Quarkonium as a Probe of QGP

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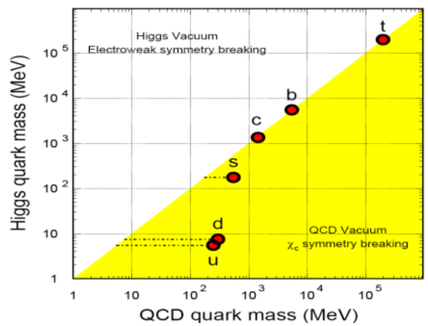
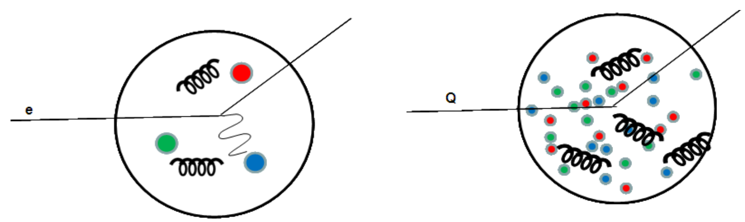
- *Why is quarkonium a thermometer of QGP ?*

Heavy quark properties are not changed in hot medium. Electrons are used to probe the QED structure of a nucleon, heavy quarks can signal the QCD structure of the fireball in HIC.

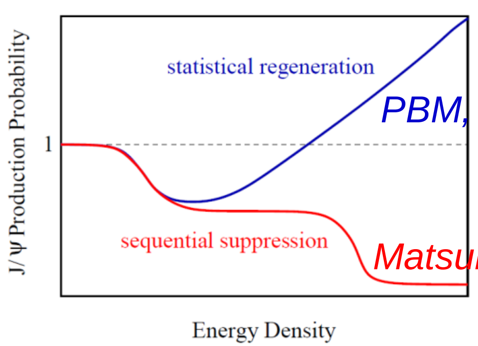




electrons and heavy quarks as QED and QCD probes

Zhu, Bleicher, Huang, Schweda, Stoecker, Xu, Zhuang, PLB647 (2007) 366-370

- *Cancellation between suppression and regeneration !*
- *How to increase the sensitivity of the thermometer ?*



PBM, Thews, Rapp,……

Matsui, Satz

- *Heavy Quark Potential*
- *Quarkonium p_t Distributions*
- *Quarkonia in Small Systems*
- *Quarkonia at FCC*
- *Multi-charmed Baryons*

$V \to F$ from Lattice Simulation

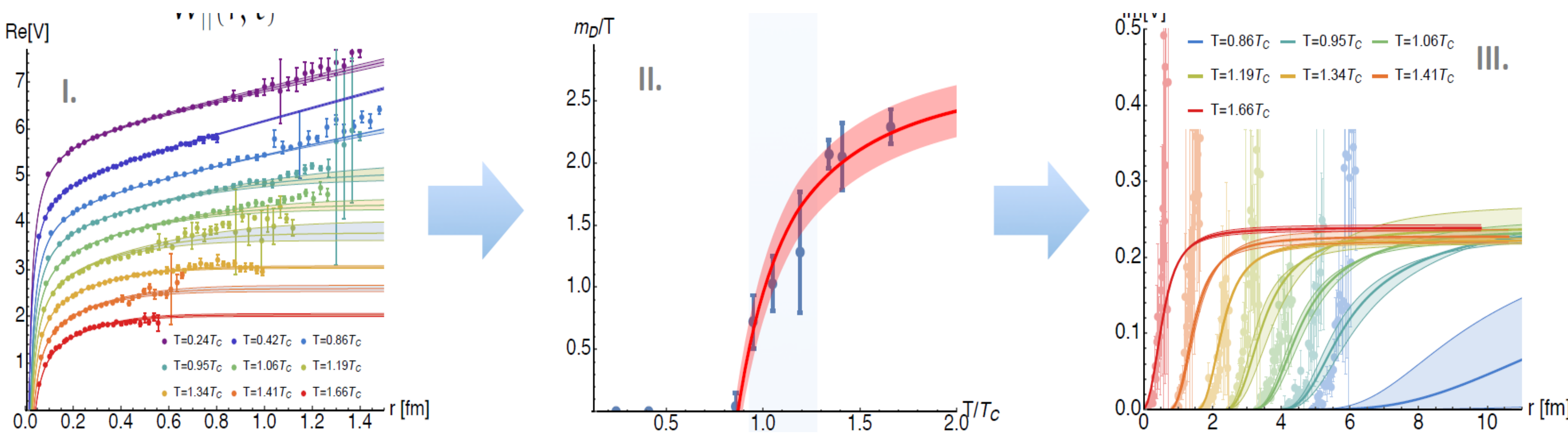
Burnier, Kaczmarek, Rothkopf, JHEP1610, 032(2016):

1) extracting potential V=Re[V] + i Im[V] from lattice simulated spectral function

→ Re[V] is close to F.

