Searching for Rare Particles in Heavy Ion Collisions

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起：*Why rare particles in HIC*
承：*Multi-charmed hadrons*
转：*True muonium*
合：*Hunting down* Ω_{ccc} *and* $(\mu_+\mu_-)$ *in HIC*

Rare Particle Enhancement in HIC

In comparison with pp collisions,

1) *the off-diagonal interaction among heavy quarks from different binary collisions leads to a strong enhancement of multi-charmed hadrons ($J/\psi, \Upsilon$, B_c, Ω_{ccc}, $c\bar{c}c\bar{c}$,…),*

2) *and the thermal production of dileptons in QGP results in a significant enhancement of true muonium ($\mu^+\mu^-$) state!*

N-body Schroedinger + Coalescence

H.He, Y.Liu and PZ, PLB746, 59(2015)

$$\left[\sum_{i=1}^{N}\left(-\frac{\vec{\nabla}_i^2}{2m_i}\right)+V(\vec{r}_1,\dots\dots\vec{r}_N,T)\right]\Psi(\vec{r}_1,\dots\dots\vec{r}_N)=E_N\Psi(\vec{r}_1,\dots\dots\vec{r}_N)$$

$$V(\vec{r}_1,\dots\dots\vec{r}_N,T)=\sum_{i\neq j}^{N}\left[V_{ij}^{c}\left(\left|\vec{r}_{ij}\right|,T\right)+V_{ij}^{s}\left(\left|\vec{r}_{ij}\right|\right)\right]$$

Lattice QCD potential: $V_{ij}^{c}\left(\left|\vec{r}_{ij}\right|,T\right),\qquad V_{ij}^{s}\left(\left|\vec{r}_{ij}\right|\right)=\beta e^{-\gamma\left|\vec{r}_{ij}\right|}\vec{s}_i\cdot\vec{s}_j$

The coalescence probability (Wigner function):

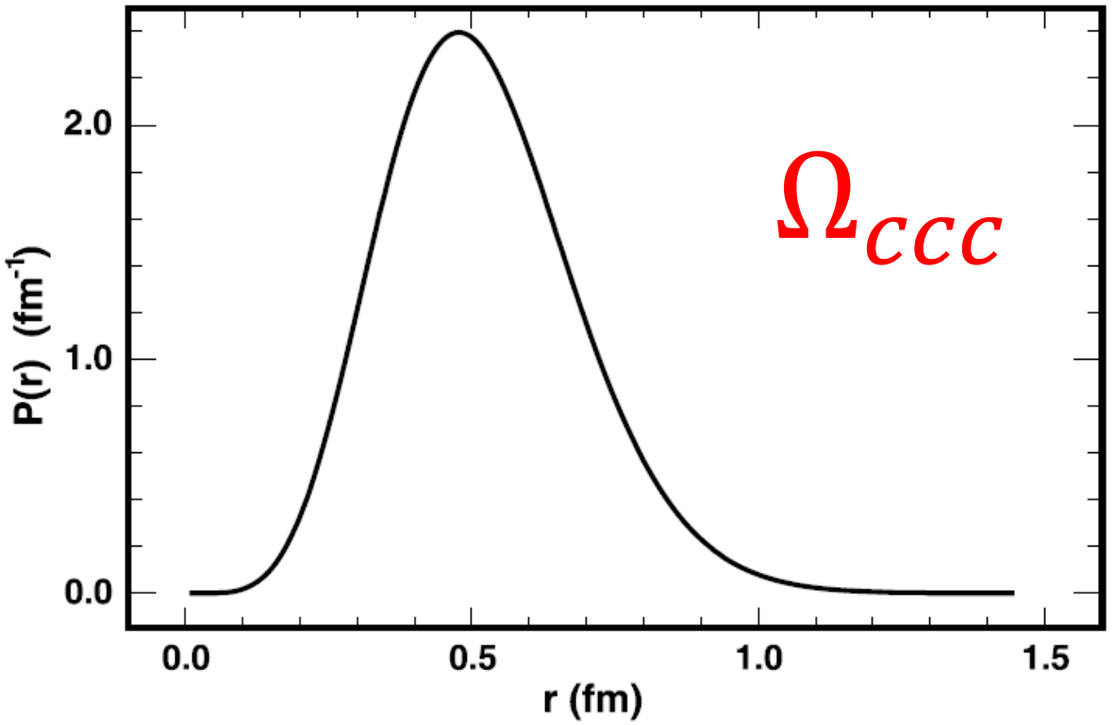
$$W(\vec{x},\vec{p})=\int d^3\vec{y}e^{-i\vec{p}\cdot\vec{y}}\Psi(\vec{x}+\vec{y}/2)\Psi^{+}(\vec{x}-\vec{y}/2)$$

$$\frac{dn}{d^3\vec{p}}=C\int_{\Sigma}\frac{p^{\mu}d\sigma_{\mu}}{(2\pi)^3}\int\frac{d^{N-1}\vec{x}d^{N-1}\vec{y}}{(2\pi)^{3N}}W(\vec{x},\vec{p})\,f_q(\vec{x}_1,\vec{p}_1)\dots\dots f_q(\vec{x}_N,\vec{p}_N)$$

