Production and spin polarization of heavy flavor in heavy-ion collisions

Baoyi Chen（陈保义）

Tianjin University（天津大学）

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Outline

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1. **Introduction** **heavy ion collisions & in-medium quarkonium**

2. **Heavy quark potential at finite T and baryon density**

   Color screening effect,

   Parton inelastic scattering

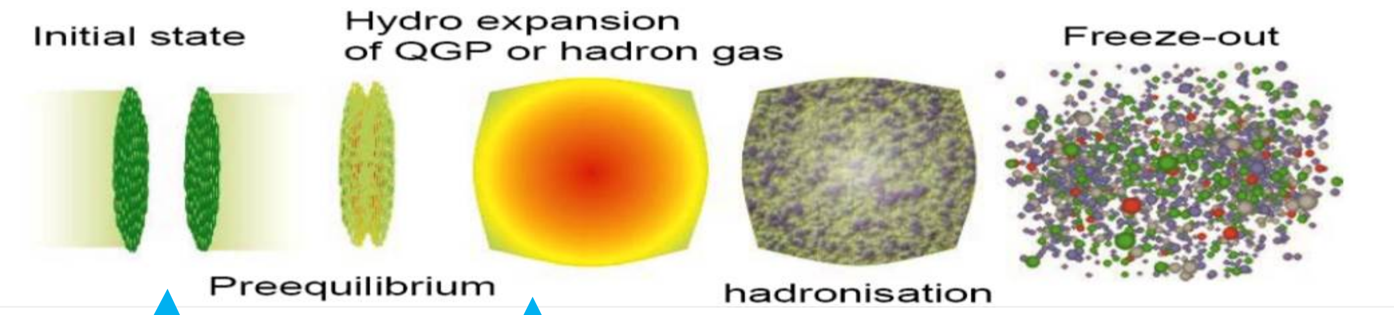
   V(r,T) from small (pp) to large (AA) collision system

3. **Spin polarization of heavy quark and quarkonium**

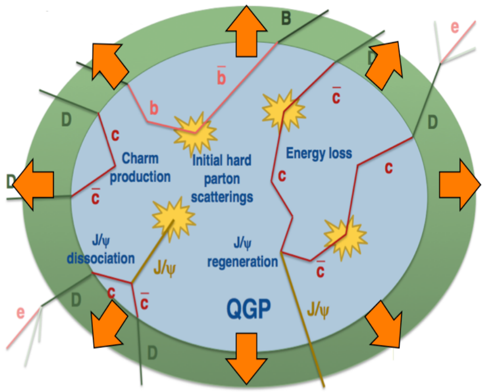
   HF coupled with rotational QGP

   Charmonium spin polarization

1.Introduction



Quarkonium:



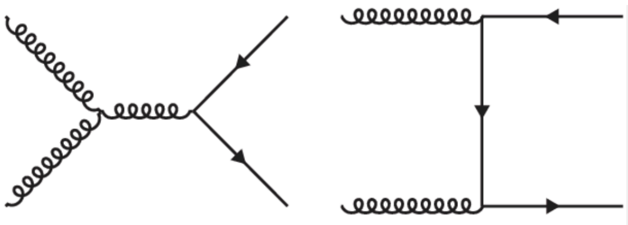
Strong EM fields; etc;

QGP anisotropic flows;
heavy quark potential
Rotations of QGP
EM fields

Coalescence
Fragmentation,
heavy quarkonium

Hadron gas:
Hadronic scattering

Color screening
Inelastic coll.
recombination



(a) s-channel Flavor (b) t-channel Flavor

$\tau_c \approx 1/(2m_c) \sim 0.06$ fm/c

Creation of charm pair,
with a tight wave package

state	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	ψ'
mass [GeV]	2.98	3.10	3.42	3.51	3.56	3.69
ΔE [GeV]	0.75	0.64	0.32	0.22	0.18	0.05

Satz, hep-ph/0512217

QGP local equilibrium: $\tau_c \approx 0.6$ fm/c
Charmonium bound state formation:
$\tau_\psi \approx 1/(\Delta E) \sim 0.3$ fm/c

Quark Heavy quarkonium as a probe of the early profiles of QGP

2.Schrodinger-type models

Previous studies:

(1) X. Guo, S. Shi, P. Zhuang, et al

Time-independent relativistic Schrodinger *PLB* 2012, PRD

(2) P. Gaussian, R. Katz, et al

Schrodinger-Langevin equation *Annals Phys. 368 (2016) 267-295*

Hamiltonian includes a white noise term and a damping term, which affects the expansion and contraction of the wave function

(3) A. Rothkopf, Y. Akamatsu, et al,

Stochastic Schrodinger equation *PRD 97 (2018) 1, 014003*

Potential includes stochastic terms, wave function decoherence to dissociate quarkonium states

(4) M. Strickland et al,

Time-dependent Schrodinger, with complex potential *Phys.Lett.B 2020*

Bottomonium suppression with real and imaginary potential

And many other references…….

2.Schrodinger-type models

Radial Schrodinger equation:

Only Singlet states

$$i\hbar\frac{\partial}{\partial t}\psi(r,t) = [-\frac{\hbar^2}{2m_\mu}\frac{\partial^2}{\partial r^2} + \frac{L(L+1)}{2m_\mu r^2} + V(r,t)]\psi(r,t)$$

r: relative distance between c and $\bar{c}$

$m_\mu = m_c/2$: scaling mass

$$\frac{\psi(r,t)}{r} = \sum_m c_m(t)e^{-iE_m t}R_{mS}(r)$$

Wavefunction of eigenstates:

$$\Psi_{klm}(\vec{r}) = R_{kl}(r)Y_{lm}(\theta,\varphi)$$

Numerical form: Crank-Nicolson method

$$i\frac{\psi_j^{n+1}-\psi_j^n}{\Delta t} = \frac{1}{2}[-\frac{1}{2m_\mu}\frac{\psi_{j+1}^n - 2\psi_j^n + \psi_{j-1}^n}{(\Delta x)^2} + V_j^n\psi_j^n - \frac{1}{2m_\mu}\frac{\psi_{j+1}^{n+1} - 2\psi_j^{n+1} + \psi_{j-1}^{n+1}}{(\Delta x)^2} + V_j^{n+1}\psi_j^{n+1}]$$

$$c_{mS}(t) = \langle R_{mS}(r)|\frac{\psi(r,t)}{r}\rangle = \int R_{mS}(r)\psi(r,t)\cdot r dr$$