2) parametrization of the potential via an extended Gauss law

→ Debye screening mass $m_D(T)$.



Other lattice simulation (H.Ohno):

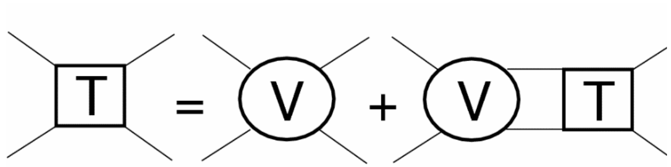
the limit temperature of J/ψ 1.25 T_c supports V=F.

The complex potential is used to describe Υ suppression at LHC (G.Wolschin).

$V \rightarrow U$ from T-matrix Approach

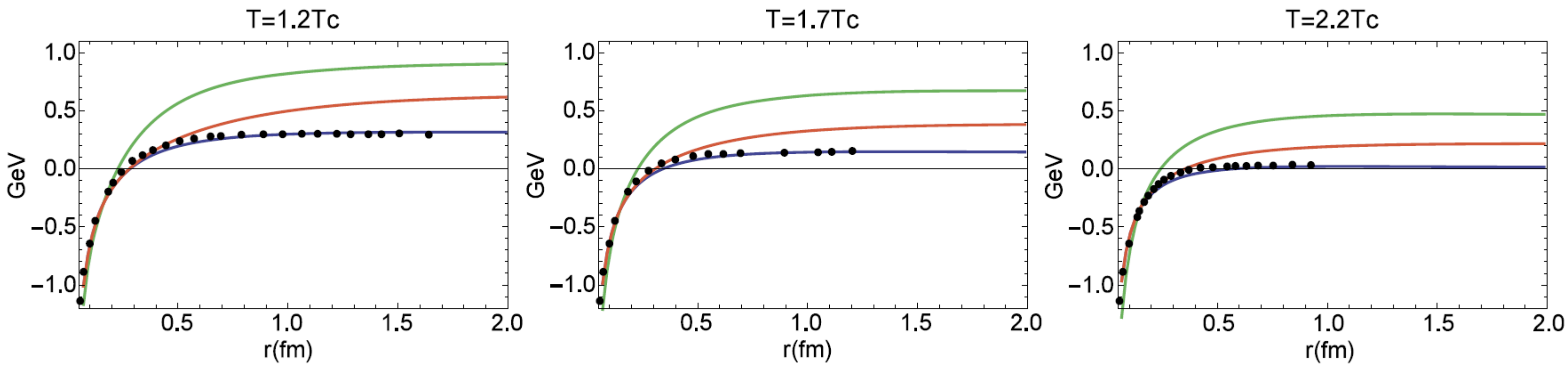
Liu & Rapp, NPA941, 179(2015):

T-matrix approach with complex potential:

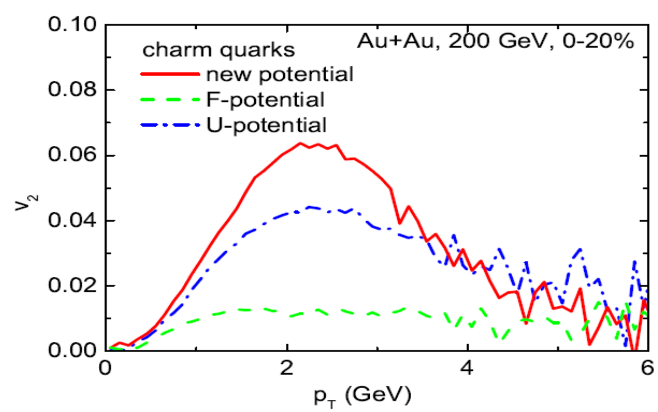


[Lippmann-Schwinger equation]

