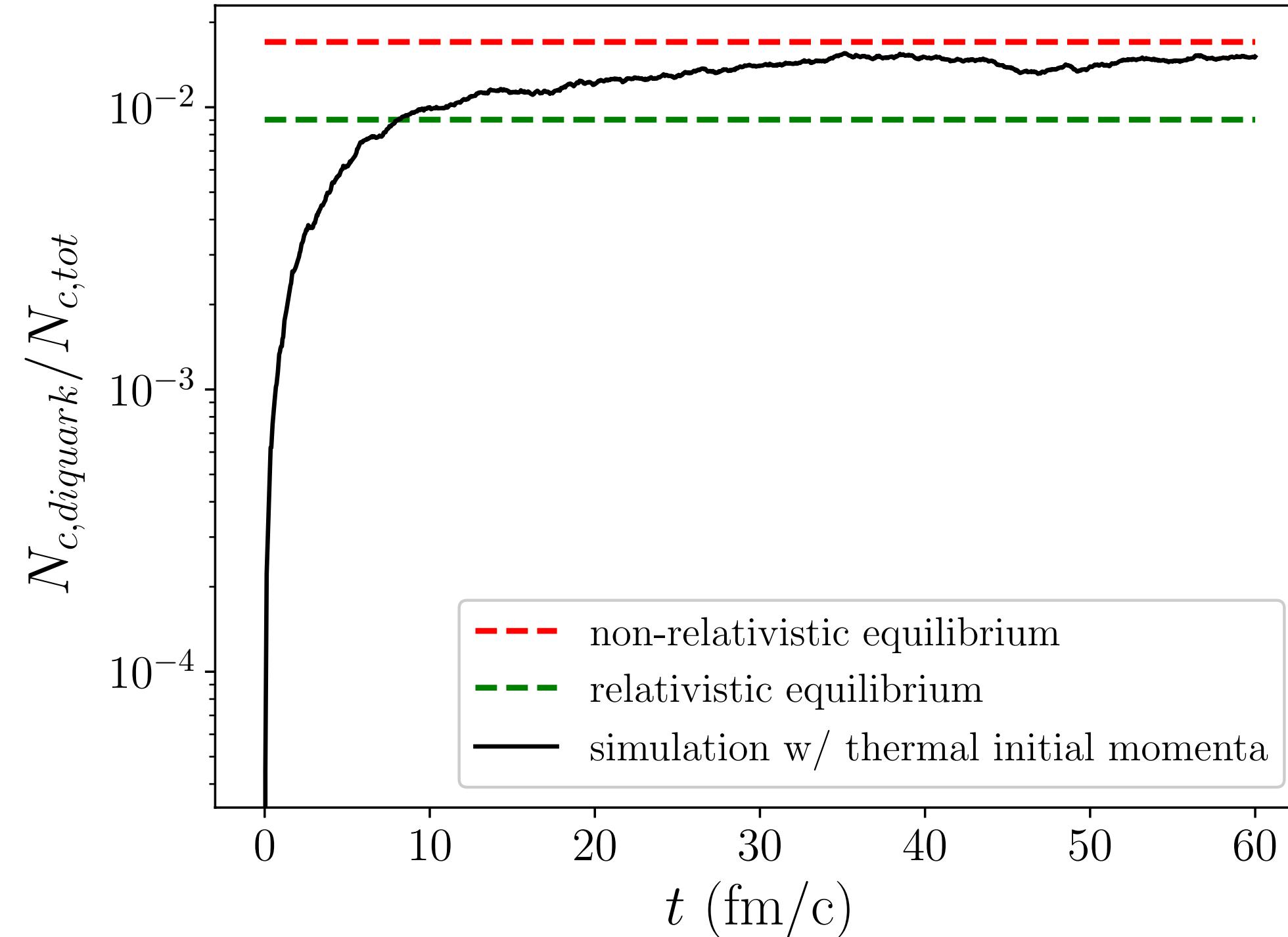
Setup:

QGP box, periodic b.c., constant T, 1S state, c quark

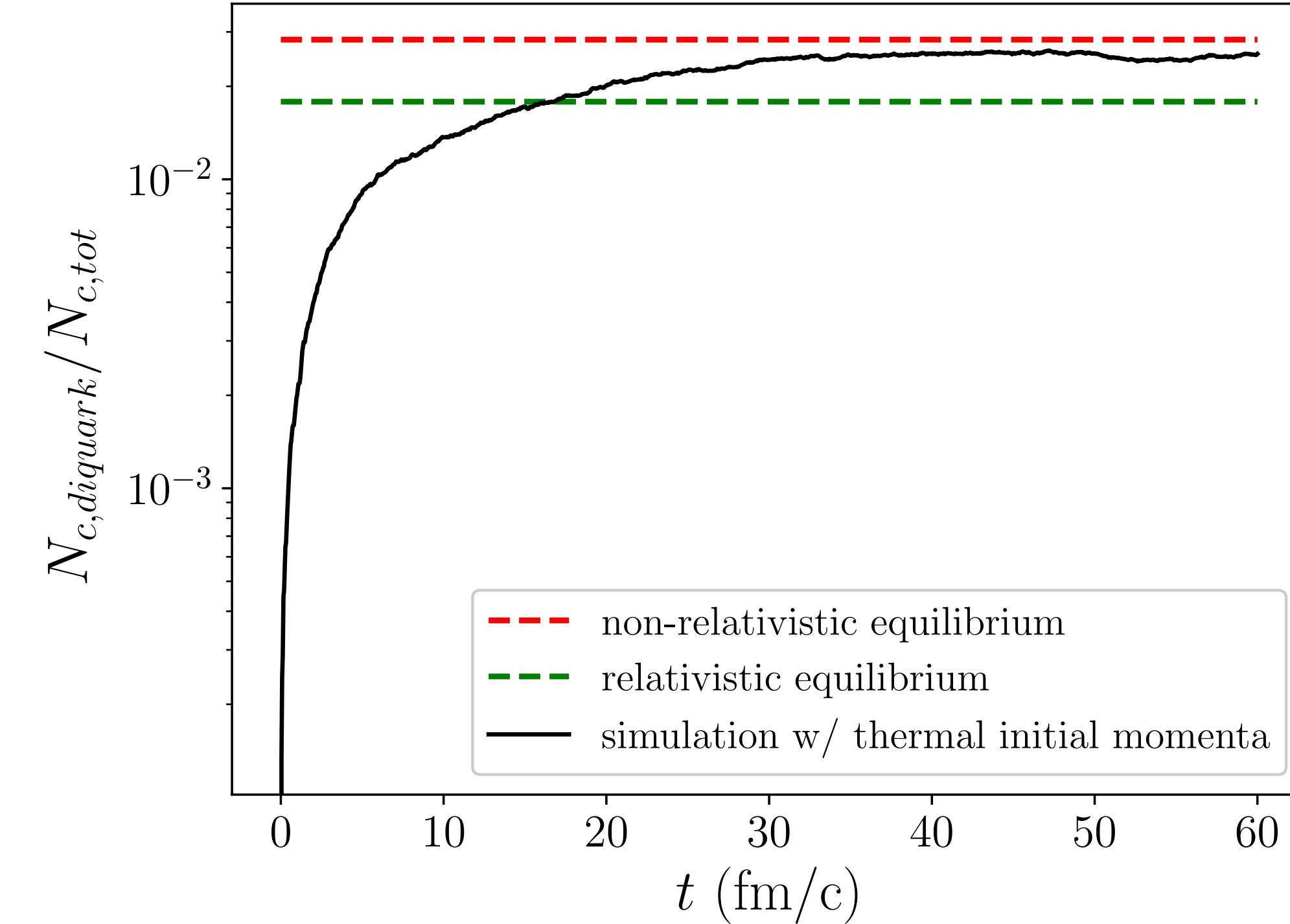
Total c flavor = 30 (fixed) = 2*#1S + #charm

Initial momenta sampled from thermal or uniform distributions