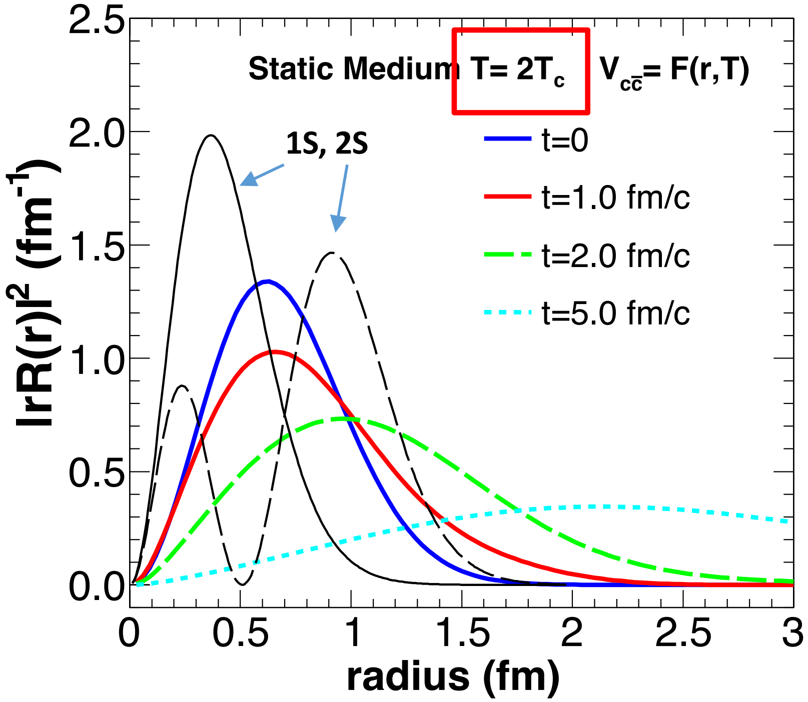
$\tau_{c\bar{c}} < 0.1\ fm$ $\quad$ $\tau_\psi < \tau_0(\sim 0.6\ fm)$

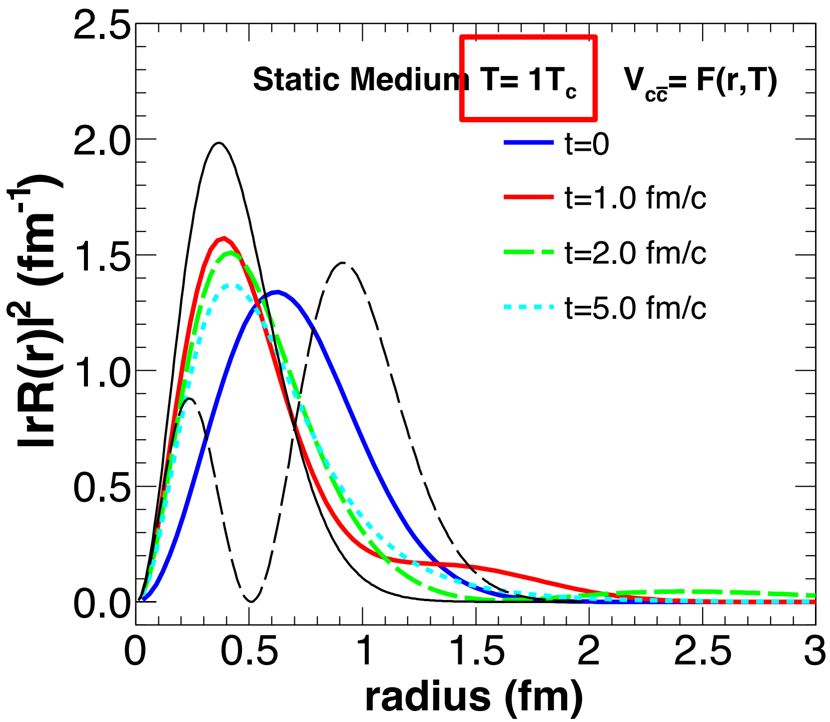
Pre-equilibrium $\quad$ QGP evolution (hydro) $\quad$ time

$V_{c\bar{c}}(r) = Cornell$ $\quad$ $V_{c\bar{c}}(r,T) = Lattice\ (F,U)$

$\tau = 0$ (Pb-Pb) $\quad$ τ_0 $c\bar{c}$ dipole $\quad$ Time-dependent Schrodinger equation

2.Schrodinger-type models





Snapshot of the $c\bar{c}$ wavefunction at different time

Imaginary V: transition from singlet to **octet and scattering states.**

At high T, wavefunction expand outside, $J/\psi \longrightarrow \psi(2S)$

At low T, wavefunction contracts, $\psi(2S) \longrightarrow J/\psi$

This is due to the radius dependence of the potential

2.Schrodinger-type models

1. $c\bar{c}$ internal Initial wavefunction:

Taken as quarkonium eigenstates
(neglect the pre-equilibrium effect)

$$\psi_{c\bar{c}}(\tau = \tau_0) = \phi_{1S,2S}(\mathbf{r})$$

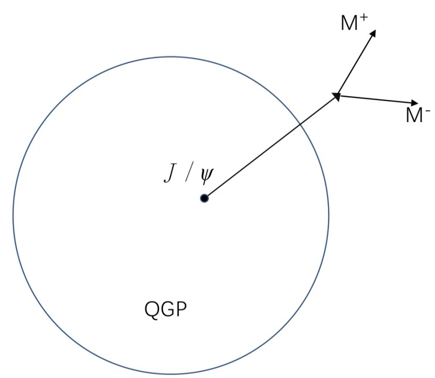
Initial direct yields

$$f_{pp}^{J/\psi} : f_{pp}^{\chi_c} : f_{pp}^{\psi(2S)} = 0.68 : 1 : 0.19$$

2. The initial momentum and spatial distribution of the center of $c\bar{c}$ dipole

$$f_\Psi(\mathbf{p}, \mathbf{x}|\mathbf{b}) = (2\pi)^3 \delta(z) T_{\rm p}(\mathbf{x}_T) T_{\rm A}(\mathbf{x}_T - \mathbf{b}) \times \mathcal{R}_{\rm g}(x_g, \mu_{\rm F}, \mathbf{x}_{\rm T} - \mathbf{b}) \frac{d\bar{\sigma}_{pp}^{\Psi}}{d^3\mathbf{p}},$$

Shadowing effect from EPS09 NLO



The initial momentum of $c\bar{c}$ dipoles in pp,
(neglect the mass difference)

$$\frac{dN_{J/\psi}}{2\pi p_T dp_T} = \frac{(n-1)}{\pi(n-2)\langle p_T^2 \rangle_{pp}} [1 + \frac{p_T^2}{(n-2)\langle p_T^2 \rangle_{pp}}]^{-n}$$

n = 3.2 $\quad \langle p_T^2 \rangle(y) = \langle p_T^2 \rangle(y=0)[1 - (\frac{y}{ymax})^2]$

$ymax$ → $\ln(\sqrt{s_{NN}}/m_\Psi)$

Including Cronin effect

$$\frac{d\bar{\sigma}_{pp}^{\Psi}}{d^3\mathbf{p}} = \frac{1}{\pi a_{gN} l} \int d^2\mathbf{q}_T e^{\frac{-\mathbf{q}_T^2}{a_{gN} l}} \frac{d\sigma_{pp}^{\Psi}}{d^3\mathbf{p}}$$

$$a_{gN} = 0.15 (GeV/c)^2$$

2.Schrodinger-type models

- **The initial yields of charmonium eigenstates**

$$n_{mS}^{t=0}(\mathbf{x}_T, p_T|\mathbf{b}, y) = n_{c\bar{c}}(\mathbf{x}_T, p_T|\mathbf{b}) \times |\langle R_{mS}(r)|\phi_0(r)\rangle|^2$$

$$|c_{mS}(t=0|\mathbf{b})|^2 = \int d\mathbf{x}_T \int_{p_{T1}}^{p_{T2}} dp_T \; n_{mS}(\mathbf{x}_T, p_T|\mathbf{b})$$