by fitting the lattice calculated F, ⇒ the real potential → F < Re[V] < U



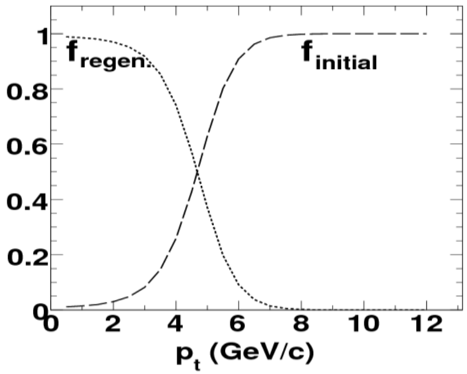
however, by calculating transport coefficients like heavy quark v_2 → Re[V] is close to U.



How to Distinguish Hot Mediums ?

$$f(p) = f_{ini}(p) + f_{reg}(p)$$

initial production: p_t *broadening due to Cronin effect and leakage effect*
regeneration: p_t *suppression due to energy loss and coalescence at later stage.*



p_t *distribution can distinguish hot mediums at SPS, RHIC & LHC !*

Dynamical approaches for quarkonia evolution in QGP:
kinetic approach (Rapp et al.),
Schroedinger-Langevin approach (Gossiaux et al.),
Langevin approach (Blaizot et al.), ……

- *quarkonium motion*

Zhu, Xu, Zhuang, PLB607, 107(2005),
Yan, Xu, Zhuang, PRL97, 232301(2006)

$$\partial f_\Psi/\partial\tau + \mathbf{v}_\Psi\cdot\nabla f_\Psi = -\alpha_\Psi f_\Psi + \beta_\Psi .$$

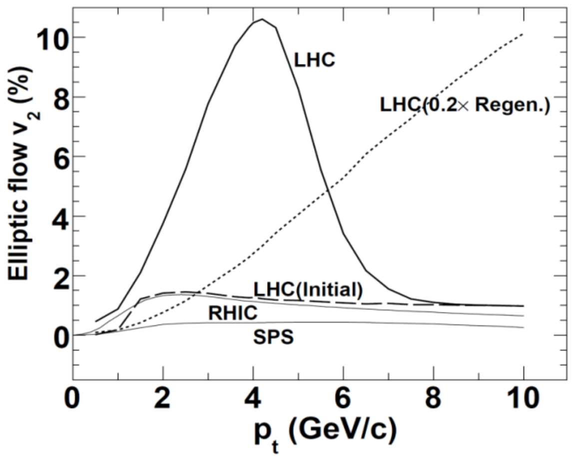
$$\alpha_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int\frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}W_{g\Psi}^{c\bar{c}}(s)f_g(\mathbf{p}_g,\mathbf{x}_t,\tau)\Theta\left(T(\mathbf{x}_t,\tau|\mathbf{b})-T_c\right),$$

$$\beta_\Psi(\mathbf{p}_t,\mathbf{x}_t,\tau|\mathbf{b}) = \frac{1}{2E_\Psi}\int\frac{d^3\mathbf{p}_g}{(2\pi)^3 2E_g}\frac{d^3\mathbf{p}_c}{(2\pi)^3 2E_c}\frac{d^3\mathbf{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}}W_{c\bar{c}}^{g\Psi}(s)f_c(\mathbf{p}_c,\mathbf{x}_t,\tau|\mathbf{b})f_{\bar{c}}(\mathbf{p}_{\bar{c}},\mathbf{x}_t,\tau|\mathbf{b})$$
$$\times(2\pi)^4\delta^{(4)}(p+p_g-p_c-p_{\bar{c}})\Theta\left(T\left(\mathbf{x}_t,\tau|\mathbf{b}\right)-T_c\right),$$

