Quarkonia as a Probe of QGP

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- *QGP in heavy ion collisions*

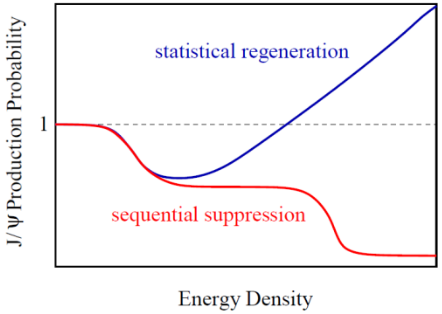
$$\begin{array}{lcccccc} & SPS & \rightarrow & RHIC & \rightarrow & LHC & \rightarrow & FCC(Future\ Circular\ Collider) \\ \sqrt{s_{NN}} = & 17\ GeV & & 200\ GeV & & 5\ TeV & & 39(63)\ TeV \end{array}$$

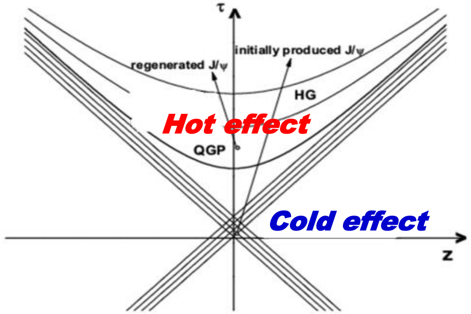
QGP formation → QGP properties

- *Quarkonium as a thermometer of the QGP*

However, the two hot nuclear effects, suppression (Matsui, Satz, …) and regeneration (PBM & Stachel, Thews et al., Rapp et al, …), work in an opposite way and therefore weaken the sensitivity of the thermometer.

The cold nuclear effects (shadowing, Cronin, energy loss, absorption,…) affect the thermometer too.





- *How to increase the sensitivity of the thermometer ?*

Outline

1. More Sensitive to the Hot Medium: Thermal Heavy Quark Production at FCC

2. More Sensitive to the Initial State: High p_t Quarkonia in Magnetic Field

3. A New Probe: Ξ_{cc} Production in Heavy Ion Collisions

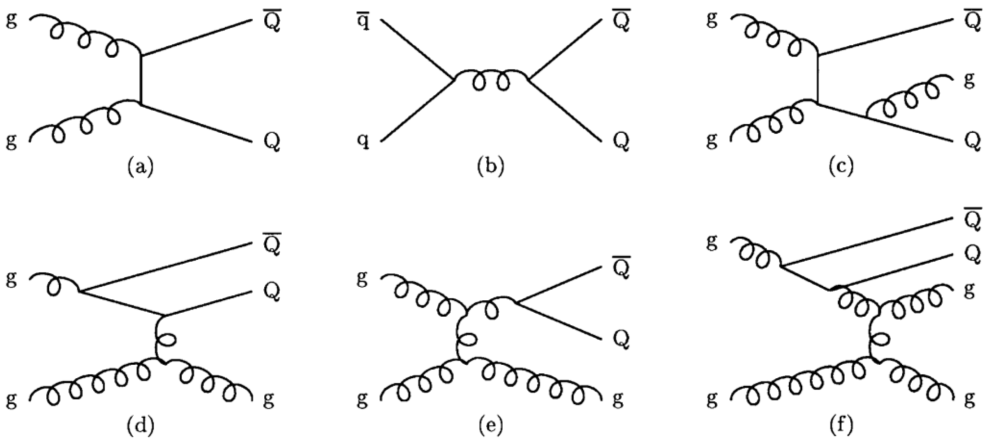
1) More Sensitive to the Hot Medium: *Thermal Heavy Quark Production at FCC*

K.Zhou, Z.Chen, C.Greiner, PZ, PLB758, 434(2016)

Heavy Quark Production in QGP

Thermal charm production in QGP becomes important at high energies:

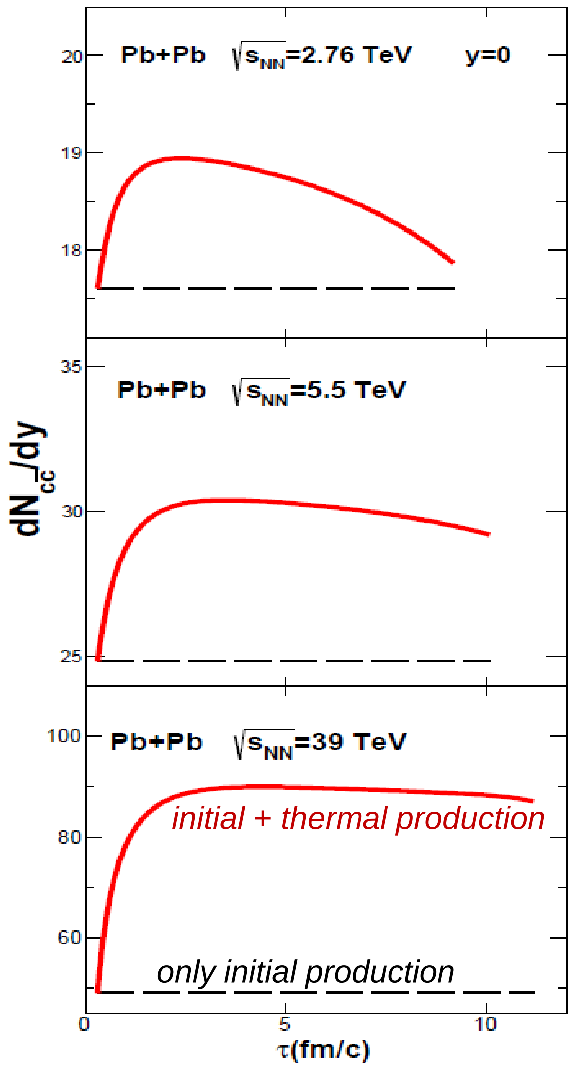
P.Levai, B.Muller and X.Wang, PRC51, 3326(1995).
B.Kaempfer and O.Pavlenko, PLB391, 185(1997).
J.Uphoff, O.Fochler, Z.Xu and C.Greiner, PRC82, 044906(2010).
B.Zhang, C.Ko and W.Liu, PRC77, 024901(2008)



(a) gluon fusion, (b) quark-antiquark annihilation, (c) pair creation with gluon emission, (d) flavor excitation, (e) gluon splitting, (f) together gluon splitting and flavor excitation.