- **Charmonium direct R_{AA} with hot medium effects,**

$$R_{pA}^{\text{direct}}(nl) = \frac{\langle |c_{nl}(t)|^2\rangle_{\text{en}}}{\langle |c_{nl}(t_0)|^2\rangle_{\text{en}}}$$

$$= \frac{\int d\mathbf{x}_\Psi d\mathbf{p}_\Psi |c_{nl}(t, \mathbf{x}_\Psi, \mathbf{p}_\Psi)|^2 \frac{dN_{pA}^{\Psi}}{d\mathbf{x}_\Psi d\mathbf{p}_\Psi}}{\int d\mathbf{x}_\Psi d\mathbf{p}_\Psi |c_{nl}(t_0, \mathbf{x}_0, \mathbf{p}_\Psi)|^2 \frac{dN_{pA}^{\Psi}}{d\mathbf{x}_\Psi d\mathbf{p}_\Psi}}$$

$$R_{pA}(J/\psi) = \frac{\sum_{nl} \langle |c_{nl}(t)|^2\rangle_{\text{en}} f_{pp}^{nl} \mathcal{B}_{nl\to J/\psi}}{\sum_{nl} \langle |c_{nl}(t_0)|\rangle^2\rangle_{\text{en}} f_{pp}^{nl} \mathcal{B}_{nl\to J/\psi}}$$

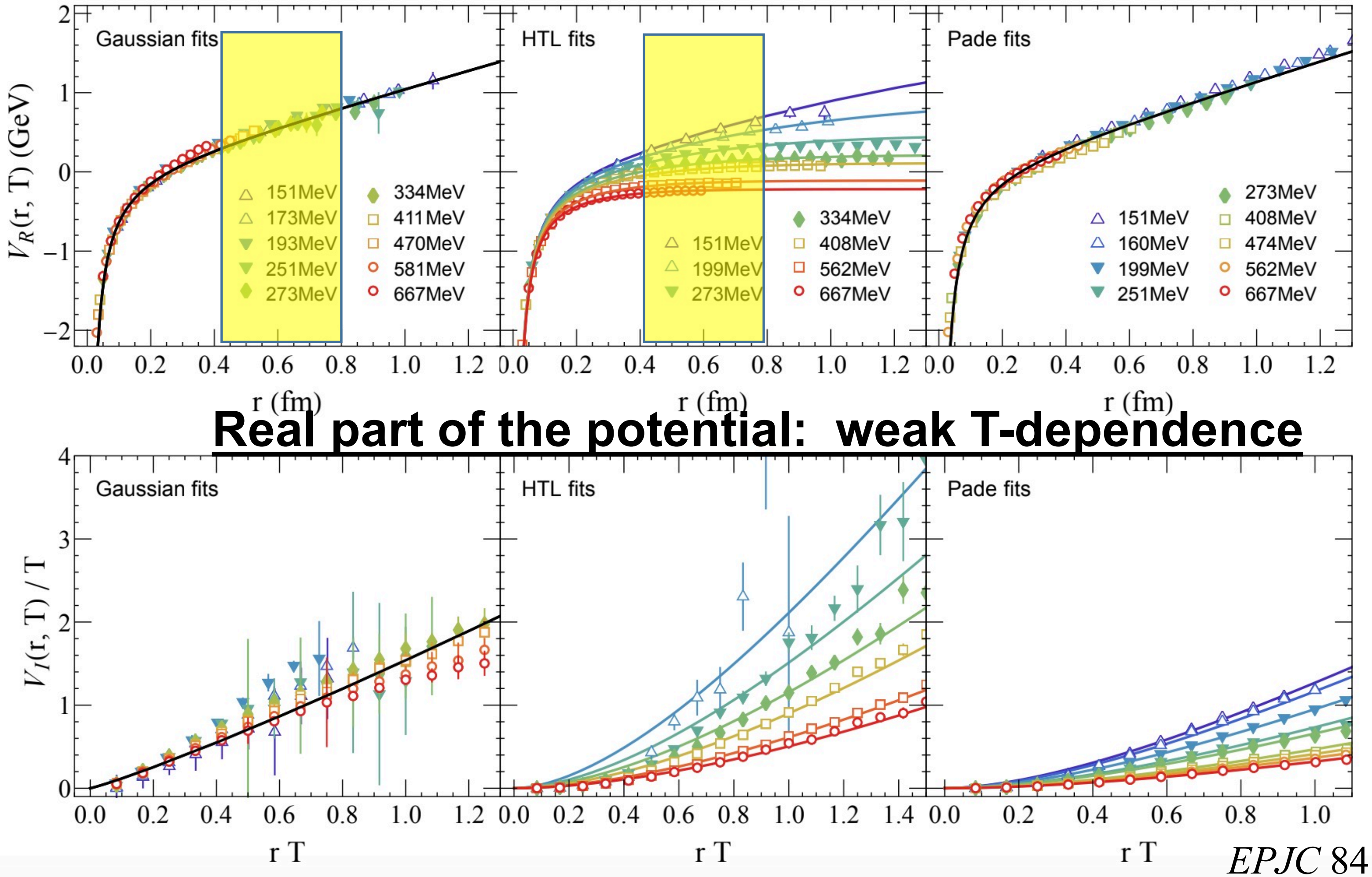
$c\bar{c}$ dipoles move inside QGP

$$\mathbf{R}_{c\bar{c}}(\tau + \Delta\tau) = \mathbf{R}_{c\bar{c}} + \mathbf{v}_{c\bar{c}} \cdot \Delta\tau$$

Heavy quark potential

Is color screening important in small system?

Weak color screening



Real part of the potential: weak T-dependence

Imag. part of the potential: strong T-dependence

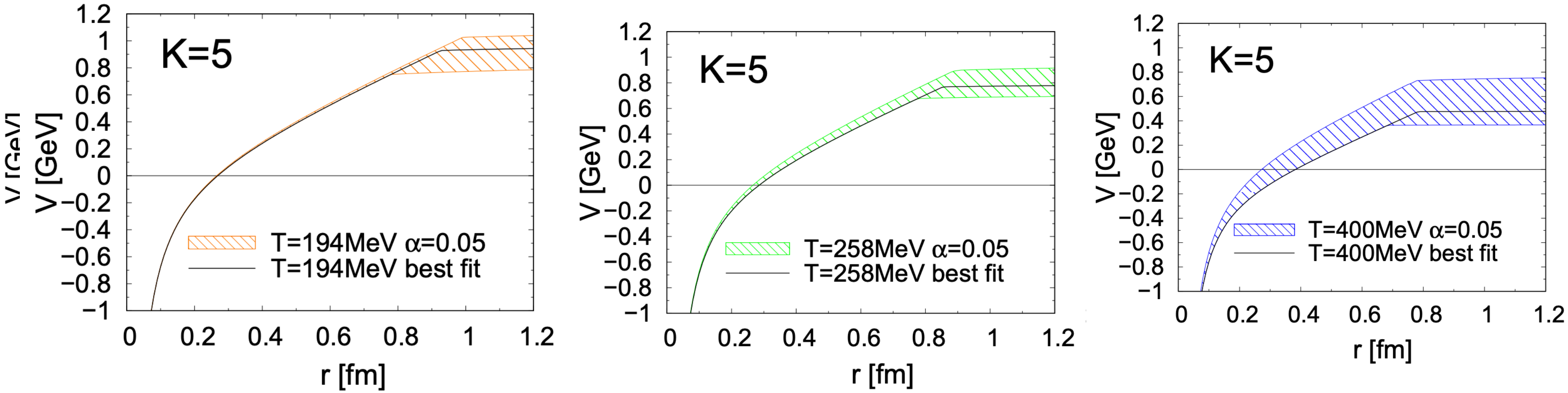
EPJC 84 (2024) 8, 869

Heavy quark potential

Brief discussion about the real part of the potential (color screening):

$$V_{Q\bar{Q}}(r) = \begin{cases} -\frac{4}{3}\alpha_s\, e^{-m_D r}/r + \sigma r & , r < R_{SB} \\ -\frac{4}{3}\alpha_s\, e^{-m_D r}/r + \sigma R_{SB} & , r > R_{SB} \end{cases}$$