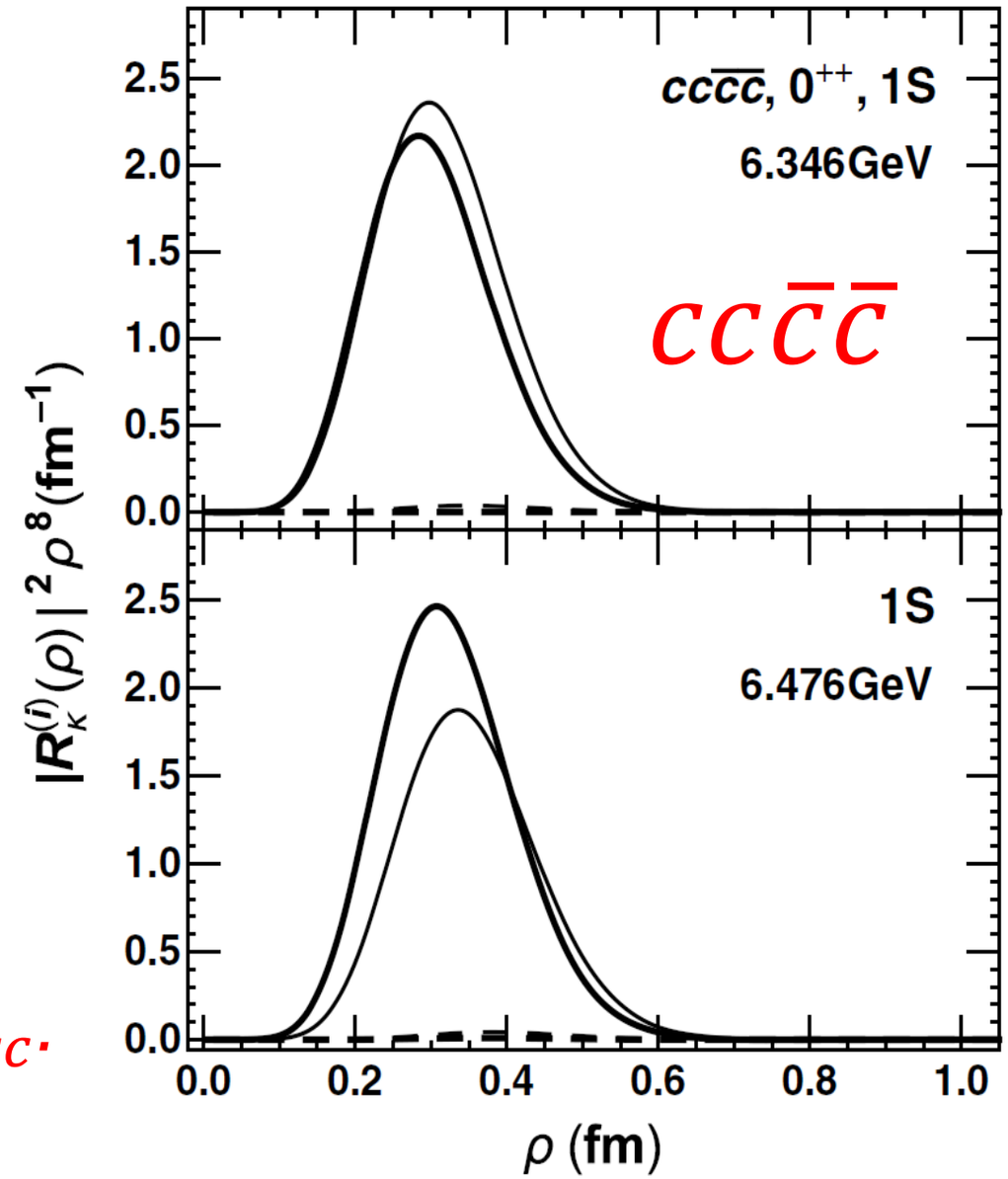
The coalescence region is determined by hydrodynamics

The heavy quark distribution is controlled by a transport equation or simply an equilibrium distribution

Wave Functions



J.Zhao, H.He and PZ, PLB771, 349(2017)



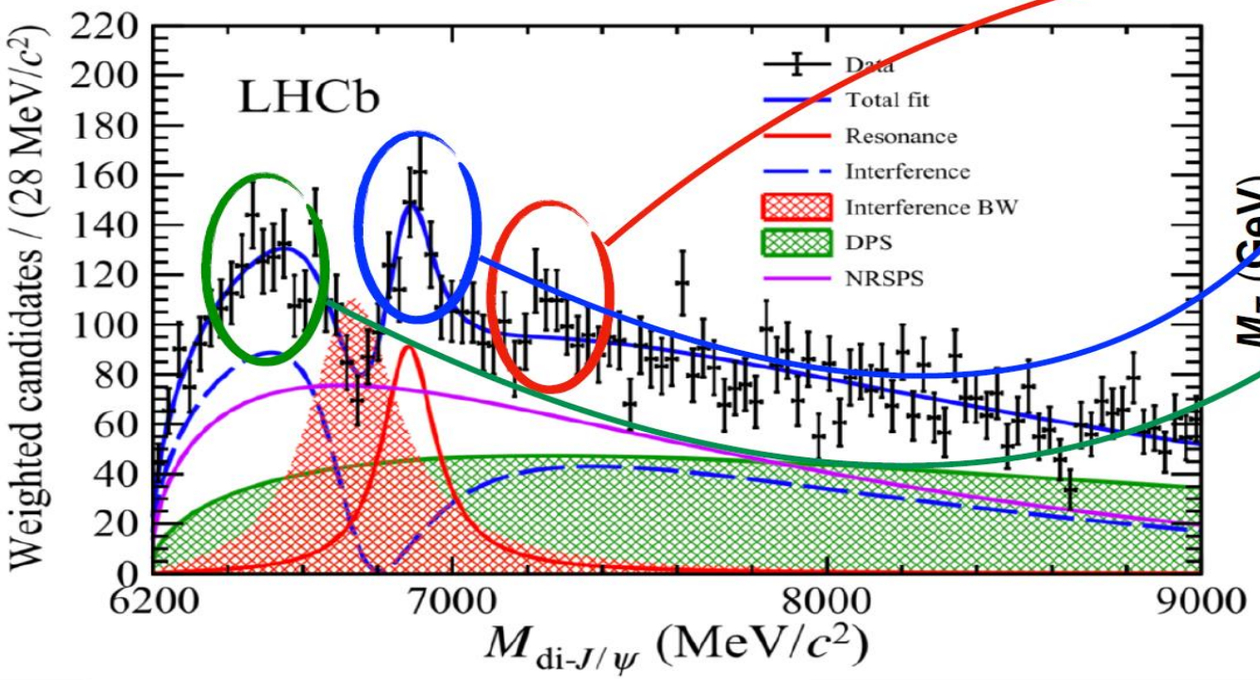
J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)

$c\bar{c}c\bar{c}$ *is more compact than* Ω_{ccc}.