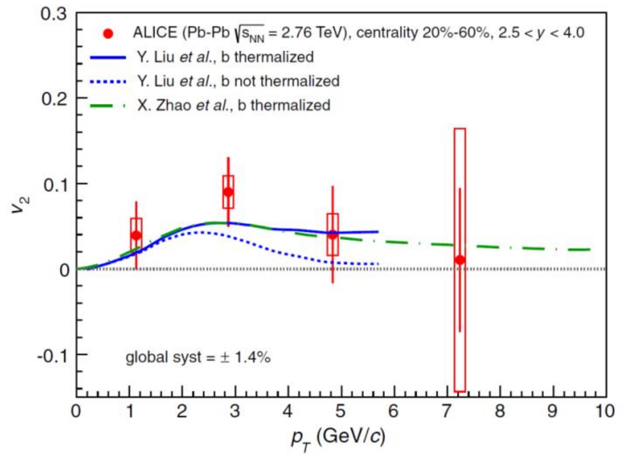
- *QGP evolution*

$\partial_\mu T^{\mu\nu} = 0, \quad \partial_\mu n^\mu = 0$ *+ Lattice QCD equation of state*

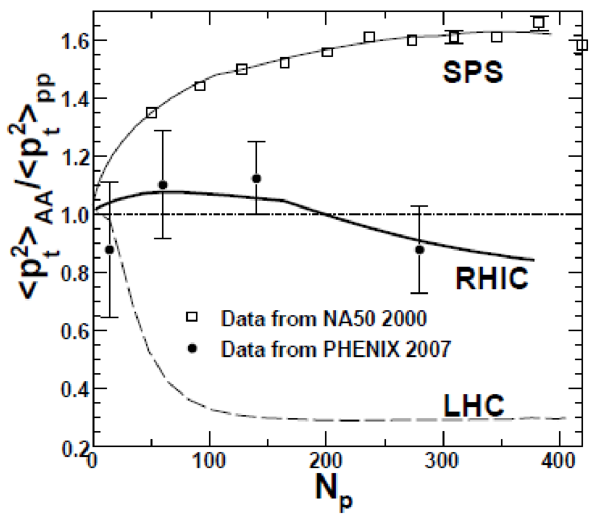
Charmonium P_t Distributions



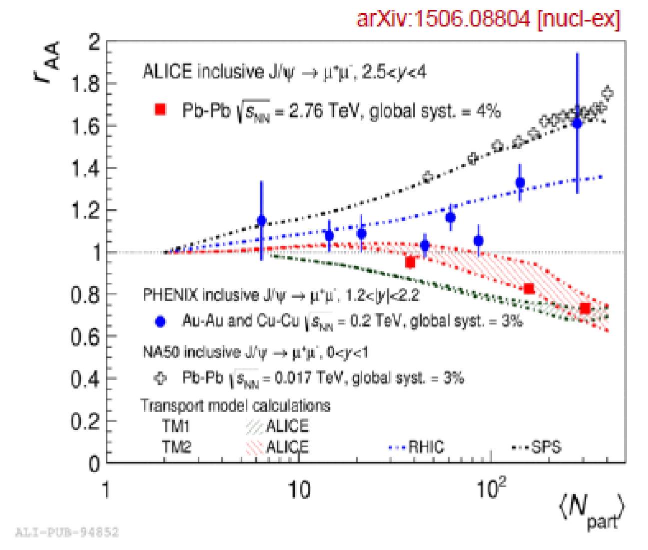
Liu, Xu, Zhuang, NPA834, 317C(2010)



ALICE Collaboration, PRL111, 162301(2013)

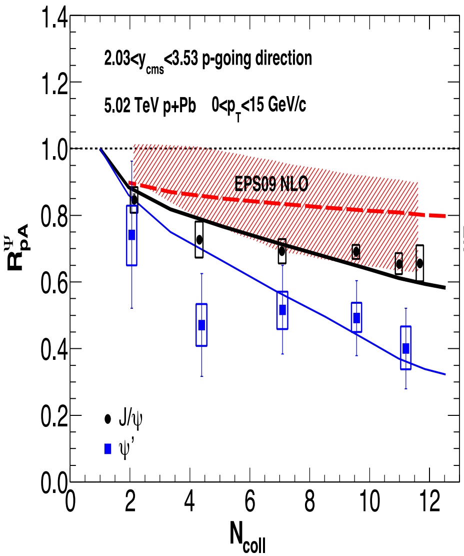


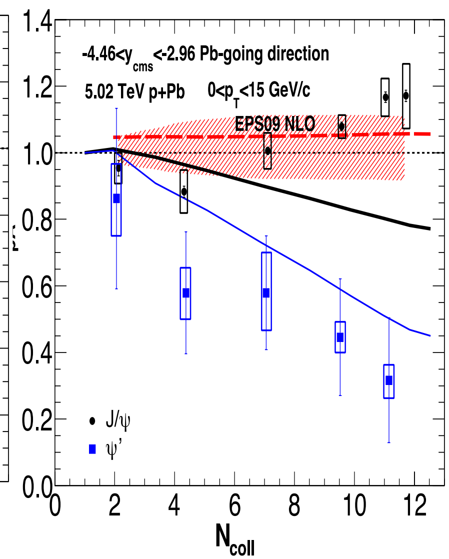
Zhou, Xu, Zhuang, NPA834, 249C(2010)