What is the effect on quarkonium regeneration ?

Heavy Quark Evolution in GGP



$$n_c(t,\mathbf{x}) = \int d^3\mathbf{p}/(2\pi)^3 f_c(t,\mathbf{x},\mathbf{p})$$

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

loss and gain rates:

$$r_{12} = \frac{dn}{d^4x} = \frac{1}{\nu}\int \frac{d^3\mathbf{p}_1}{(2\pi)^3 2E_1}\frac{d^3\mathbf{p}_2}{(2\pi)^3 2E_2} 4F_{12}\sigma_{12} f_1 f_2,$$

*NLO production cross section

P.Nason, S.Dawson, and R.Ellis, NPB 303, 607(1988); 327, 49(1989).
M.L.Mangano, P.Nason and G.Ridolfi, NPB373, 295(1992).

*parton masses and coupling constant are T-dependent

E.Braaten and R.Pisarski, PRD45, 1827(1992).
S.Plumari, W.M.Alberico, V.Greco and C.Ratti, PRD84, 094004(2011)

*thermalized parton distribution functions

*hydrodynamics for QGP evolution

*detailed balance between loss and gain terms

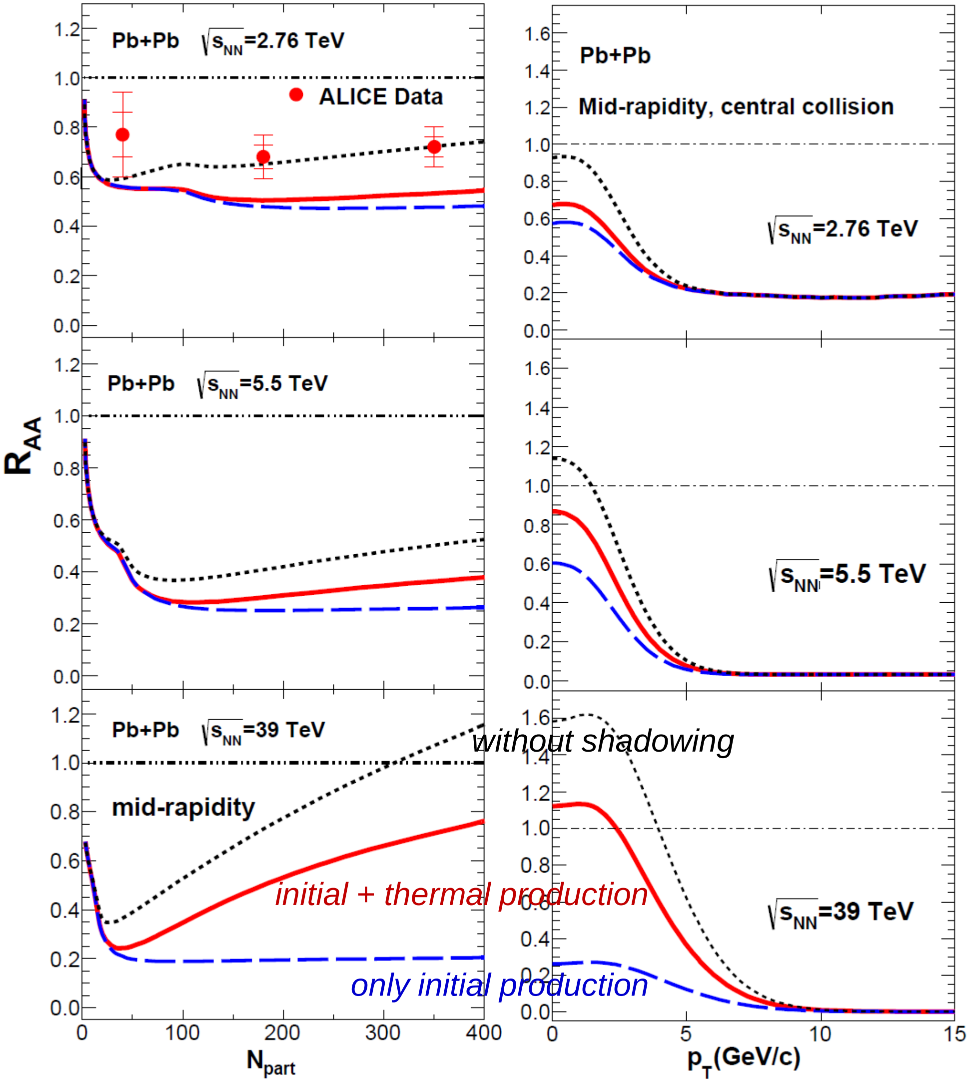
*shadowing effect (EKS98, EPS09), strong charm suppression!

charm quark number evolution in QGP: significant enhancement (~50%) at FCC !

see also the work by Yunpeng Liu and Che-Ming Ko, arXiv:1604.01207

Quarkonium Evolution in QGP

Transport + hydrodynamics: L.Yan, N.Xu and P.Zhuang, PRL97, 232301(2006)
Result at LHC: K.Zhou, N.Xu, Z.Xu and P.Zhuang, PRC89, 054911(2014)