$QQ\bar{Q}\bar{Q}$ in Vacuum

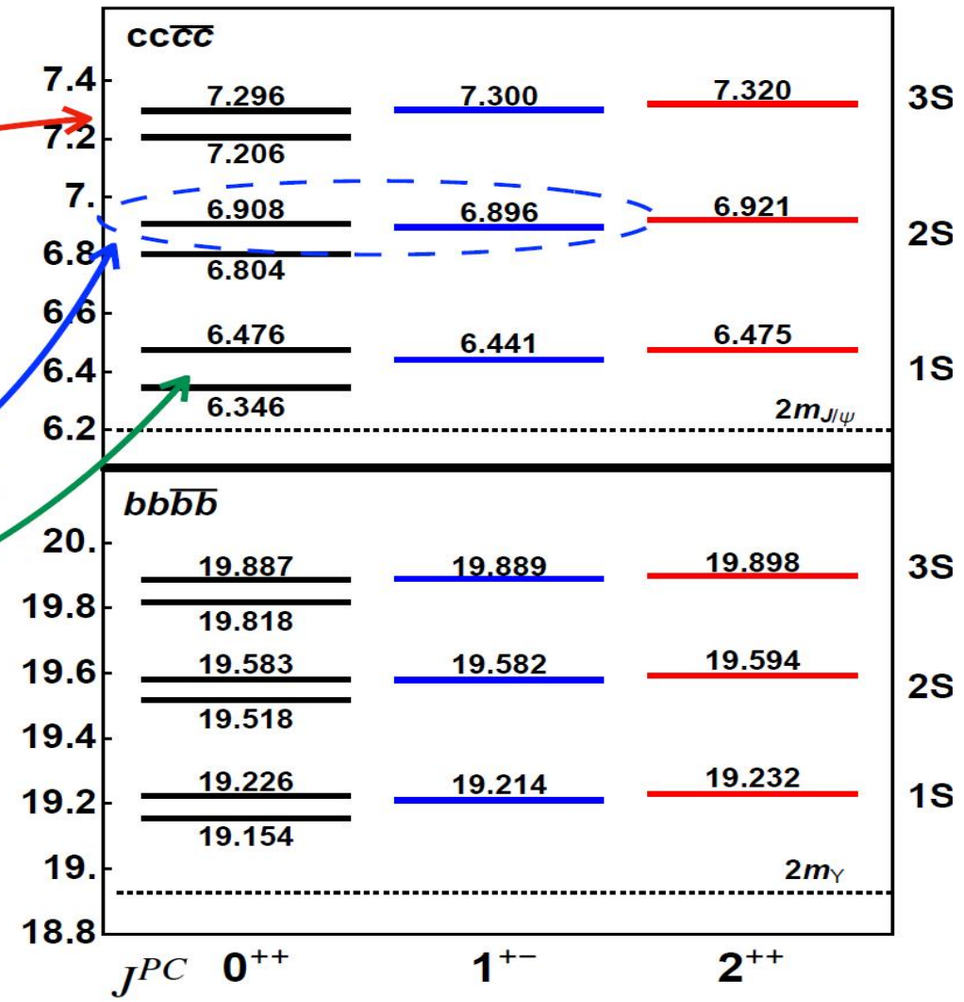
J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)

LHCb Collaboration, Science Bulletin 65, 1983(2020)

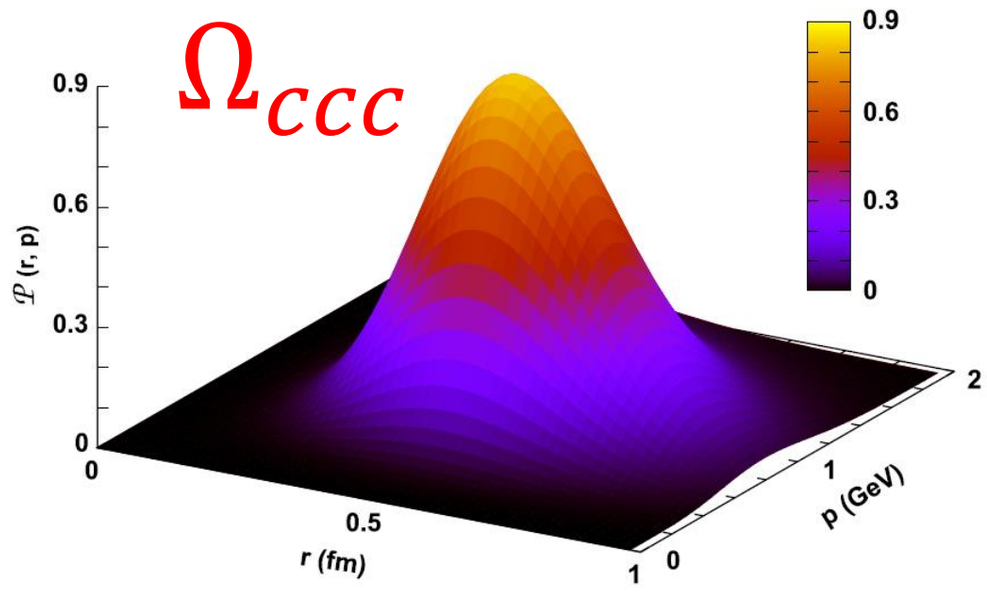


$$m[X(6900)] = 6905 \pm 11 \pm 7\ \text{MeV}/c^2$$

$$\Gamma[X(6900)] = 80 \pm 19 \pm 33\ \text{MeV}$$

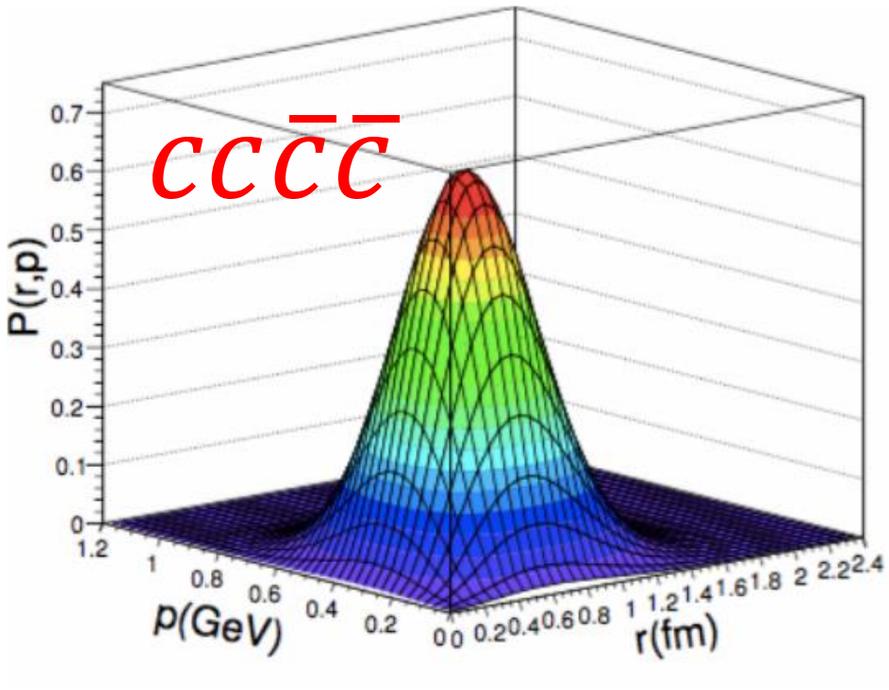


Wigner Functions



J.Zhao and PZ, PLB775, 84(2017)