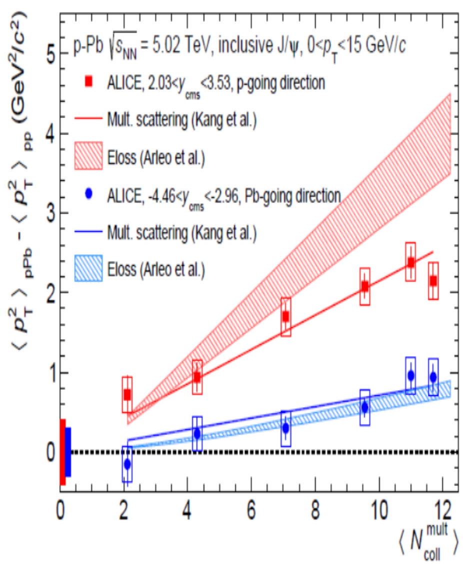


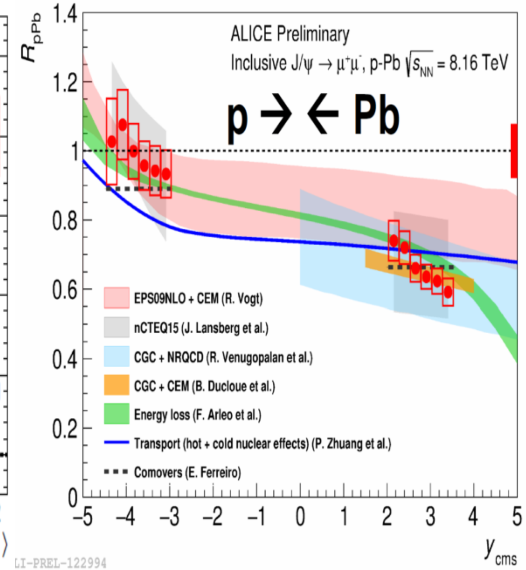
ALICE Collaboration, JHEP1605, 179(2016)

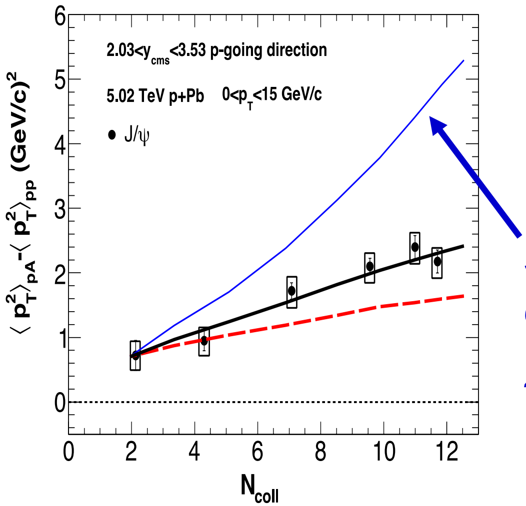
Charmonia in p+A











1) Cold medium effect explains J/ψ distributions reasonably well,

2) The difference between J/ψ and ψ' shows a sizeable hot medium effect on ψ',

3) Much more strong p_T broadening for ψ', need to be confirmed experimentally.

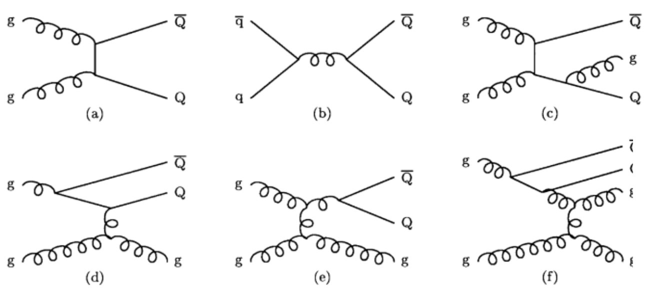
4) Puzzle: J/ψ enhancement and ψ' suppression at backward rapidity!