T=350 MeV



T=250 MeV



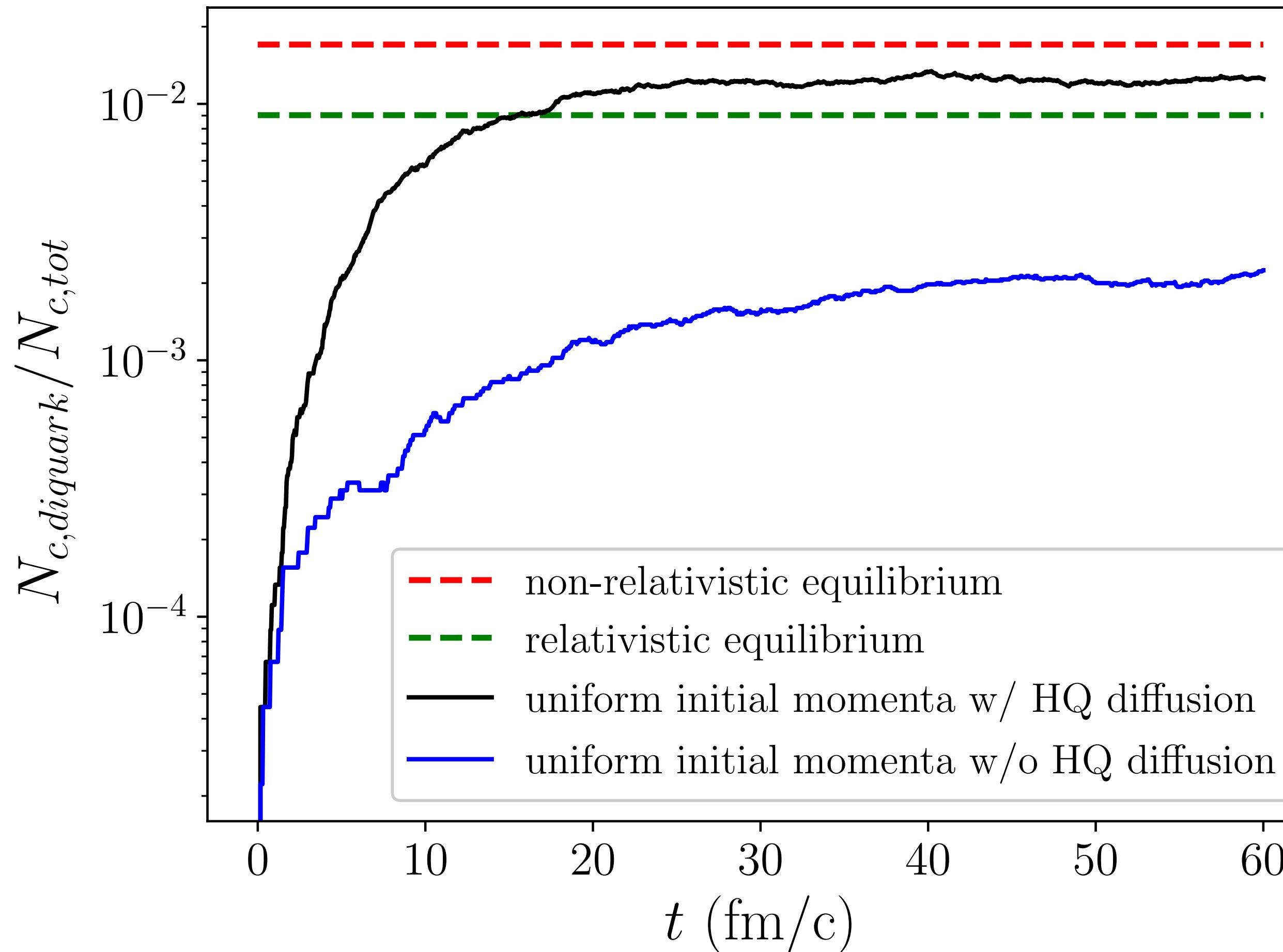
$$N_i^{\text{eq}} = g_i \text{Vol} \int \frac{d^3 p}{(2\pi)^3} \lambda_i e^{-E_i(p)/T}$$