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

$$\alpha_\Psi = \frac{1}{2E_T}\int \frac{d^3\mathbf{k}}{(2\pi)^3 2E_g}\sigma_{g\Psi}(\mathbf{p},\mathbf{k},T)4F_{g\Psi}(\mathbf{p},\mathbf{k})f_g(\mathbf{k},T,u_\mu)$$

$$\sigma_{g\Psi}(\mathbf{p},\mathbf{k},T) = \frac{\langle r^2\rangle_\Psi(T)}{\langle r^2\rangle_\Psi(0)}\sigma_{g\Psi}(\mathbf{p},\mathbf{k},0),$$

thermal charm production at FCC leads to:

- *a deep valley in $J/\psi\ R_{AA}(N_p)$*
- *significant enhancement*

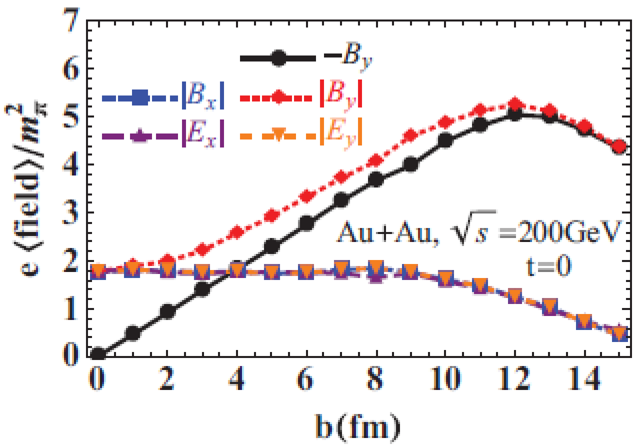
$$R_{AA}(N_p) = 0.2 \rightarrow 0.75,$$
$$R_{AA}(p_t) < 1 \rightarrow > 1$$

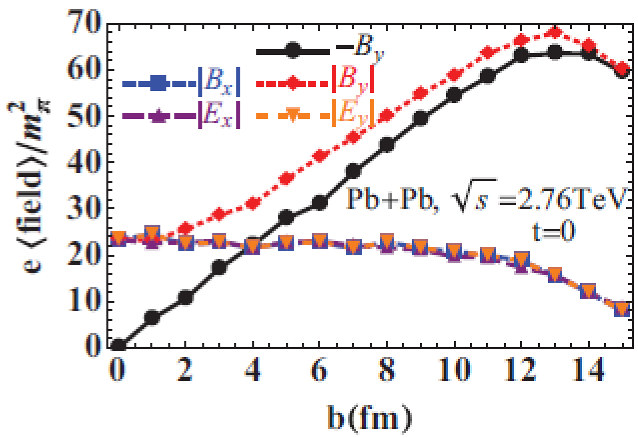
2) More Sensitive to the Initial State: *High p_t Quarkonia in Magnetic Field*

X.Guo, S.Shi, N.Xu, Z.Xu, PZ, PLB751, 215(2015)

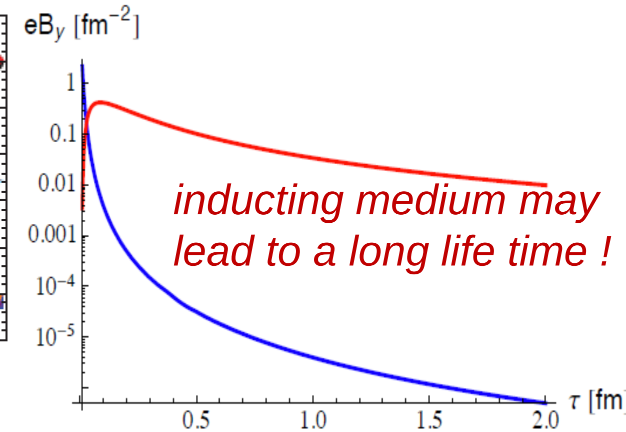
Charmonia as a Probe of Initial B Field

Deng and Huang, PRC 85, 044907 (2012):





Gursoy, Kharzeev, and Rajagopal, PRC89, 054905(2014):



strongest magnetic field in nature but lasts ~0.1 fm/c only !

high p_t charmonium is an ideal probe of the initial B field:

- *created in the early stage,*
- *sensitive to the B field,*
- *not affected by the later hot medium.*

idea:

time evolution of a $c\bar{c}$ state $|c\bar{c}\rangle$: $i\frac{\partial}{\partial t}|c\bar{c}\rangle = \hat{H}(B(t))|c\bar{c}\rangle$

anisotropic formation in B field: $|\langle\Psi|c\bar{c}\rangle|^2$

anisotropic p_t distribution: $P_\Psi(p_t,\varphi)$.

Time-dependent Schroedinger Equation

$$i\frac{\partial}{\partial t}\Phi(t) = \hat{H}\Phi(t), \qquad \hat{H} = \frac{\left(\vec{p}_c - q_c\vec{A}_c\right)^2}{2m_c} + \frac{\left(\vec{p}_{\bar{c}} - q_{\bar{c}}\vec{A}_{\bar{c}}\right)^2}{2m_c} - \frac{(q_c\vec{s}_c + q_{\bar{c}}\vec{s}_{\bar{c}})\cdot\vec{B}}{m_c} + V_{c\bar{c}}(r)$$

$$V_{c\bar{c}}(r) = -\frac{\alpha}{r} + \sigma r + \beta e^{-\gamma r}\vec{s}_c \cdot \vec{s}_{\bar{c}}$$

parameters are determined in vacuum, see Alford, Strickland, 2013.