Chen, Guo, Liu, and Zhuang, PLB765 (2017) 323

Charmonium Enhancement at FCC

- Charm production in QGP:

Levai, Muller and Wang, PRC51, 3326(1995).
Kaempfer and Pavlenko, PLB391, 185(1997).
Uphoff, Fochler, Xu and Greiner, PRC82, 044906(2010).
Zhang, Ko and Liu, PRC77, 024901(2008),……



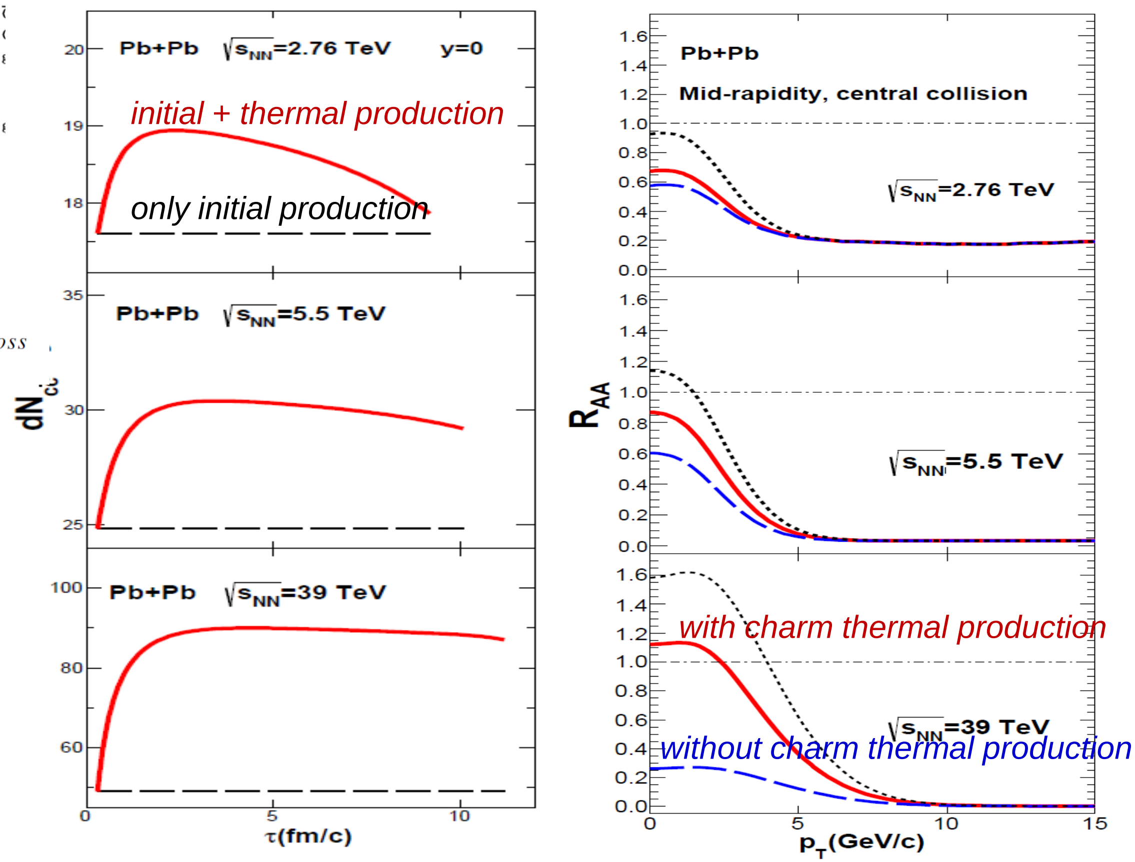
- Charm evolution in QGP

$$\frac{1}{\cosh\eta}\partial_\tau n_c + \nabla_T \cdot (n_c \mathbf{v}_T) + \frac{1}{\tau\cosh\eta} n_c = r_{gain} - r_{loss}$$

80% enhancement at FCC !

- Charm evolution in QGP

J/ψ enhancement at low p_T:
$R_{AA}(p_t) < 1 \ \rightarrow \ R_{AA}(p_t) > 1$!