DX, Liu, Rapp,
***PLB* 796 (2019) 20-25**



Extract real part of potential from bottomonium

other references Tsinghua Transport:
Bottomonium with V=U
***Liu, Chen, Zhuang, PLB* 697 (2011) 32-36**

See also Prof. Shuzhe Shi's talk: V_{DNN} : time-independent Sch.

temperature regions in **small collision systems**

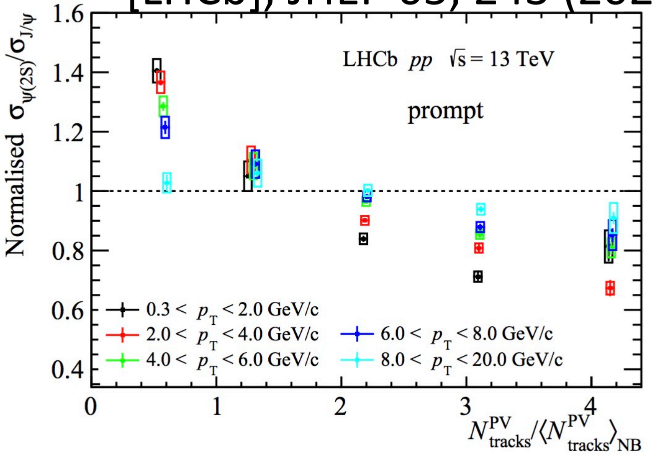
reening at **T (~ 200 MeV)** close to Tc; a bit stronger color screening at higher T

- **Distance dependence**: weak color screening **at small radius**, significant effect at large r

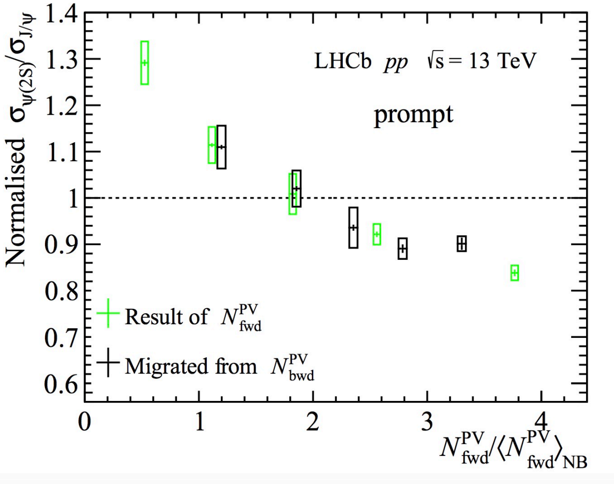
3. Charmonium in pp 13 TeV

Ratio of charmonium suppression in pp 13 TeV

[LHCb], JHEP 05, 243 (2024)



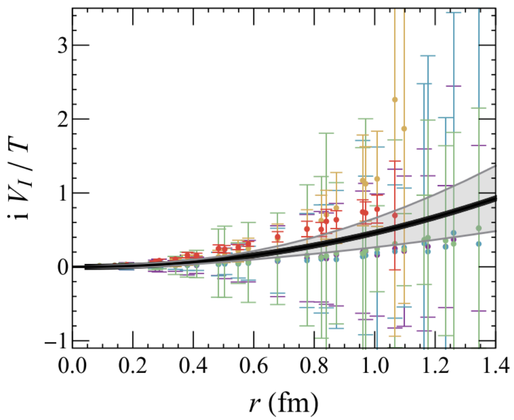
More suppression

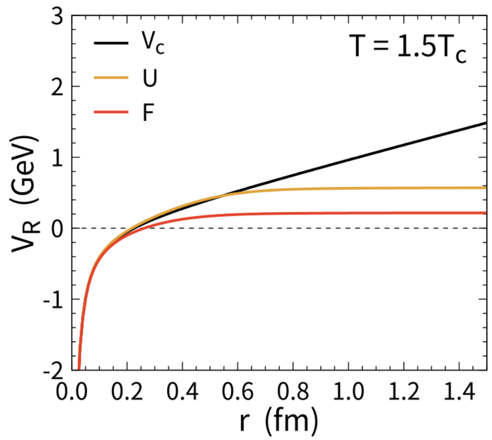


Co-mover model

- **Charmonium has been suggested as a probe of the early stage of HIC before.**
- **relative suppression 2S/1S: not affected by the effects before the formation of $c\bar{c}$**

$$V_R \approx -\frac{\alpha}{r} + \sigma r \quad \text{in pp (pA)}$$



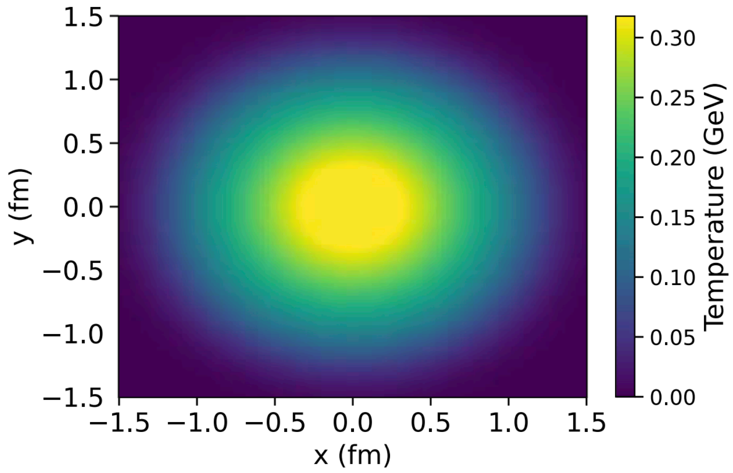


Wen, Du, Shi, BC, CPC **46 (2022) 114102**

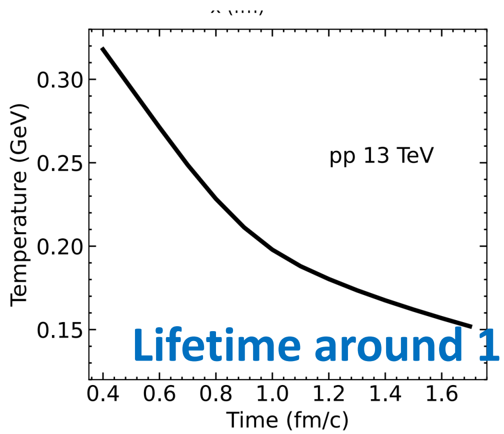
3. Charmonium in pp 13 TeV

Initial conditions in pp:

Proton size: $$\rho_p = \frac{\rho_0}{1+e^{(r-r_p)/a_p}}$$ $\boldsymbol{r_p = 0.9}$ fm, $\boldsymbol{a_p \cong 0.1}$ fm



Smooth hydro profile from MUSIC, pp 13 TeV



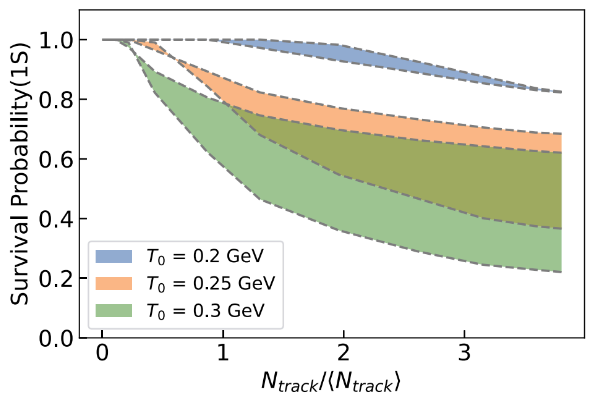
Lifetime around 1.5 fm/c

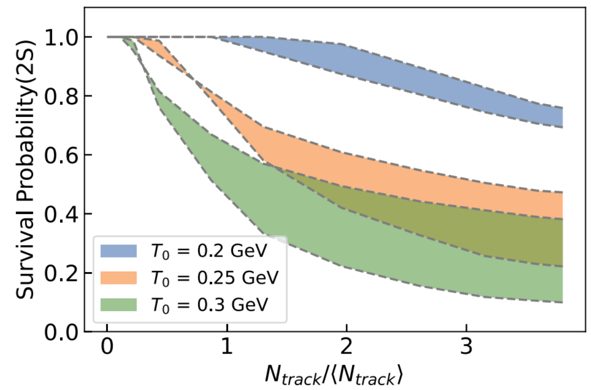
Employ relative suppression of charmonium 2S/1S to extract the initial hot medium

- Initial momentum distribution of charm dipole

$$\frac{d^2N_\Psi}{d\phi p_T dp_T} = \frac{(n-1)}{\pi(n-2)\langle p_T^2\rangle}[1+\frac{p_T^2}{(n-2)\langle p_T^2\rangle}]^{-n}$$

$$< p_T^2 >= 15\,(GeV/c)^2$$
$$n = 3.2$$





Bai, BC, EPJC **84 (2024) 1193**

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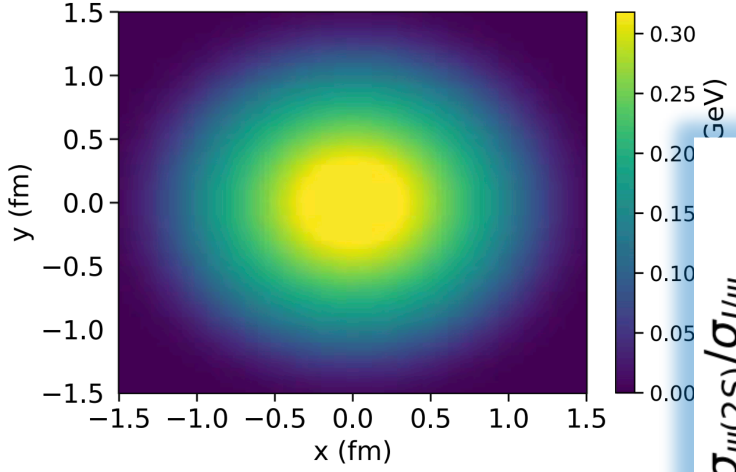

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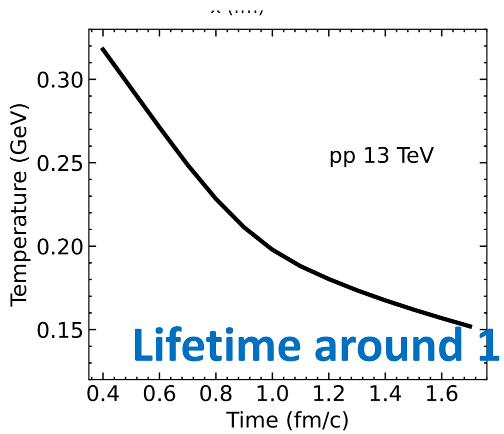