$$\vec{R} = \frac{\vec{r}_c + \vec{r}_{\bar{c}}}{2},\ \vec{r} = \vec{r}_c - \vec{r}_{\bar{c}},\ \vec{P} = \vec{p}_c + \vec{p}_{\bar{c}},\ \vec{p} = \frac{\vec{p}_c - \vec{p}_{\bar{c}}}{2},$$

kinetic momentum $\vec{P}_k = \vec{P} - q_c\vec{A}_c - q_{\bar{c}}\vec{A}_{\bar{c}}$, *conserved momentum* $\vec{P}_{ps} = \vec{P} + q_c\vec{A}_c + q_{\bar{c}}\vec{A}_{\bar{c}}$,

$$\hat{H} = \hat{H}_0 + \hat{H}_B, \qquad \hat{H}_B = -\frac{(q_c\vec{s}_c + q_{\bar{c}}\vec{s}_{\bar{c}})\cdot\vec{B}}{m_c} - \frac{q_c}{2m_c}\left(\vec{P}_{ps} \times \vec{B}\right)\cdot\vec{r} + \frac{q^2}{4m_c}\left(\vec{B} \times \vec{r}\right)^2$$

Lorentz force, controlling the $c\bar{c}$ behavior

expanding Φ in terms of the charmonium states:

$$\Phi\left(\vec{P}_{ps}, \vec{R}, \vec{r}, t\right) = \frac{1}{\sqrt{2\pi}} e^{i\left(\vec{P}_k\cdot\vec{R} - \frac{\vec{P}_{ps}t}{4m_c}\right)} \sum_\psi C_\psi\left(\vec{P}_{ps}, t\right) e^{-iE_\psi t}\psi(\vec{r}),$$

$$\hat{H}_0\psi(\vec{r}) = E_\psi\psi(\vec{r})$$

$$\frac{d}{dt}C_\psi\left(\vec{P}_{ps}, t\right) = \sum_{\psi'} e^{i\left(E_\psi - E_{\psi'}\right)t} C_{\psi'}\left(\vec{P}_{ps}, t\right) \int d^3\vec{r}\,\psi^*(\vec{r})\hat{H}_B\psi'(\vec{r})$$

the probability for the $c\bar{c}$ to be in the state $|\psi\rangle$ is $|C_\psi\left(\vec{P}_{ps}, t\right)|^2$

Parameters for Heavy Ion Collisions

initial magnetic field distribution:

$$B = \begin{cases} B\vec{e}_y, & 0 < t < t_B \quad and \quad \frac{x^2}{(R_A - b/2)^2} + \frac{y^2}{(b/2)^2} + \frac{\gamma^2 z^2}{(b/2)^2} < 1 \\ 0, & otherwise \end{cases}$$

$b = 8\ fm,\ R_A = 6.6\ fm,$

RHIC: $eB = 5m_\pi,\ t_B = 0.5fm,\ \gamma = 100$

LHC: $25m_\pi,\quad 0.2fm,\quad 1400$

initial wave function:

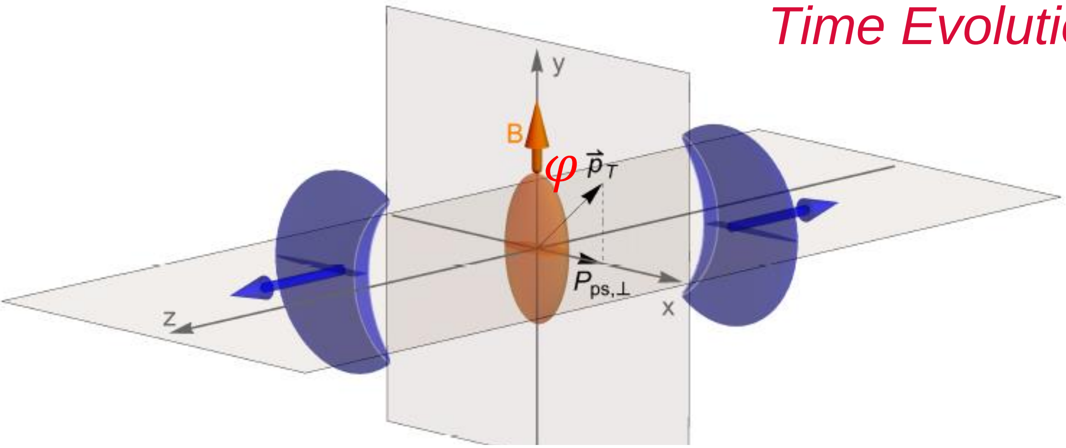
$$\Phi(\vec{r}, t=0) = (2\pi\sigma^2)^{-\frac{3}{4}} e^{-\frac{(\vec{r}-\vec{r}_0)^2}{4\sigma^2}} = \sum_\psi C_\psi \psi(\vec{r}),$$

$$\vec{r}_0 = r_0(sin\theta_0 cos\varphi_0, sin\theta_0 sin\varphi_0, cos\theta_0),$$

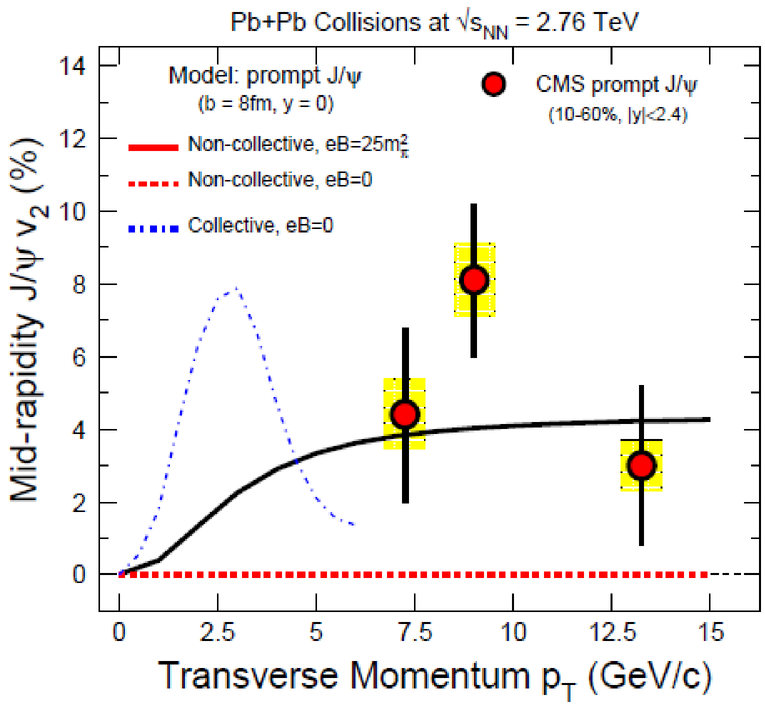
r_0 *and* σ *are determined by the feed back of* ψ' *and* χ_c *in* $p+p$:

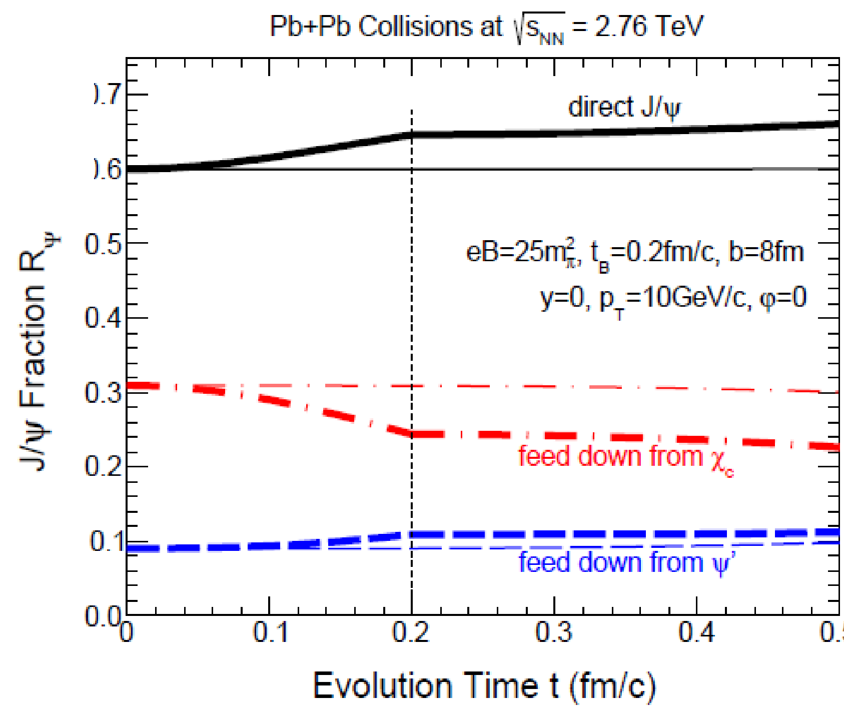
$\mathrm{R}(\chi_c) = 30\%$ and $\mathrm{R}(\psi') = 10\%$ $(LHCb)$

Time Evolution and Non-collective Flow



$$R_\Psi(t) = \frac{|C_\Psi(t)|^2 \mathcal{B}(\Psi \to J/\psi)}{\sum_\Psi |C_\Psi(t)|^2 \mathcal{B}(\Psi \to J/\psi)}$$





Non-collective v_2 created by the B field

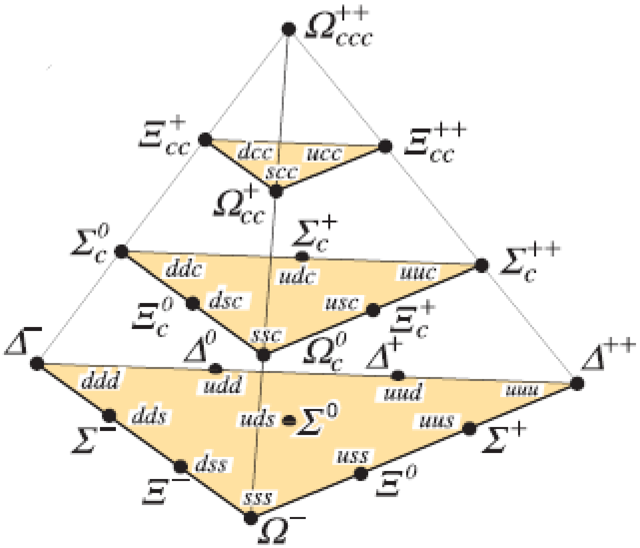
thick lines: A+A *thin lines: p+p*

ψ' and J/ψ enhancement by 10% and χ_c suppression by 23%

3. A New Probe: Ξ_{cc} Production in Heavy Ion Collisions

J.Zhao, H.He, PZ, arXiv:1603.04524

Ξ_{cc}, not yet discovered



SELEX claimed the observation in 2003, but FOCUS, Belle, BaBar, and LHCb failed to reproduce the results.

Ξ_{cc} production needs at least 2 pairs of $c\bar{c}$, the production cross section in a p+p collision is very small even at LHC energy.

The $c\bar{c}$ pairs in an A+A collision at LHC can reach 100, the probability to discover Ξ_{cc} in A+A is largely enhanced!

Ξ_{cc}, a unique signal of QGP

Current signals of QGP: jet quenching, J/ψ suppression, strangeness enhancement, electromagnetic probes, ……

All these observables are produced in both p+p and A+A, the signal is defined as the quantitative difference between p+p and A+A.

If Ξ_{cc} is discovered in A+A, however, it is a unique signal of QGP, since it is not produced in p+p at the same energy.