$$\lambda_{cc(1S)} = \lambda_c^2 \quad g_{cc(1S)} = 3 \times 3 \quad g_c = 3 \times 2$$

$$N_c^{\text{eq}} + 2N_{cc(1S)}^{\text{eq}} = N_{c,tot}$$

Detailed Balance

T=350 MeV



three momentum components sampled from
uniform distribution between 0 and 5 GeV

**Dissociation-combination
interplay drives to detailed balance**

**Heavy quark/diquark diffusion
necessary to drive kinetic
equilibrium of system**

Collision Event Simulation

- Initial production: assume no diquarks initially

$$\text{FONLL, scale} = \sqrt{M^2 + p_T^2}$$

Cacciari, Greco, Nason, JHEP 9805 (1998) 007
Cacciari, Frixione, Nason, JHEP 0103 (2001) 006

Nuclear PDF (cold nuclear matter effect)

Eskola, Paukkunen, Salgado,
JHEP 0904 (2009) 065

Trento, sample position, hydro. initial condition

Bernhard, Moreland, Bass, Liu, Heinz,
Phys.Rev.C94,no.2,024907(2016)

- Medium background: 2+1D viscous hydrodynamics

Song, Heinz, Phys.Rev.C77,064901(2008)
Shen, Qiu, Song, Bernhard, Bass, Heinz,
Comput. Phys. Commun.199,61 (2016)

- Consider only 1S, hadronize into (ccu) or (ccd)

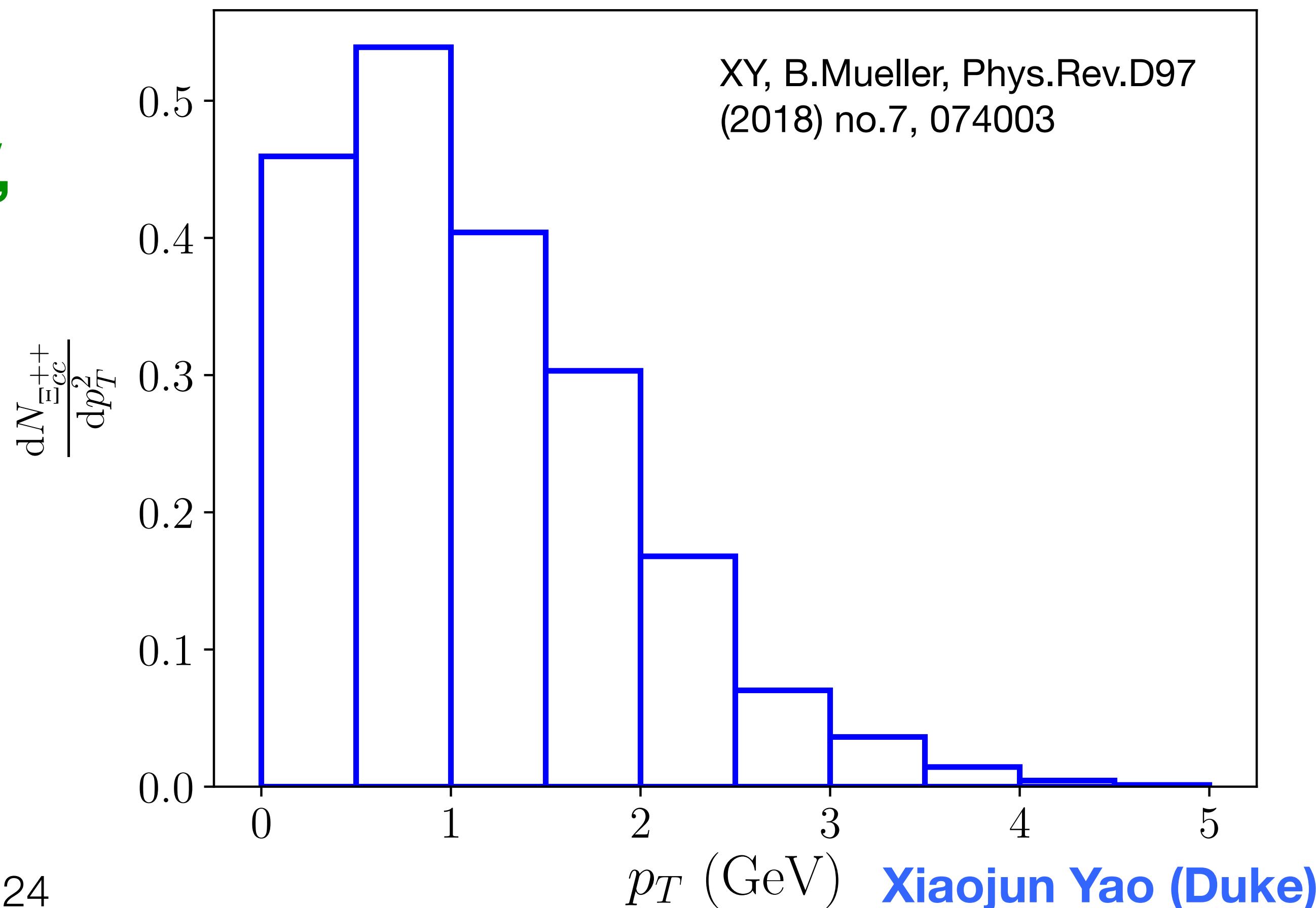
Doubly Charmed Baryon Production in Heavy Ion Collisions