$\rightarrow \quad \frac{N_{AA}/N_{coll}}{N_{pp}} \sim 100$



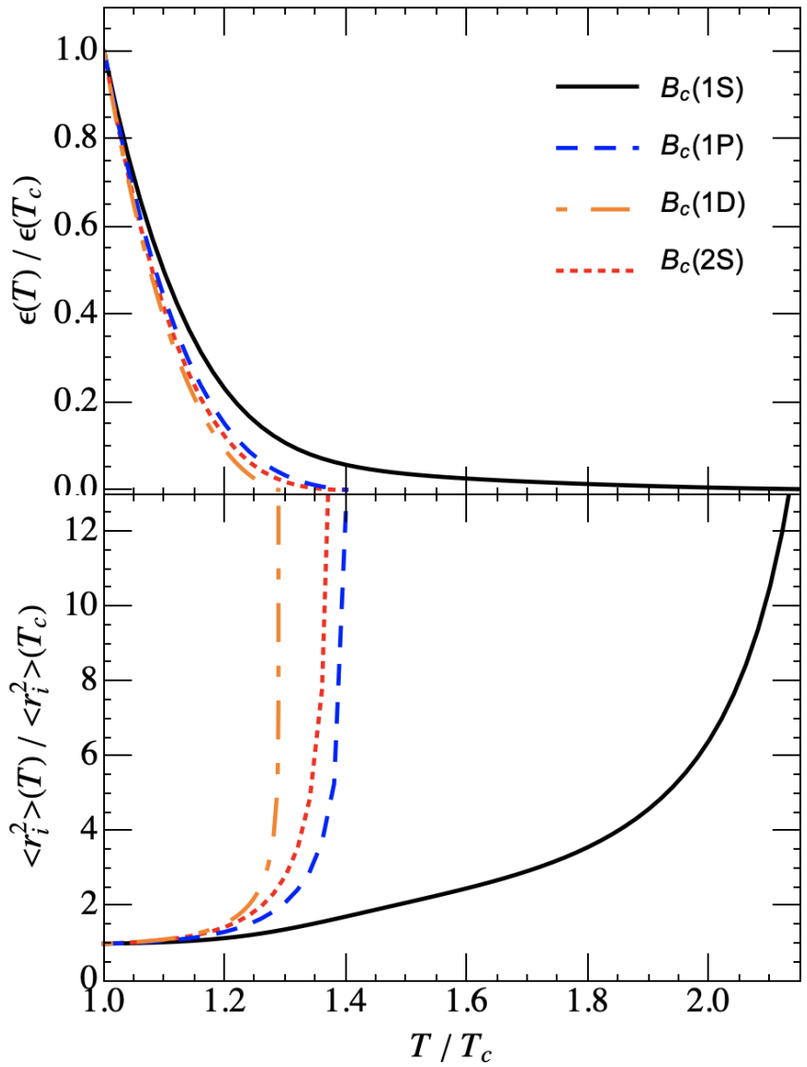
J.Zhao, S.Shi and PZ, PRD102, 114001 (2020)

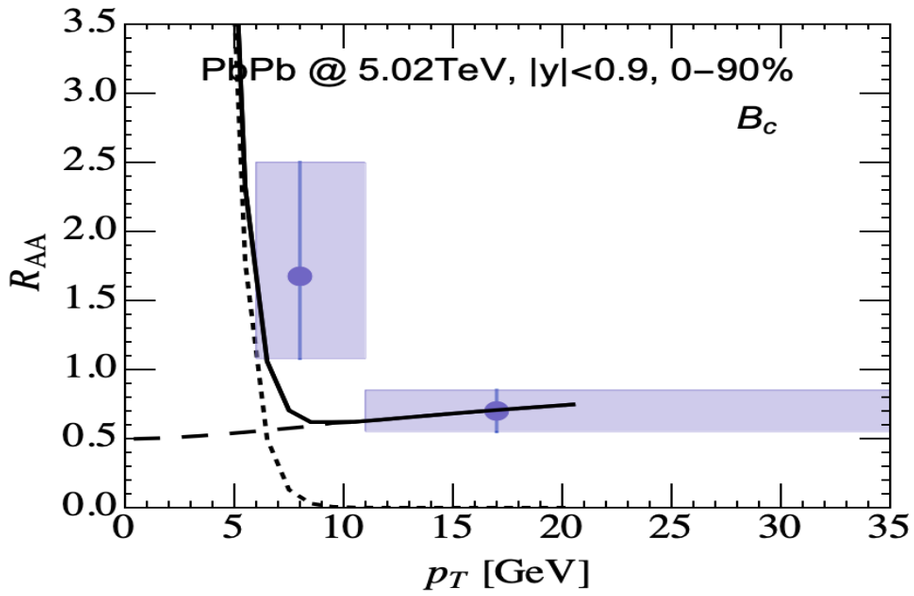
$\rightarrow \quad \frac{N_{AA}/N_{coll}}{N_{pp}} \sim 10$

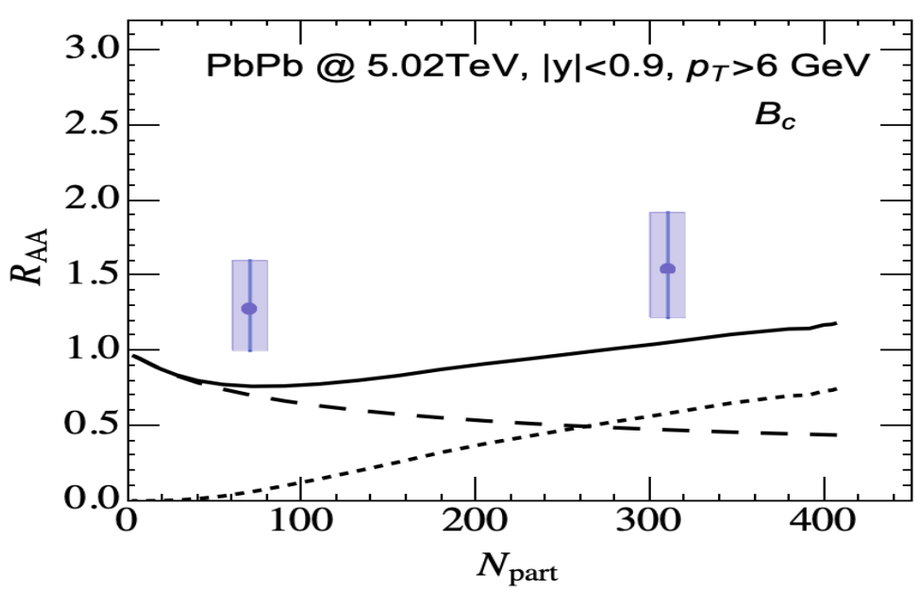
Off-diagonal interactions !