3-body schroedinger equation

$$\hat{H}\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3) = E_T\Psi(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3),\qquad V = \sum_{i<j} v(\mathbf{r}_i,\mathbf{r}_j)$$

$$\hat{H} = \sum_{i=1}^{3}\frac{\hat{\mathbf{p}}_i^2}{2m_i} + V(\mathbf{r}_1,\mathbf{r}_2,\mathbf{r}_3)\qquad v(\mathbf{r}_i,\mathbf{r}_j) = (-\alpha/|\mathbf{r}_i-\mathbf{r}_j| + \sigma|\mathbf{r}_i-\mathbf{r}_j|)/2$$

1) α, σ, m_c and m_q are fixed by fitting D and charmonium spectra,

2) Ξ_{cc} is formed at T_c, assuming $V(T_c) = V(0)$

* $\vec{r}_1, \vec{r}_2, \vec{r}_3 \;\rightarrow\; \vec{R}$ (global coordinate), $\vec{r}_x, \vec{r}_y$ (relative coordinates)

$$\Psi(\mathbf{R},\mathbf{r}_x,\mathbf{r}_y) = \Theta(\mathbf{R})\Phi(\mathbf{r}_x,\mathbf{r}_y)$$

* $\vec{r}_x, \vec{r}_y \rightarrow r, \Omega = (\theta_x, \phi_x, \theta_y, \phi_y, \alpha = arctg\frac{r_y}{r_x})$ (hyperspherical coordinates)

$$V(r,\Omega) \;\rightarrow\; \Phi(r,\Omega) = \sum_\kappa \phi_\kappa(r) Y_\kappa(\Omega)$$

$$\left[\frac{\partial^2}{\partial r^2} + \frac{5}{r}\frac{\partial}{\partial r} - \frac{k(k+4)}{r^2} + \epsilon\right]\phi_\kappa = \sum_{\kappa'} V_{\kappa\kappa'}\phi_{\kappa'}\qquad V_{\kappa\kappa'}(r) = \int Y_\kappa^*(\Omega)V(r,\Omega)Y_{\kappa'}(\Omega)d\Omega$$

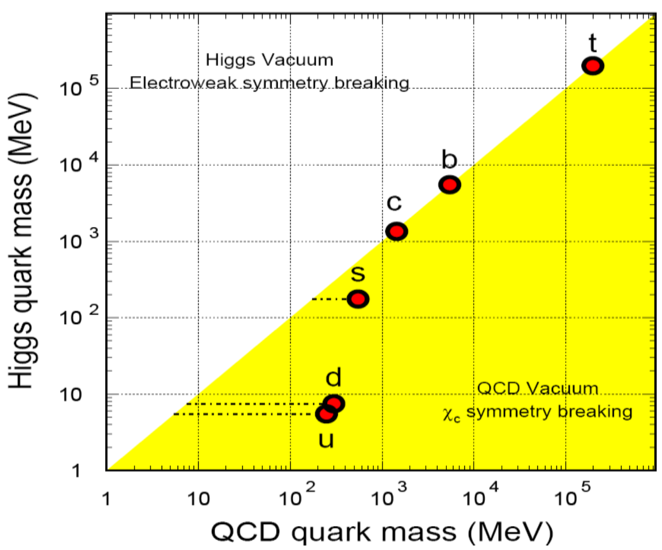
relativistic correction

$$\Delta\epsilon_0 = \langle\Phi_0|\Delta\hat{H}|\Phi_0\rangle + \sum_n \frac{|\langle\Phi_n|\Delta\hat{H}|\Phi_0\rangle|^2}{\epsilon_0-\epsilon_n}\qquad m_{\Xi_{cc}^+} = 2m_c + m_q + \epsilon_0 + \Delta\epsilon_0 = 3.584\ \mathrm{GeV}$$

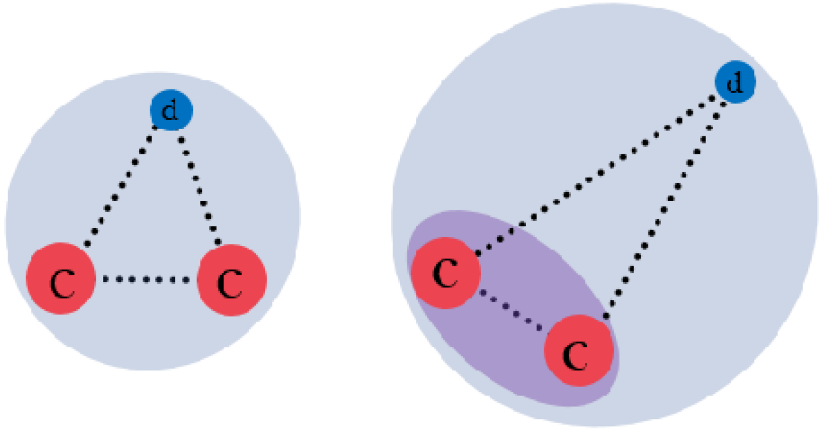
$$\Delta\Phi_0(r,\Omega) = \sum_n \frac{\langle\Phi_n|\Delta\hat{H}|\Phi_0\rangle}{\epsilon_0-\epsilon_n}\Phi_n,\qquad \langle r\rangle_{\Xi_{cc}^+} = \frac{\int dr d\Omega r^6\,|\Phi_0+\Delta\Phi_0|^2}{\int dr d\Omega r^5\,|\Phi_0+\Delta\Phi_0|^2} = 0.41\ \mathrm{fm}.$$

Chiral Symmetry and Ξ_{cc} Structure

for Ξ_{cc}, the coalescence happens at the hadronization hypersurface where the broken chiral symmetry is restored, and the light quark mass drops down significantly,



$$m_c(T_c) \simeq m_c(0),$$
$$m_q(T_c) \simeq 100\ \text{MeV} < m_q(0) \simeq 300\ \text{MeV}$$



Average r_i(fm)	Model 1 (m_d=0.3GeV)	Model 2 (m_d=0.1GeV)
$< r_{cc} >$	0.4437	0.4620
$< r_{(cc)-q} >$	0.5294	0.9662

Ξ_{cc} in elementary collisions is a three quark state (ccq),
but Ξ_{cc} in heavy ion collisions is more like a quark-diquark state (cc-q).