Setup:

2760 GeV Pb-Pb collision with centrality 0-10%
coupled Boltzmann for charm quark and diquark
assume only charm quark produced initially, diquark comes from (re)combination

Predicted production rate
in 2760 GeV PbPb, $-1 < y < 1$, $0 < pT < 5$ GeV,
 Ξ_{cc}^{++} **0.02 per collision**
with melting temperature = 250 MeV:
 Ξ_{cc}^{++} **0.0125 per collision**

Study heavy quark combination
from measurements



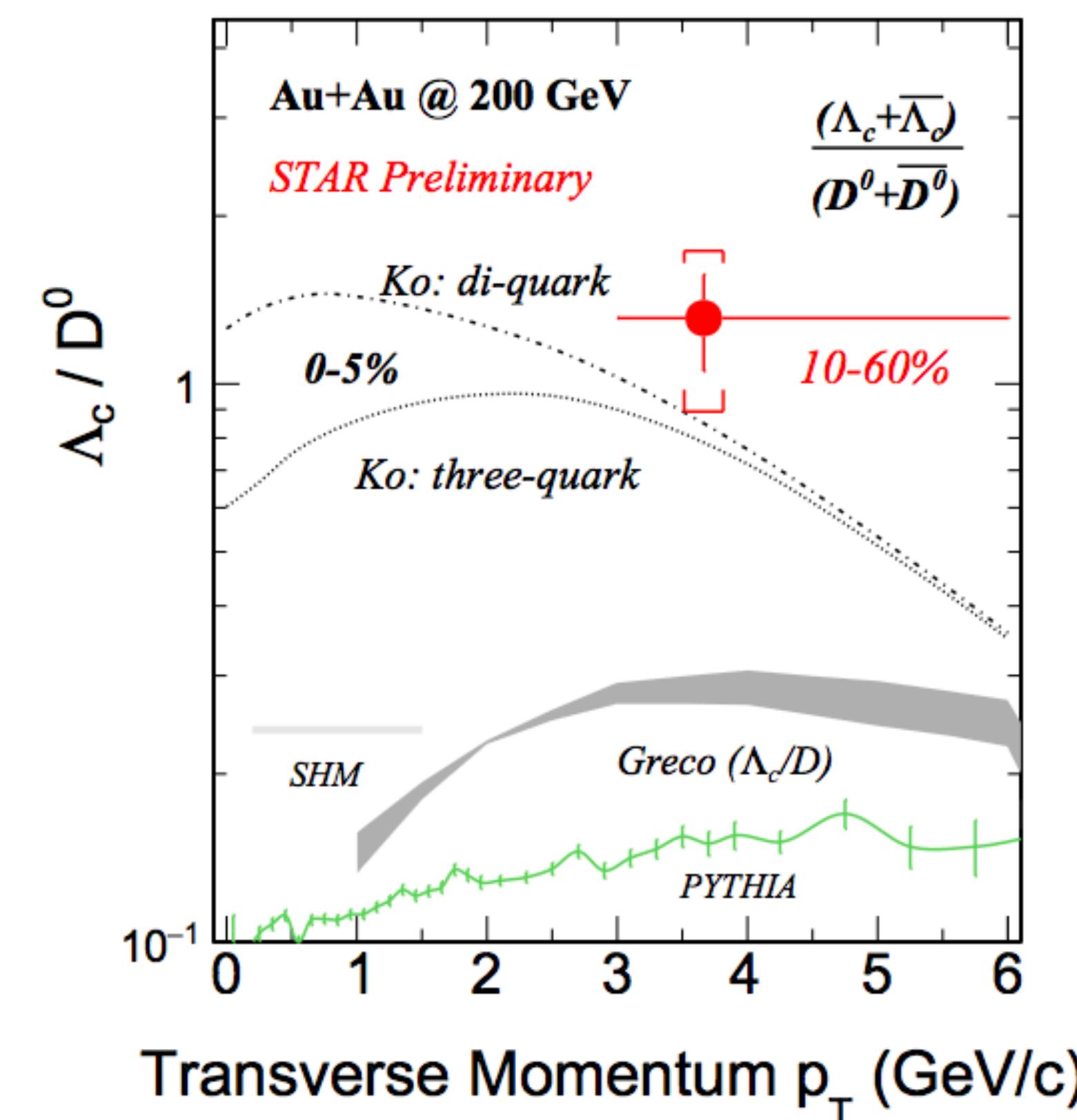
Doubly Heavy Tetraquark Production in Heavy-ion