B_c

J.Zhao and PZ, Eur.Phys.J.A61, 41(2025)



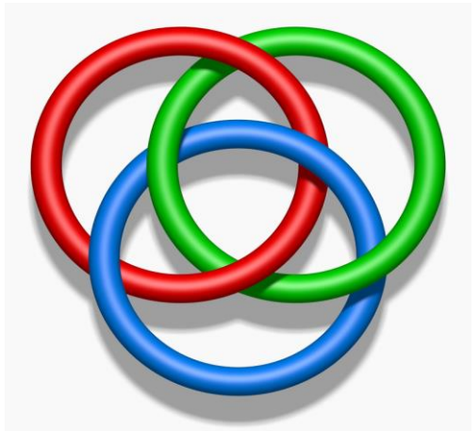




see also L.Zhang, X.Li, W.Xing, S.Cao and G.Qin, Phys.Rev.C111, 5(2025)

Ω_{ccc} as a Borromean Ring and an Efimov State

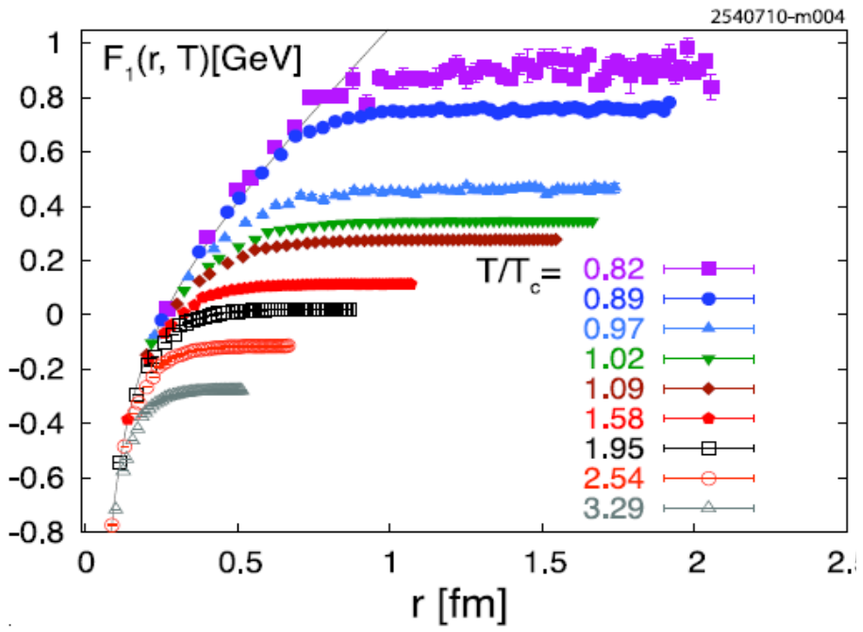
J.Zhao and PZ, PLB775,84(2017)

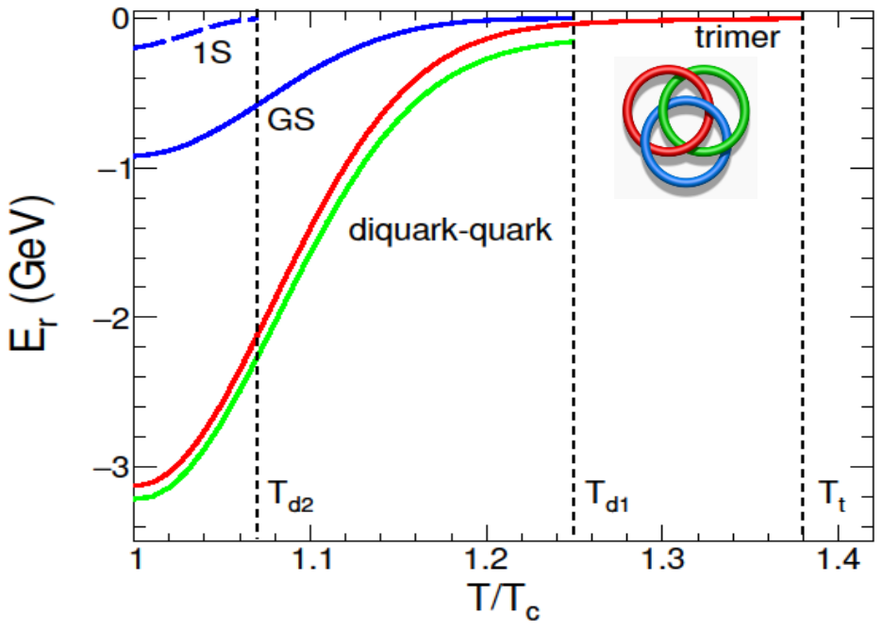


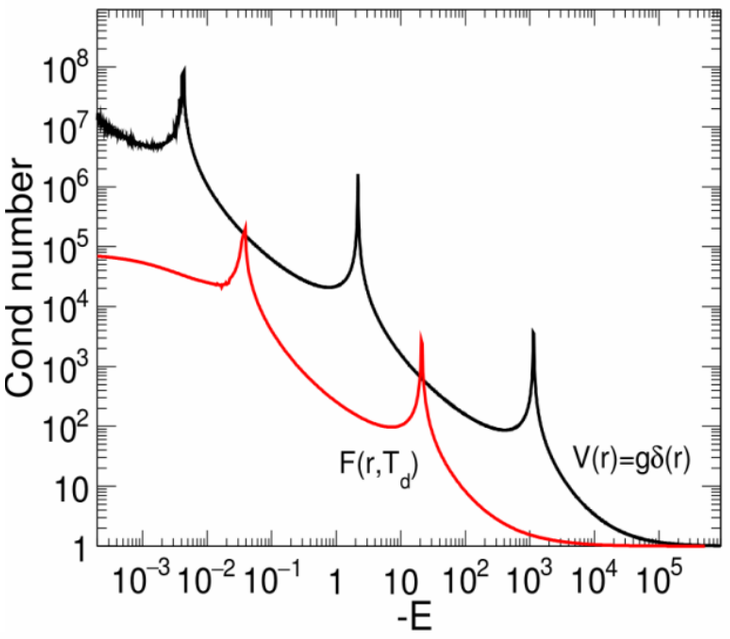
Question: Is it possible to realize Efimov state at quark level?