Extreme Ξ_{cc} Enhancement

coalescence probability

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

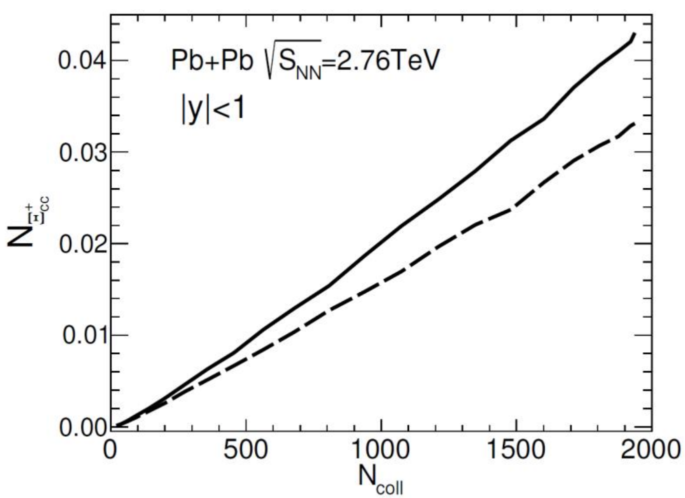
momentum distribution

$$\frac{dN}{d^2\mathbf{P}_T d\eta} = C\int \frac{P^\mu d\sigma_\mu(R)}{(2\pi)^3}\frac{d^4r_x d^4r_y d^4p_x d^4p_y}{(2\pi)^6} f_c(\tilde{r}_1,\tilde{p}_1) f_c(\tilde{r}_2,\tilde{p}_2) f_q(\tilde{r}_3,\tilde{p}_3) W(r_x,r_y,p_x,p_y)$$

thermalized quark distributions

the hypersurface is defined through the hydrodynamics

$\partial_\mu T^{\mu\nu} = 0$ + *EoS of QCD*



to eliminate the simple superposition of p+p collisions and focus on the hot medium effect, we introduce the effective cross section per binary collision at $\sqrt{s_{NN}} = 2.76$ TeV:

$$\tilde{\sigma}_{AA}^{\Xi^+_{cc}} = N_{\Xi^+_{cc}}/\Delta y \sigma_{pp} \qquad \tilde{\sigma}_{pp}^{\Xi^+_{cc}} = \tilde{\sigma}_{AA}^{\Xi^+_{cc}}/N_{coll}$$

$$\sigma_{pp} = 62\ mb \ \rightarrow \qquad \tilde{\sigma}_{pp}^{\Xi^+_{cc}} = 412 \text{ nb}$$

it is much larger than

$\sigma_{pp}^{\Xi^+_{cc}} = 61$ nb *in p+p at $\sqrt{s_{NN}} = 14$ TeV*

Ξ_{cc} production is extremely enhanced in nuclear collisions !

Summary

1) *Thermal heavy quark production becomes significant at fireball temperature* $T \gtrsim 500$ MeV, *which leads to a qualitative change from* $R_{AA} < 1\ at\ LHC\ \ to\ R_{AA} > 1\ at\ FCC$.

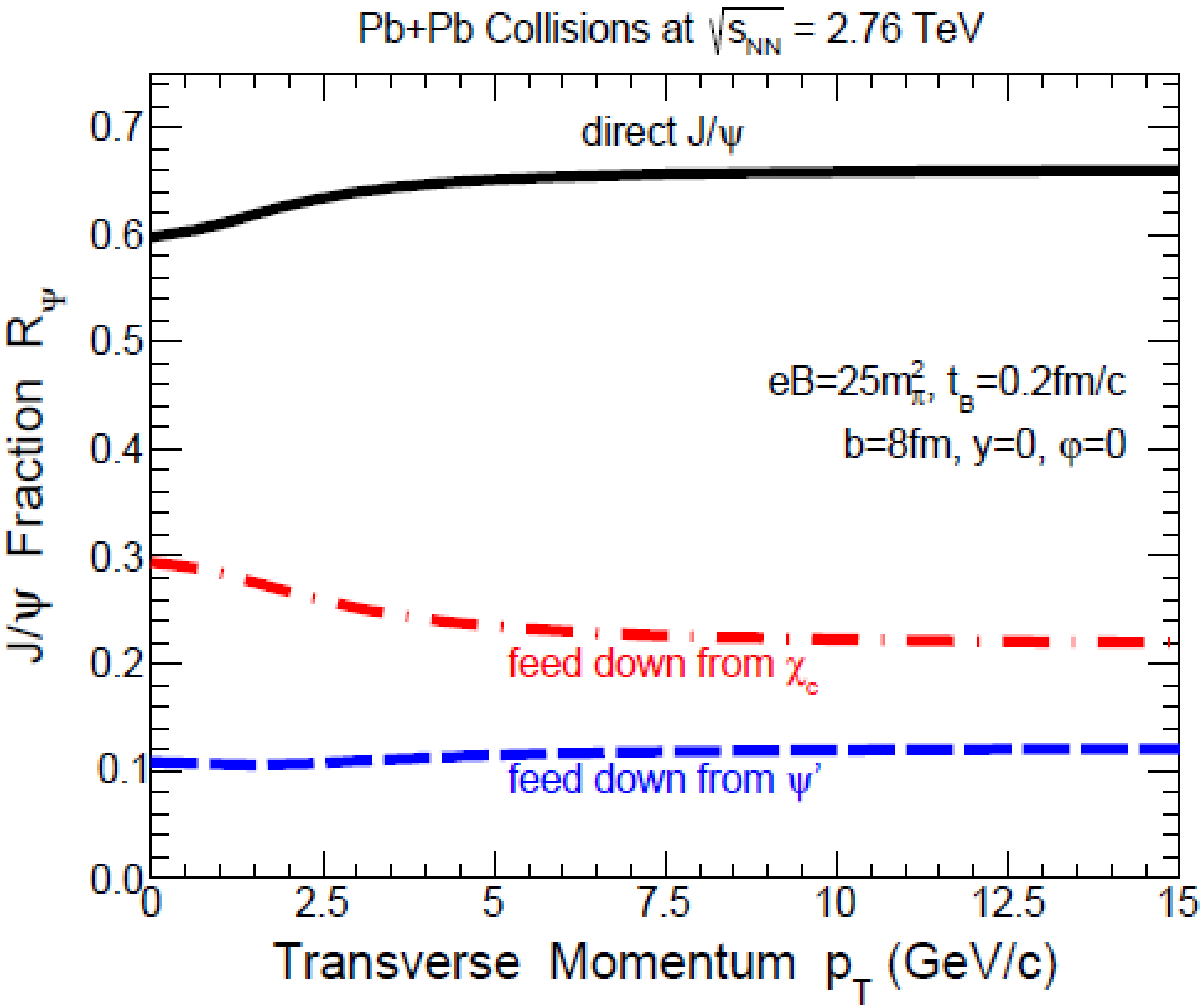
2) *high momentum charmonia are sensitive to the initially produced magnetic field, which leads to a non-collective flow at* $p_t > 7\ \mathrm{GeV/c}$.