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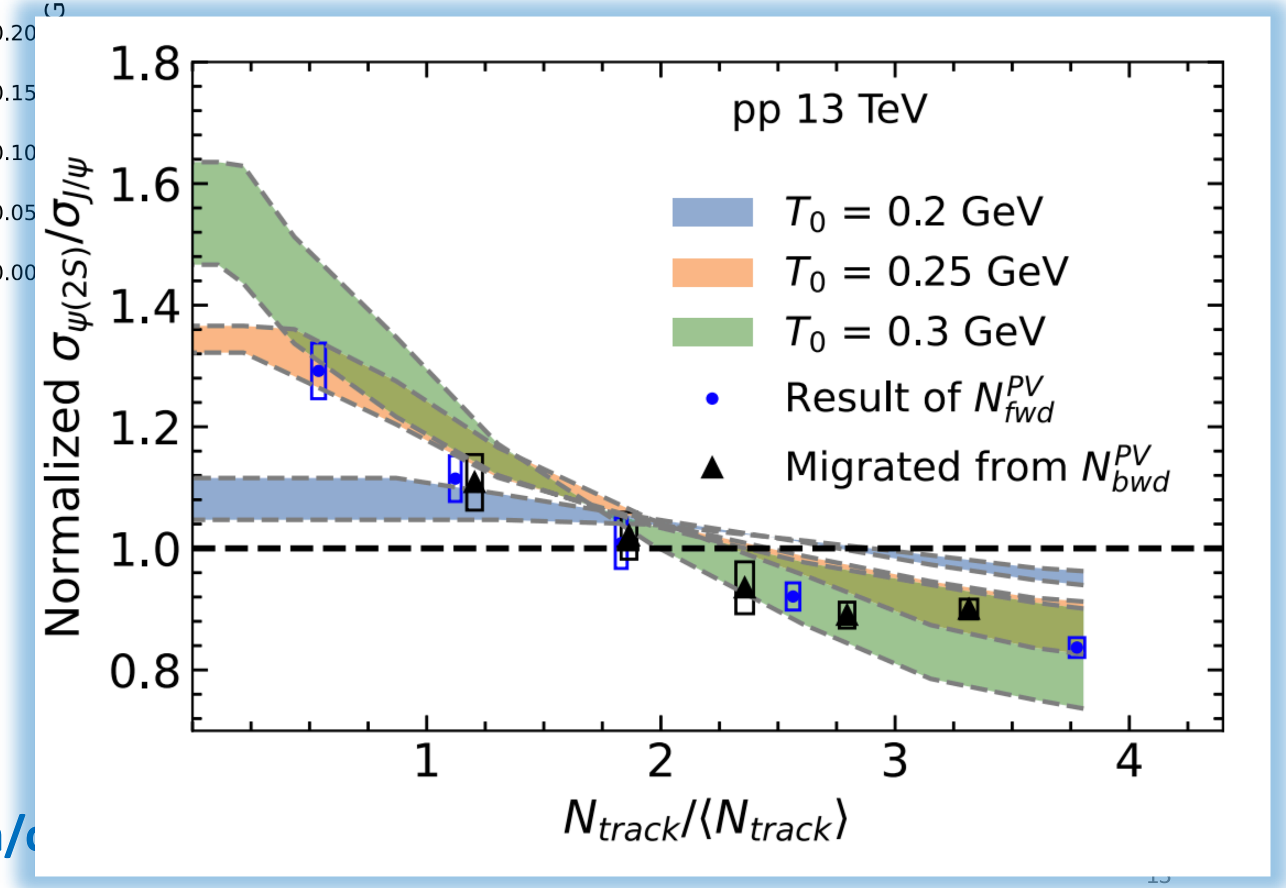
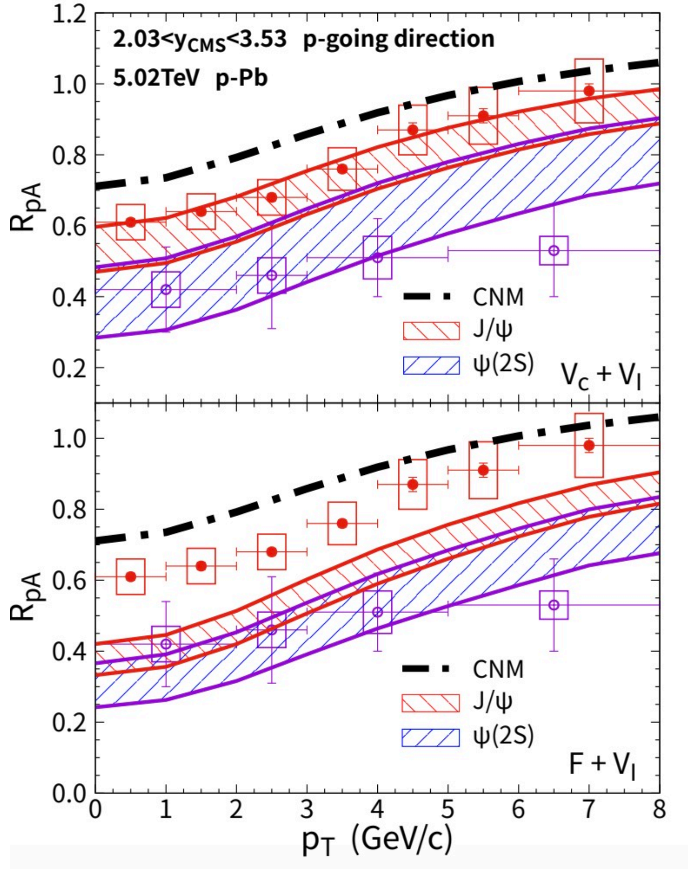


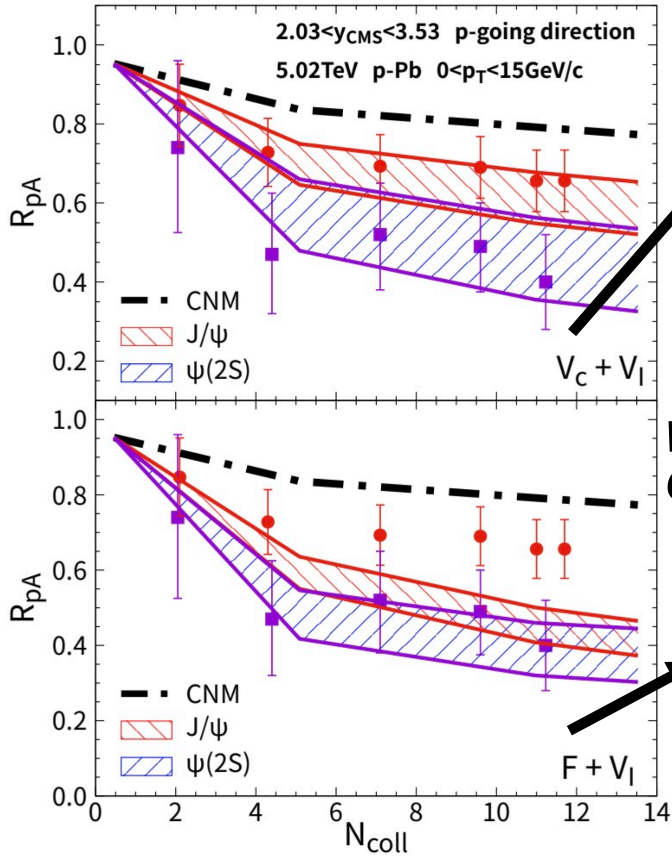
Bai, BC, EPJC 84 (2024) 1193

3. Charmonium in p-Pb 5.02 TeV

From pp to p-Pb collisions:

- **A bit larger collision system**
- **Include Cold-Nuclear-Matter effects:**
  - **(anti-)shadowing: EPS 09 NLO**
  - **Cronin effect:** $< p_T^2 > + a_{gN} \cdot L$





Weak color screening (V→ Vc + inelastic collision)

***Wen, Du, Shi, BC ; CPC* 46 (2022) 114102**

Real part: free energy (strong color screening)

$$\mathbf{V(r,T) = V_R + V_I}$$

$$i\hbar\frac{\partial}{\partial t}\psi(r,t) = \left[-\frac{\hbar^2}{2m_\mu}\frac{\partial^2}{\partial r^2} + V(r,T) + \frac{L(L+1)\hbar^2}{2m_\mu r^2}\right]\psi(r,t)$$

$$F(r,T) = -\frac{\alpha}{r}e^{-m_D r} + \frac{\sigma}{m_D}(1 - e^{-m_D r})$$

3. Bottomonium in 5.02, 2.76, 0.2 TeV

- **Initial momentum distribution in pp**

$$\frac{dN_{pp}^{\Upsilon}}{d\phi p_T dp_T} = \frac{(n-1)}{\pi(n-2)\langle p_T^2\rangle_{pp}}[1+\frac{p_T^2}{(n-2)\langle p_T^2\rangle_{pp}}]^{-n}$$