Answer: *In vacuum, no, because of the long range interaction.*

At finite temperature, probably yes, due to the screened quark potential.







short range potential at high T !

$\frac{E_n}{E_{n+1}} = e^{2\pi/s_0} = 515$, *Efimov state !*

$(\mu^+\mu^-)$ *in Vacuum*

- *A pure QED system*
- *Lifetime:* $\mathcal{O}(1)$ ps, *6 decades smaller than the life time of* μ
- *Decay channel:* $(\mu^+\mu^-) \rightarrow e^+e^-$, 98%
- *Binding energy:* $\varepsilon_n \sim -1.4/n^2$ KeV
- *Mass:* $m_n \sim 2m_\mu = 211$ MeV
- *Mean radius:* $r_n \sim \left(m_\mu \varepsilon_n\right)^{1/2} = 512\, n$ fm
- *Formation time:* $\tau_n \sim r_n = 1.72 \times 10^{-21}$s

$(\mu^+\mu^-)$ *in QGP*

- *QGP temperature:* T_{QGP}*~hundreds of* MeV
- *QGP lifetime:* τ_{QGP}*~10 fm* $\sim\mathcal{O}(10^{-23})$ s $\ll\ \tau_n$
- *QGP radius:* r_{QGP}*~10* fm $\ll r_n$

- *The interaction between* μ^+ *and* μ^- *is Coulomb-like outside the QGP and Yukawa-like with photon screening radius* $r_D \sim 2.11/T$ *inside the QGP.*

- *QGP serves as a source of* μ^+ *and* μ^-*,while not interfering with the formation and decay of the bound state* $(\mu^+\mu^-)$*.*

Parton Mass and Coupling in QGP

Extracted from Lattice QCD:

$$m_g^2(T) = \frac{g^2(T)}{6}\left(N_c + \frac{1}{2}N_f\right)T^2,$$

$$m_q^2(T) = \frac{N_c^2 - 1}{8N_c}g^2(T)T^2,$$

$$m_s(T) = m_q(T) + 0.045\ \text{GeV},$$

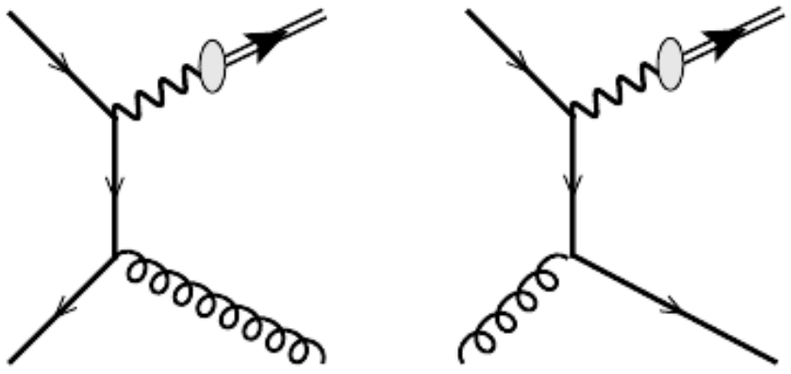
$$g^2(T) = \begin{cases} \frac{48\pi^2}{(11N_c - 2N_f)\log\left[\lambda^2\left(\frac{T}{T_c} - 0.56\right)^2\right]}, & T \geq T^*, \\ g^2(T^*)\left(\frac{T^*}{T}\right)^{3.1}, & T < T^*, \end{cases}$$

where $T_c = 158$ MeV, $T^* = 1.19\,T_c$ and $\lambda = 2.42$.

The process $(\mu^+\mu^-) \to q\bar{q}$ is kinematically forbidden due to the thermal quark mass.

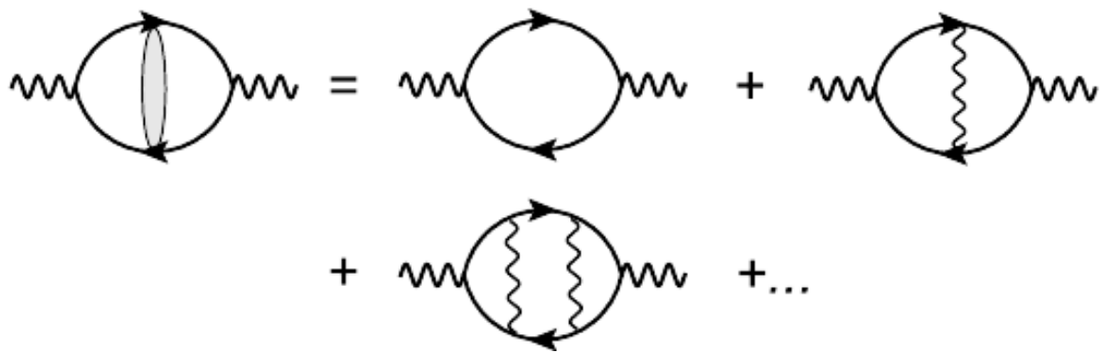
$(\mu^+\mu^-)$ Production Process

- *LO:* $q\bar{q} \to (\mu^+\mu^-)$ *is kinematically forbidden.*
- *NLO:* $q\bar{q} \to (\mu^+\mu^-)g$ and $qg \to (\mu^+\mu^-)q$



Y.Chen and PZ, 1204.4389
Z.Liang, Q.Yang, H.Zhang, J.Zhao and PZ, 2505.10070

- *Coulomb resummation*



- *Photon-*$(\mu^+\mu^-)$ *vertex*

$$iZ_n = i\frac{\alpha^2}{4\pi}\sqrt{\frac{m_\mu^3 m_n}{n^3}}$$

Transport in QGP

- $(\mu^+\mu^-)$*is not thermalized with the QGP.*
- *Neglecting the dissociation in QGP, the Boltzmann equation*

$$\left(\frac{\partial}{\partial t}+\frac{\mathbf{p}}{E}\frac{\partial}{\partial \mathbf{r}}\right) f(k_1) = \sum_{i=1,2} C_{\mathrm{NLO},i}[f(k_1)]$$