3) *it is most probable to discover doubly and triply charmed baryons in heavy ion collisions at LHC, and the discovery is a unique signature of QGP formation.*

we encourage ALICE, LHCb and STAR experts to search for the new particles Ξ_{cc} *and* Ω_{ccc} *experimentally.*

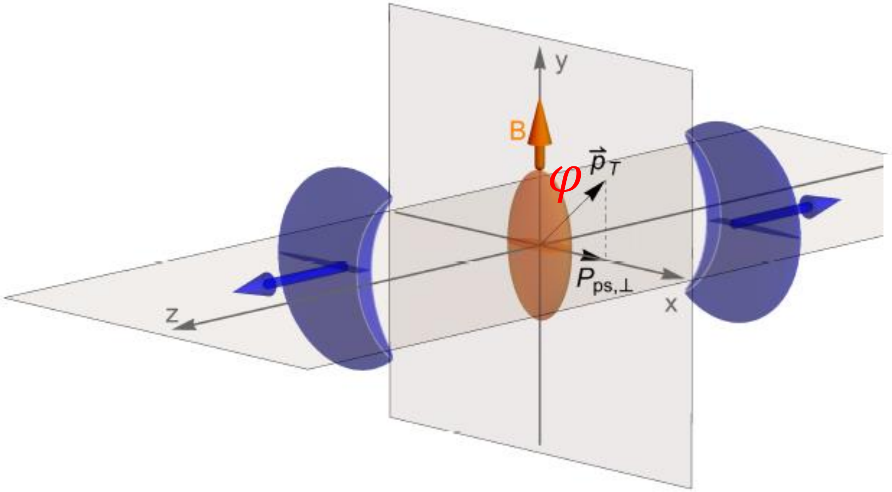
Backup

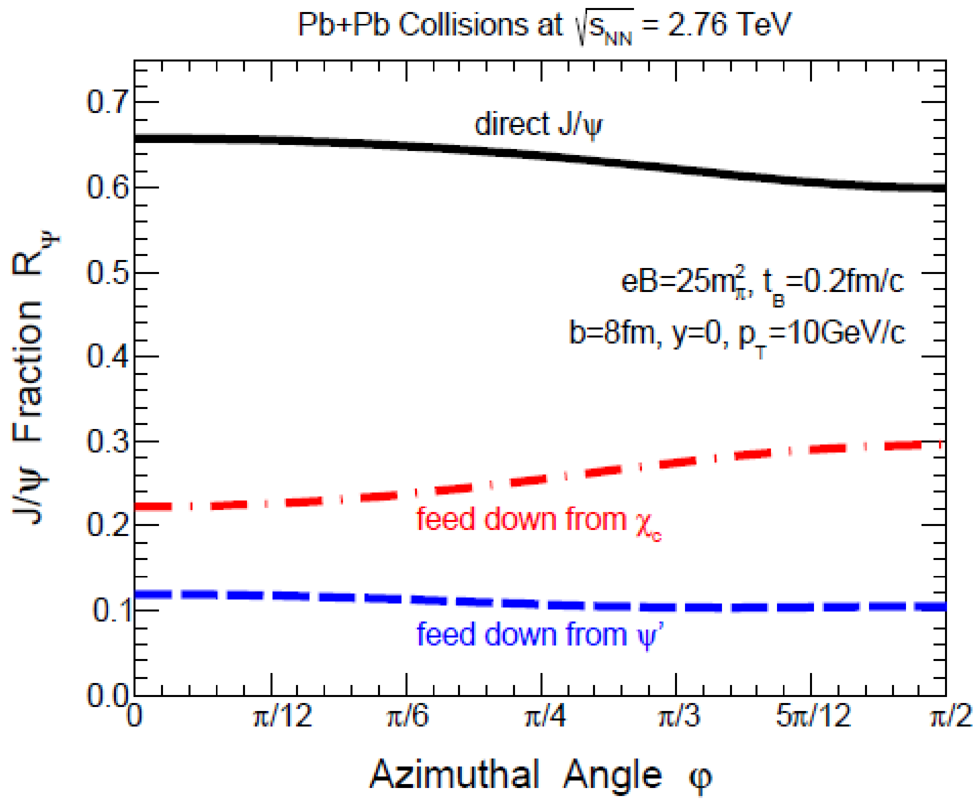
P_t dependence



strong enhancement or suppression at high P_t, due to the Lorentz force.

Anisotropic production





1) *anisotropic charmonium formation in the B field.*
2) *strong enhancement or suppression at $\varphi = 0$, but almost no change at $\varphi = \pi/2$.*

decay modes of Ω_{ccc}

Decay through weak interaction, for instance

nonleptonic cascade decay mode (Chen 2011):

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

semileptonic decay mode (Bjorken, 1986):

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

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)