Same calculation can be extended to study doubly heavy tetraquarks

Only difference: hadronization: coalescence with two light quarks v.s. one

Hadronization of doubly heavy baryon similar to hadronization of singly heavy meson

Hadronization of doubly heavy tetraquarks similar to hadronization of singly heavy baryon



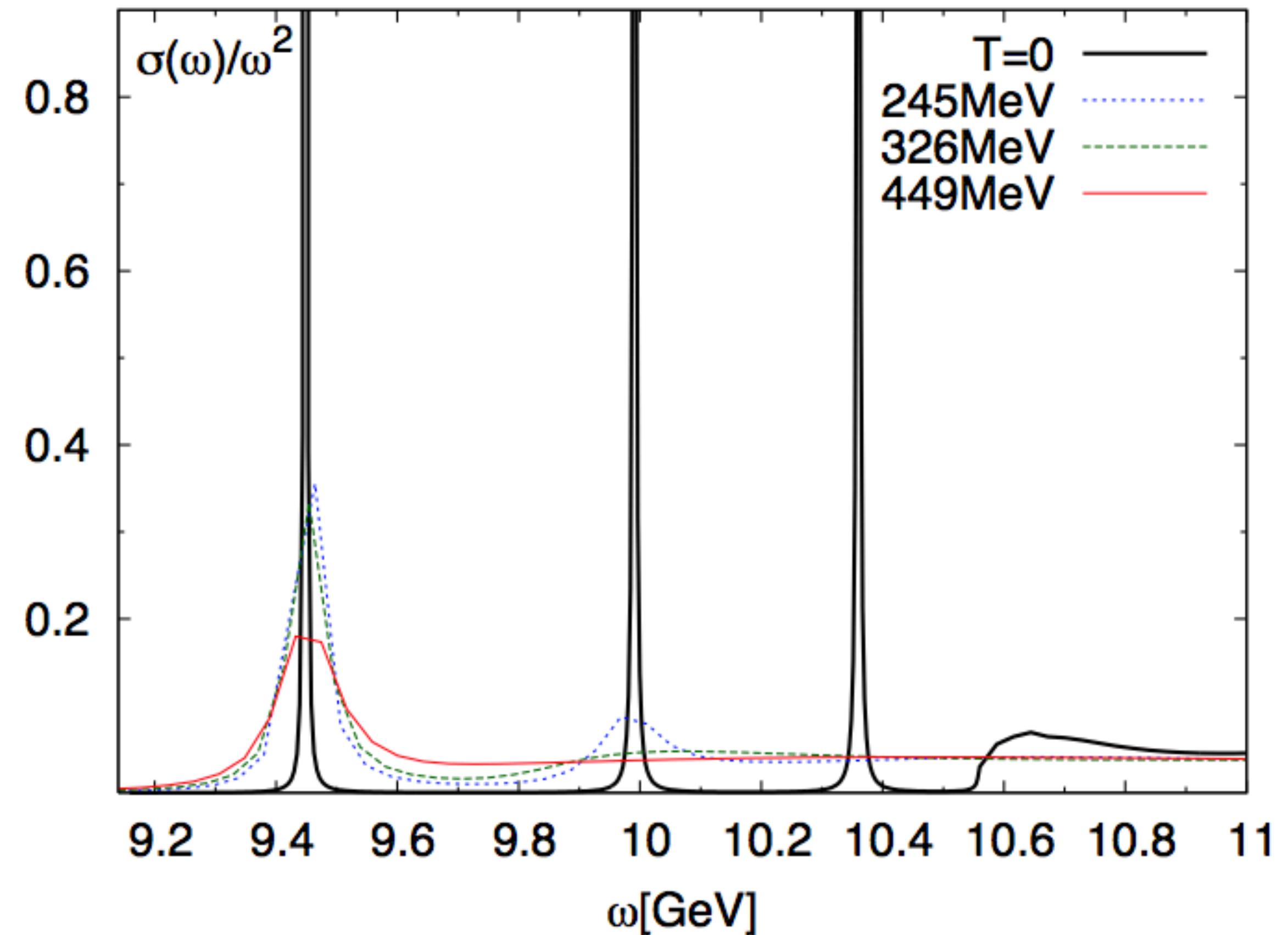
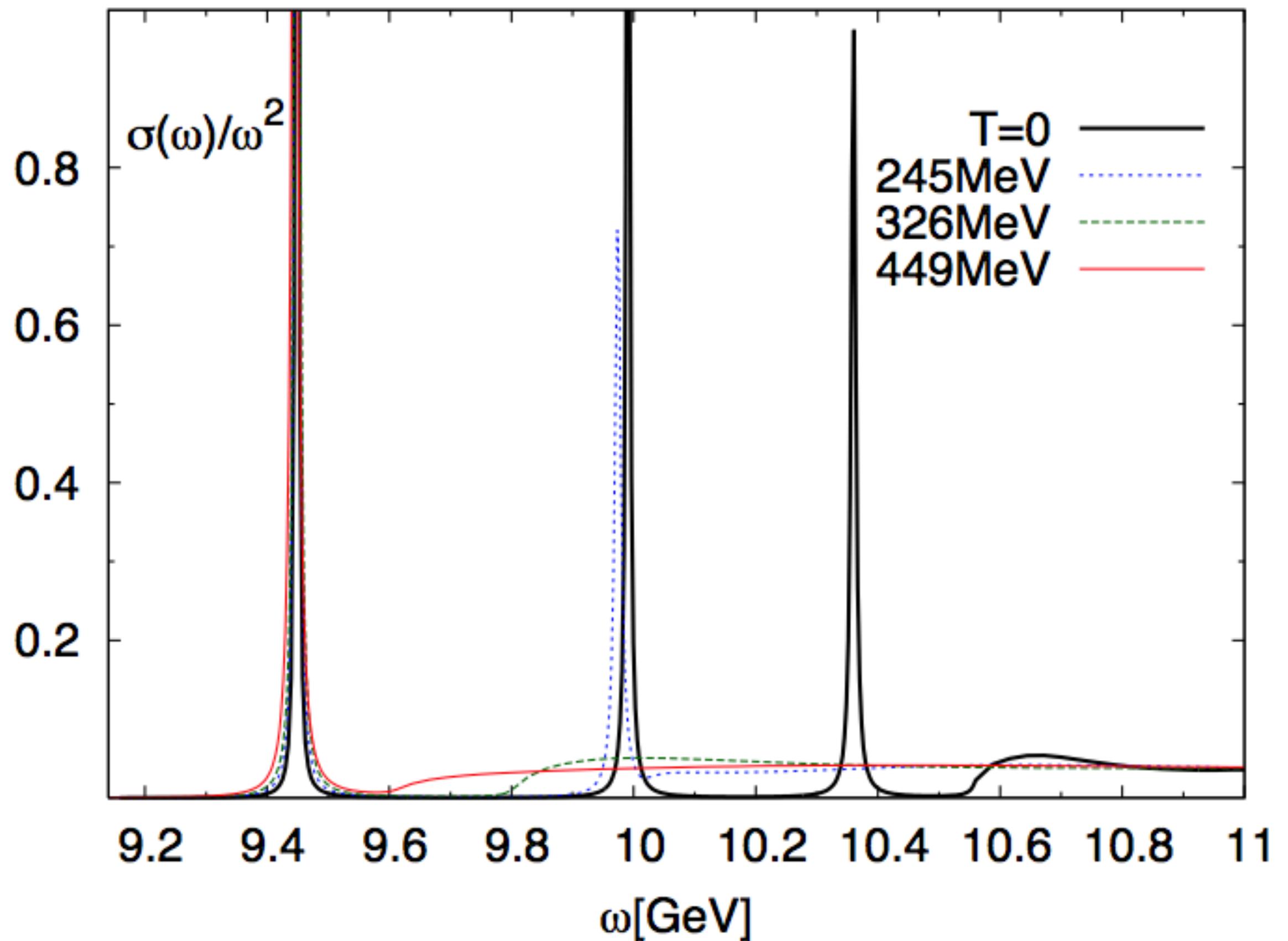
**enhancement of
singly heavy baryon
observed at STAR**