$< p_T^2 >= (80, 55, 28)(GeV/c)^2$

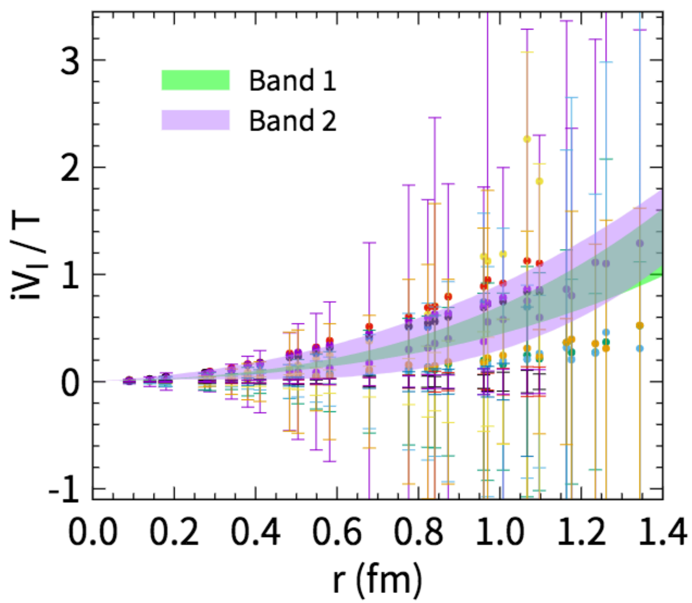
At 5020, 2760, 200 GeV

$n = 2.5$

- **Direct yields of bottomonium states at 5.02 TeV**

State	$\Upsilon(1s)$	$\chi_b(1p)$	$\Upsilon(2s)$	$\chi_b(2p)$	$\Upsilon(3s)$
$\sigma_{\rm exp}(nb)$	57.6	33.51	19	29.42	6.8
$\sigma_{\rm direct}(nb)$	37.97	44.2	18.27	37.68	8.21

Medium temperature (b=0)
T(5.02TeV)=510 MeV
T(2.76TeV)=484 MeV
T(200GeV)=390 MeV

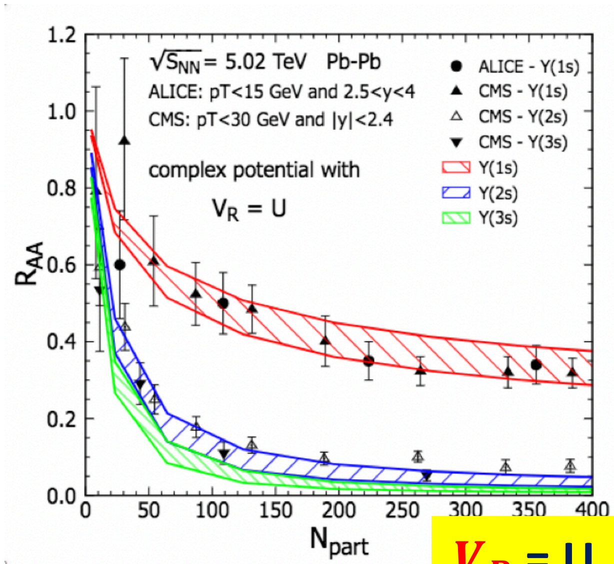


This ratio between different states are also used in 2.76 TeV and 200 GeV

Two kinds of imaginary potential are fitted

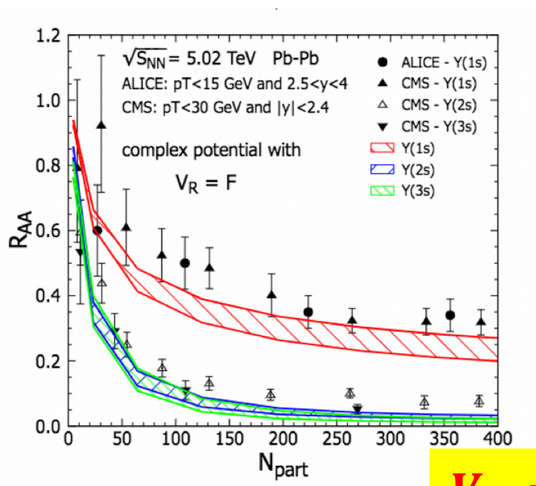
- Smaller band: fit the central value and shifted upward slightly to consider partial uncertainty.
- Larger band: one sigma uncertainty is included.