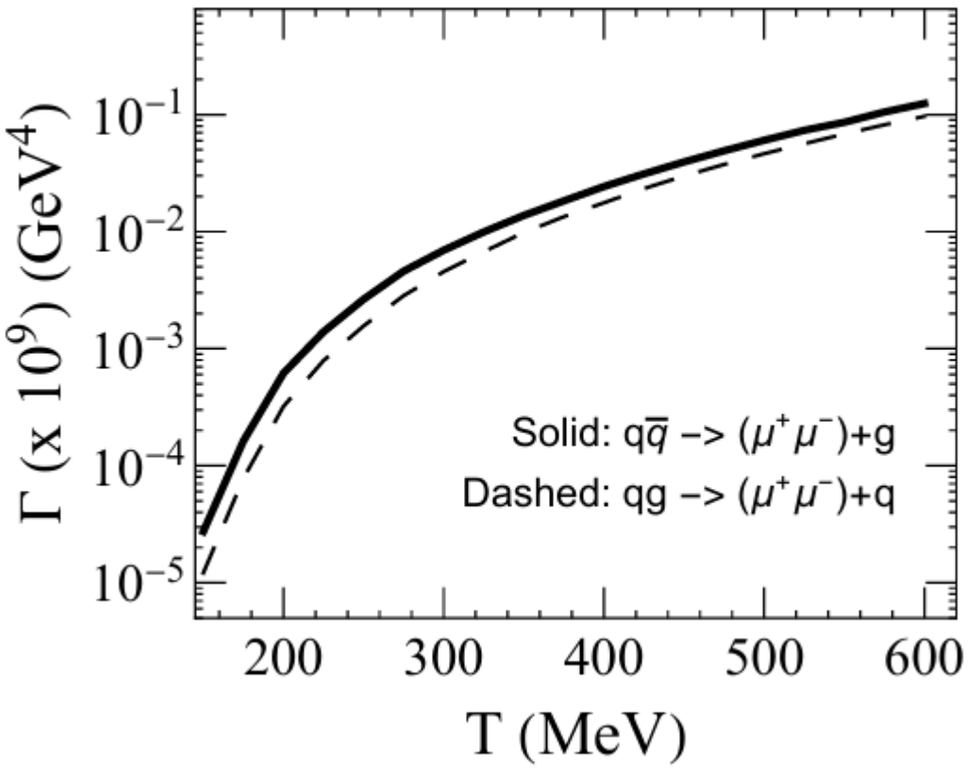
$$C_{\mathrm{NLO},1} = \frac{1}{E_{k_1}} \sum_{f,n} \int \frac{d^3p_1}{(2\pi)^3 2E_{p_1}} \frac{d^3p_2}{(2\pi)^3 2E_{p_2}} \frac{d^3k_2}{(2\pi)^3 2E_{k_2}}$$

$$\times \sum_{s,s',\lambda,i} |\mathcal{M}_1|^2 f_q(p_1) f_{\bar{q}}(p_2) \left(1+f_g(k_2)\right)$$

$$\times (2\pi)^4 \delta^{(4)}(p_1+p_2-k_1-k_2),$$

- *Production rate*

$$\Gamma \equiv \int C_{\mathrm{NLO}} d\mathbf{k}_1/(2\pi)^3$$



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Yield

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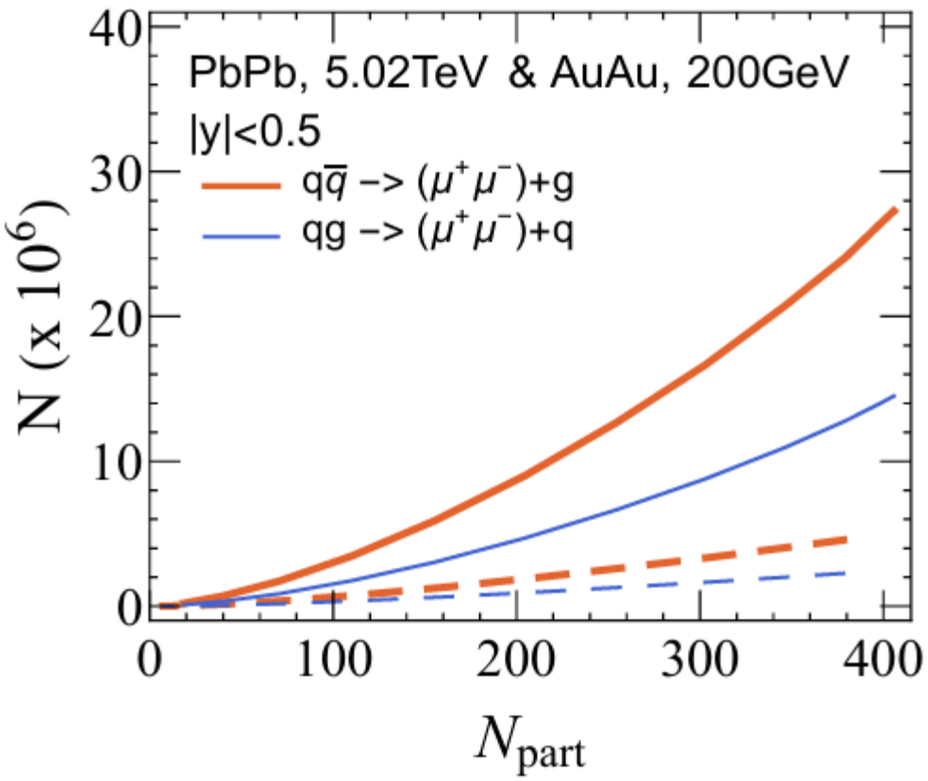
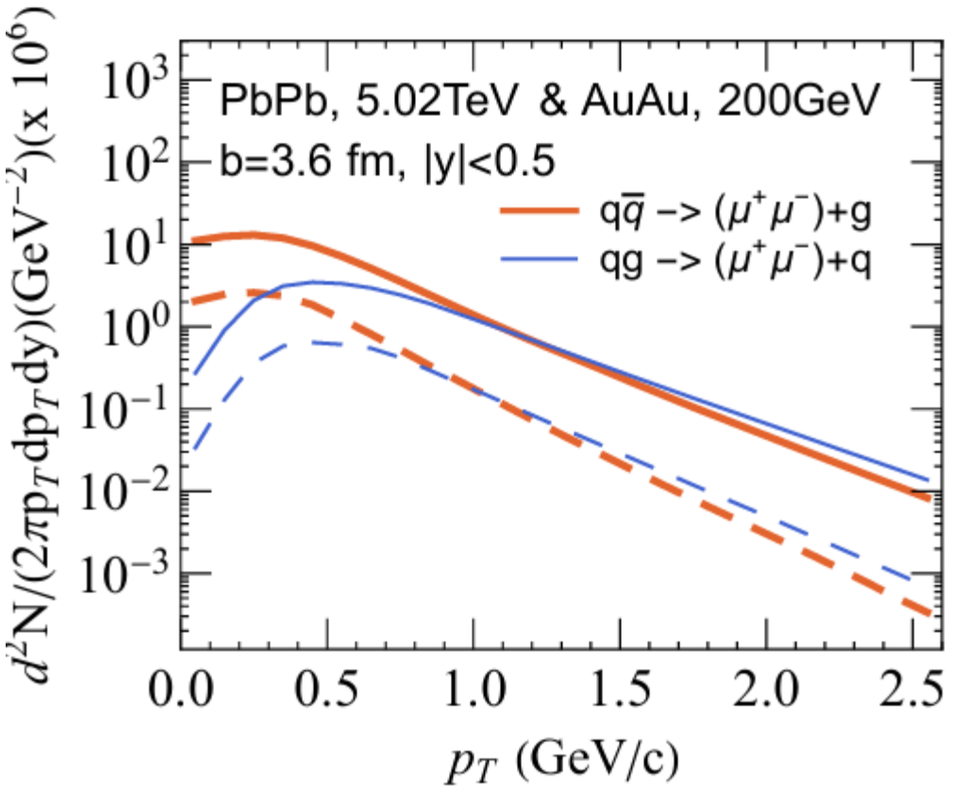
$(\mu^+\mu^-)$ distribution