**expect enhancement of
doubly heavy tetraquarks
in heavy-ion collisions**

Summary

- Screening effect
- Boltzmann equations: in-medium formation and dissociation of heavy diquarks
- Effective field theory pNRQCD
- Approach equilibrium
- Production of doubly heavy baryon and tetraquarks in heavy-ion collisions
- Experimental effort

Backup: Imaginary Part More Important



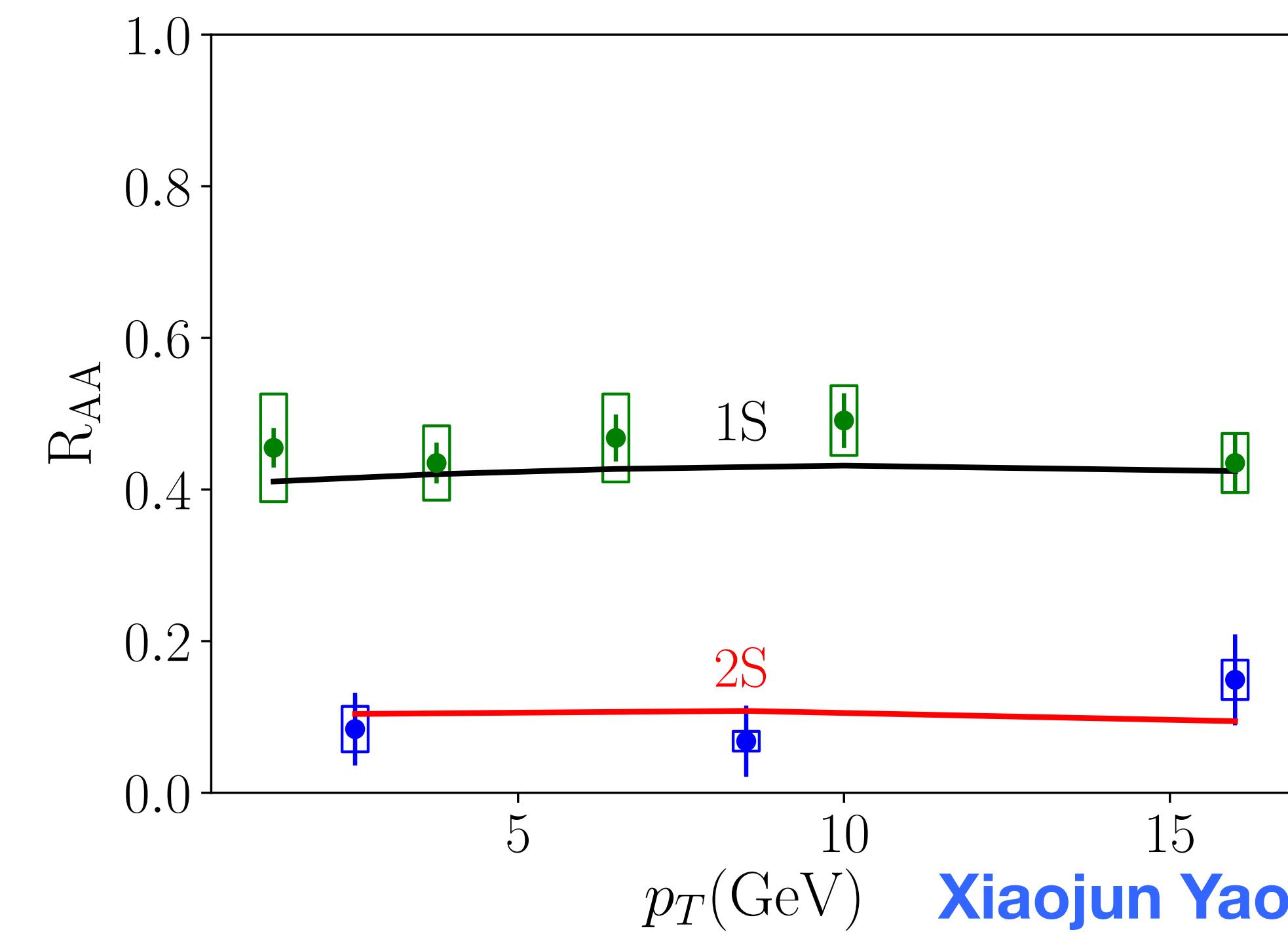
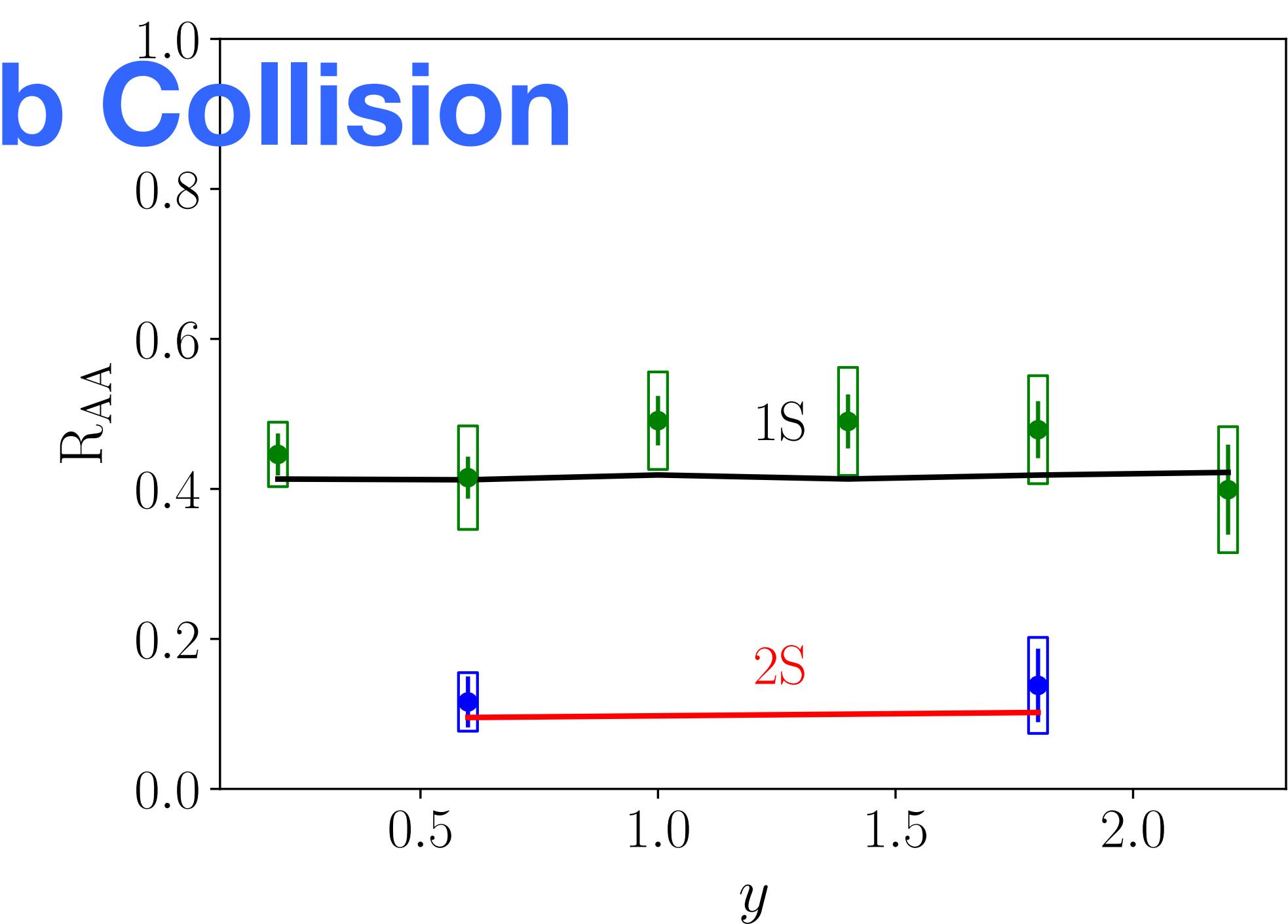
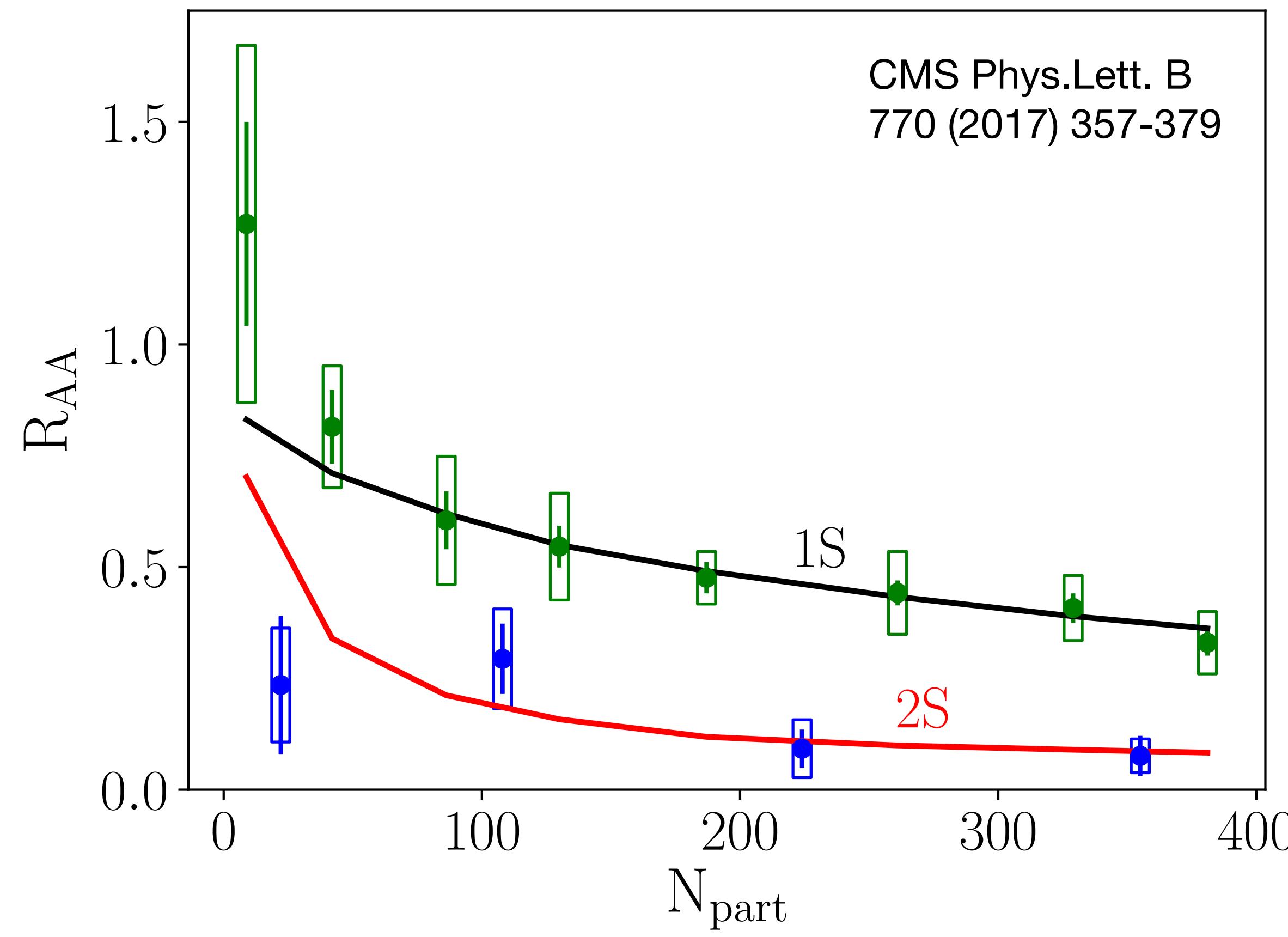
C. Miao, A. Mocsy, P. Petreczky arXiv:1012.4433

Backup: Upsilon in 2760 GeV PbPb Collision

$$\alpha_s = 0.3$$

$$T_{\text{melt}}(2S) = 210 \text{ MeV}$$

$$V_s = -C_F \frac{0.42}{r}$$



Backup: Upsilon in 200 GeV AuAu Collision