Zhou, Chen, Greiner, Zhuang, PLB758, 434(2016)

Motivation to Study Multi-charmed Baryons

1) Ω_{ccc} and Ξ_{cc} are hardly produced in pp collisions, due to small production cross section
$\sigma(\Omega_{ccc})$ = 0.06~0.13 nb at 7 GeV and 0.1~0.2 nb at 14 GeV (Bjorken 1986 and Chen, 2011)
$\sigma(\Xi_{cc})$~10 nb at 1.8 TeV (PRL89 (2002) 112001).

SELEX Collaboration claimed the observation of Ξ_{cc}, but FOCUS, BaBar, Belle, LHCb failed to reproduce it in elementary collisions.

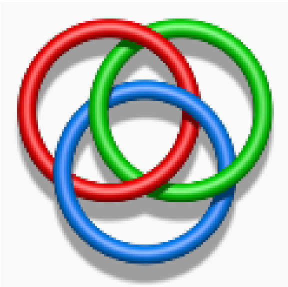
2) However, coalescence among uncorrelated charm quarks in A+A may significantly enhance the production probability,

$$N(\Xi_{cc}) \sim N_c^2, \quad N(\Omega_{ccc}) \sim N_c^3, \quad N_c \sim 100 \text{ at LHC !}$$

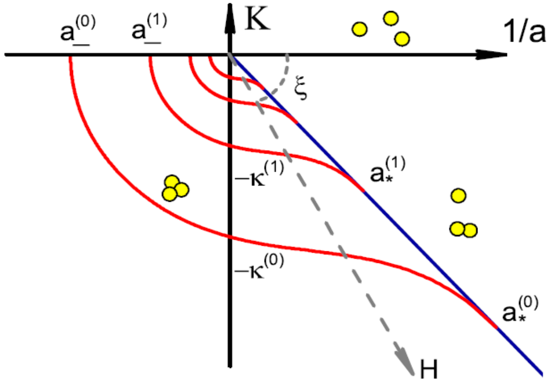
3) If they are discovered in A+A collisions, it is a unique signal of QGP!

4) Exotic baryon states at quark level

1) Borromean rings



2) Efimov states (PLB33, 563(1970)), discovered in cold atom gas (T.Kraemer et al., Nature 440, 315(2006)).



Significant Enhancement and Exotic States

He, Liu, Zhuang, PLB746, 59(2015), Zhao, He, Zhuang, arXiv:1603.04524, PLB, (2017)

- **Schroedinger equation at finite T**

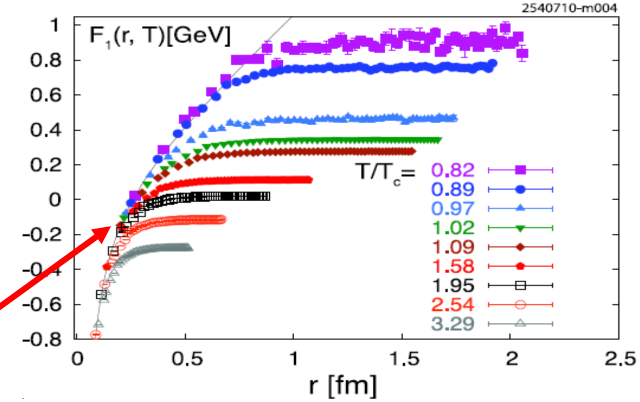
$$\hat{H}\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,T) = E(T)\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,T),$$

$$\hat{H} = \sum_{i=1}^{3}\frac{\hat{\mathbf{p}}_i^2}{2m_c} + V_{ccc}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,T),$$

$$V_{ccc}(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3,T) = \sum_{i<j} V_{cc}(|\mathbf{r}_i-\mathbf{r}_j|,T)$$

$$V_{cc} = V_{c\bar{c}}/2.$$

short range potential at high T !