$$f(\mathbf{p}_T, y, \mathbf{x}_T, \eta, \tau) = \int_{\tau_0}^{\tau} d\tau' \frac{C_{\rm NLO}[f(\mathbf{p}_T, y, \mathbf{X}_T, H, \tau')]}{\cosh(\Delta(y-\eta))} \times \Theta(T(\mathbf{X}_T, H, \tau') - T_c), \quad (7)$$

Yield

$$N(\tau) = \frac{1}{(2\pi)^3} \int d^2\mathbf{p}_T d^2\mathbf{x}_T dy d\eta \tau E_T \cosh(y-\eta) \times f(\mathbf{p}_T, y, \mathbf{x}_T, \eta, \tau).$$

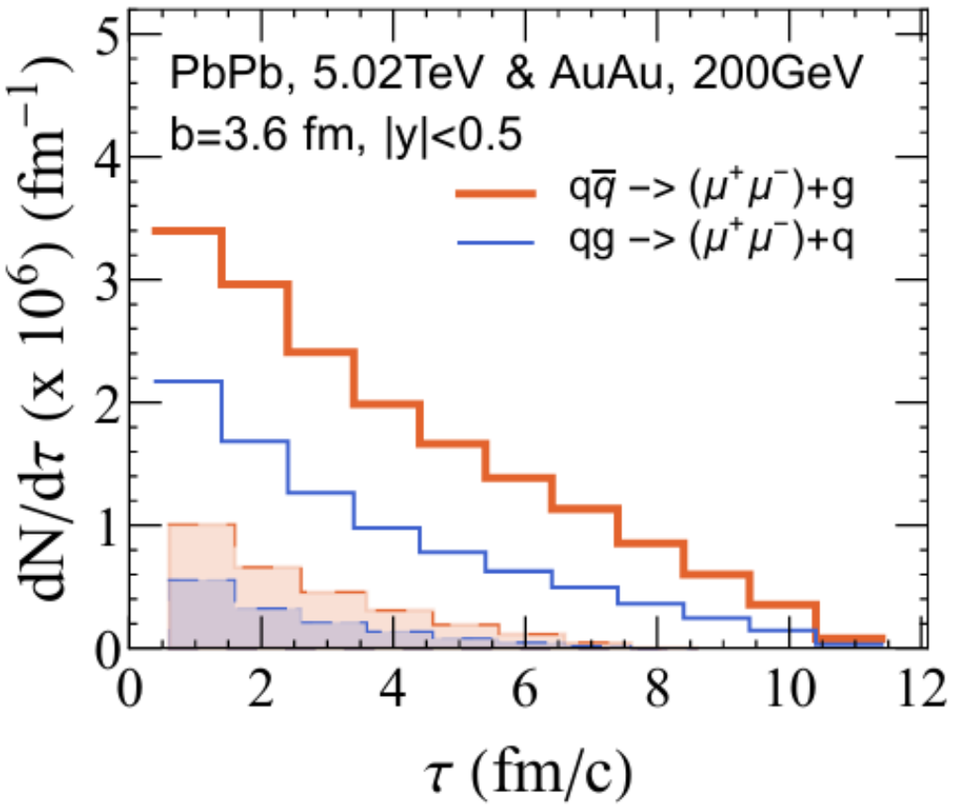




In a billion central Pb+Pb collisions, there are approximately 10^4 and 10^5 $(\mu^+\mu^-)$ at RHIC and LHC energy !

Time Dependence

- *Like e^+e^- production which is usually used to measure the medium temperature, $(\mu^+\mu^-)$ is sensitive to the initial condition of the QGP: it is produced mainly in the initial stage.*



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Conclusions

- *Rare particle enhancement in HIC is a unique signal of QGP formation.*

- *HIC may offer the most promising opportunity for the first observation of Ω_{ccc} and $(\mu^+\mu^-)$.*

Difficulty for detecting Ω_{ccc}: Cascade decay

Nonleptonic cascade decay mode

$$\begin{aligned}
\Omega_{ccc}^{++} \rightarrow \quad & \Omega_{ccs}^{+} \quad + \pi^{+} \\
& \downarrow \\
& \Omega_{css}^{0} \quad + \pi^{+} \\
& \downarrow \\
& \Omega_{sss}^{-} \quad + \pi^{+}
\end{aligned}$$

Semi-leptonic decay mode

$$\Omega_{ccc}^{++} \rightarrow \quad \Omega_{sss}^{-} \quad + 3\mu^{+} + \; 3\nu_{\mu}$$

Difficulty for detecting ($\mu^+\mu^-$): Background