- **Wigner function**

$$W(\mathbf{r},\mathbf{p}) = \int d^6\mathbf{y}\, e^{-i\mathbf{p}\cdot\mathbf{y}}\,\psi\left(\mathbf{r}+\frac{\mathbf{y}}{2}\right)\psi^*\left(\mathbf{r}-\frac{\mathbf{y}}{2}\right)$$

- **Coalescence on hadronization surfac**

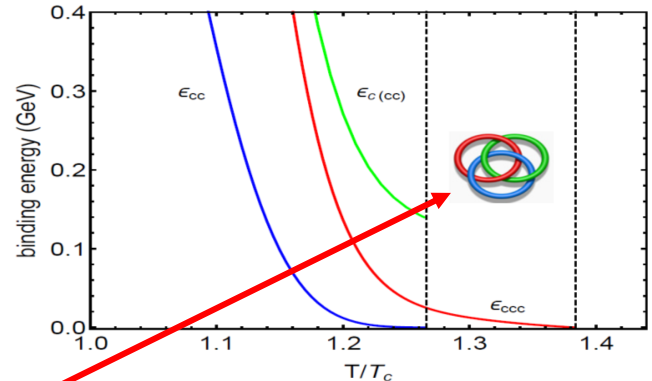
in central Pb+Pb at 2.76 TeV,

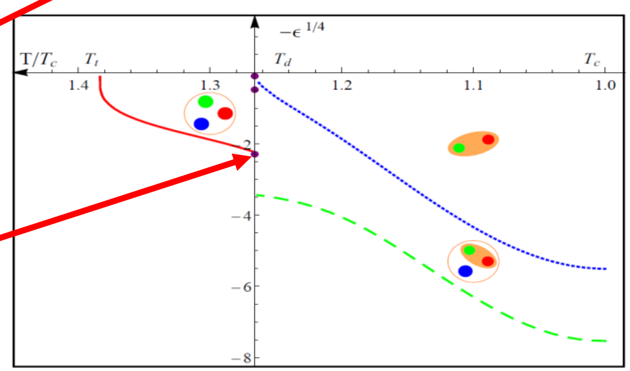
$\sigma_\Omega \sim 3.5\times 10^4\ nb$

in p+p at 7 TeV,

$\sigma_\Omega \sim 0.1\ nb$

Conclusion: enhancement by 6 orders !





- **Borromean ring and Efimov states**

possible realization in heavy ion collisions !

Summary

1) *Quarkonium is still a smoking gun in probing QGP, the p_t distribution is sensitive to the fireball properties.*

2) *P+A: Dominant cold medium effects at RHIC, but a sizeable hot medium effect at LHC.*

3) *A+A: Quarkonium v_2, $r_{AA} = \frac{\langle p_t^2 \rangle_{AA}}{\langle p_t^2 \rangle_{pp}}$ and $R_{AA}(p_t)$ can distinguish hot mediums at SPS, RHIC and LHC： from p_t enhancement at SPS to p_t suppression at LHC !*

4) *Charmed baryons: It is most probable to discover Ω_{ccc} and Ξ_{cc} in A+A, and the discovery is a unique signal of QGP formation.*

5) *Exotic baryon states: Borromean states and Efimov states of Ω_{ccc} at finite temperature, and possible realization in heavy ion collisions.*

6) *There are still some puzzles, like J/ψ enhancement in p+A and excess of low p_t J/ψ.*

decay modes of Ω_{ccc}

Decay through weak interaction, for instance

nonleptonic cascade decay mode (Chen 2011):

$$\Omega_{ccc}^{++} \to \Omega_{ccs}^{+} + \pi^{+}$$
$$\downarrow$$
$$\Omega_{css}^{0} + \pi^{+}$$
$$\downarrow$$
$$\Omega_{sss}^{-} + \pi^{+}$$

semileptonic decay mode (Bjorken, 1986):

$$\Omega_{ccc}^{++} \to \Omega_{sss}^{-} + 3\mu^{+} + 3v_{\mu}.$$

Ξ_{cc} Decay mode and experiment status

- $\Xi_{cc}^{+} \to \Lambda_c^{+} K^{-} \pi^{+}$ (Observation reported by SELEX 2003)
- $\Xi_{cc}^{+} \to D^{0} p K^{-} \pi^{+}$ (Searched by Belle2006)
- $\Xi_{cc}^{+} \to D^{+} p K^{-}$ (Searched by FOCUS 2003, Belle2006)
- $\Xi_{cc}^{+} \to \Xi_c^{+} \pi^{+} \pi^{-}$ (Searched by BarBar2006)
- $\Xi_{cc}^{+} \to \Xi_c^{0} \pi^{+}$

"The improved LHCb and Belle II (2019) is promising in observing Ξ_{cc} "

Search for the Doubly Charmed Baryon at LHCb, Ph.D thesis, ZHONG Liang (2015)