3. Bottomonium in 5.02, 2.76, 0.2 TeV

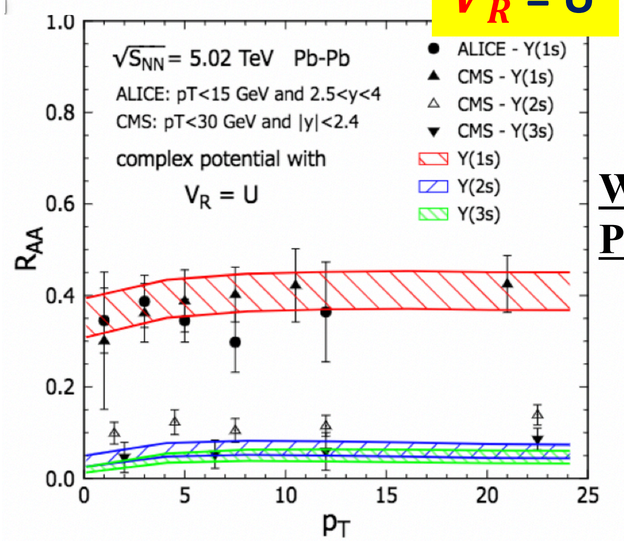


V_R = U

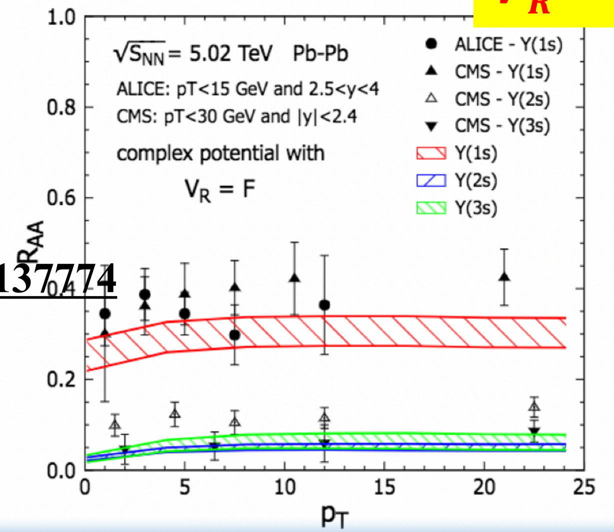
5.02 TeV Pb-Pb



$V_R = F$



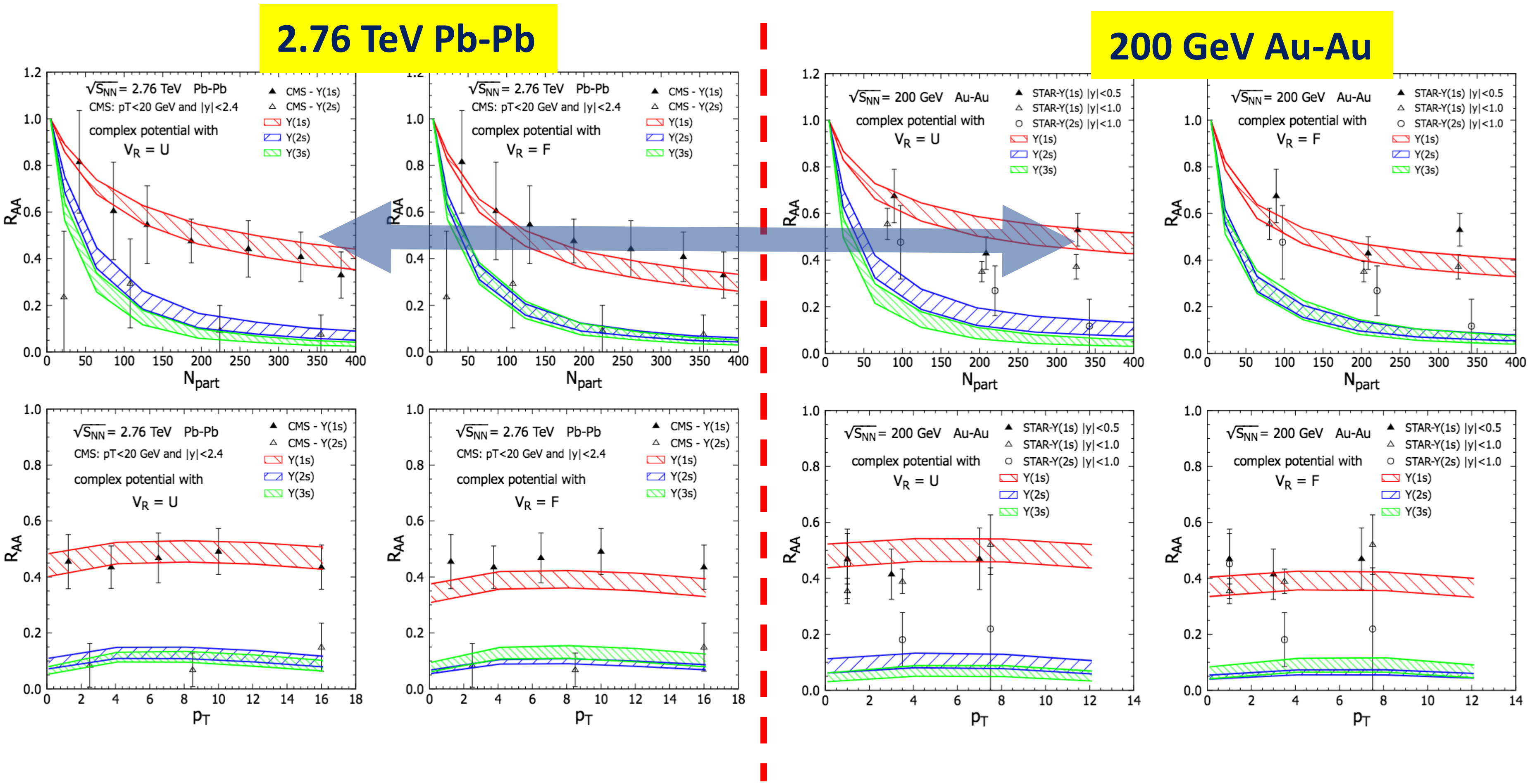
Wen, BC,
PLB 839 (2023) 137774



Flat tendency in $R_{AA}(p_T)$ suggests weak/no regeneration

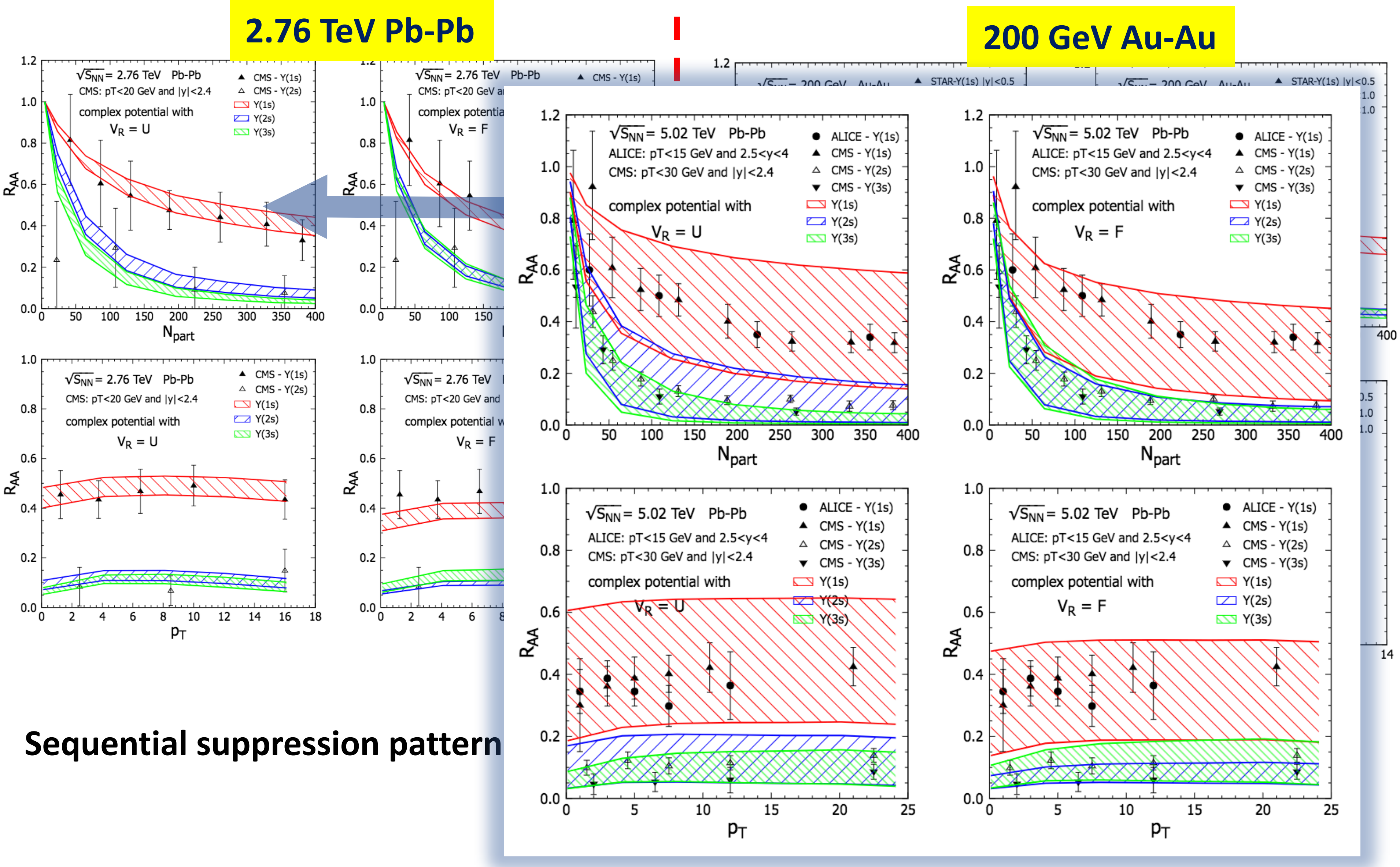
- **Clear sequential suppression pattern is observed when using V=U**

3. Bottomonium in 5.02, 2.76, 0.2 TeV



Sequential suppression pattern in all collision energies by taking strong V

3. Bottomonium in 5.02, 2.76, 0.2 TeV



Sequential suppression pattern

R_{AA} **sensitive to the uncertainty in the imaginary potential,**
helps to constrain the heavy quark potential via deep learning methods.

3.HQ potential at finite μ_B

Introduce baryon chemical potential in HQ potential

$$V_R(r,T,\mu_B) = -\frac{\alpha}{r}e^{-m_d r} + \frac{\sigma}{m_d}(1-e^{-m_d r})$$

$$V_I(r,T,\mu_B) = -i\frac{g^2 C_F T}{4\pi}\tilde{f}(\hat{r}),$$

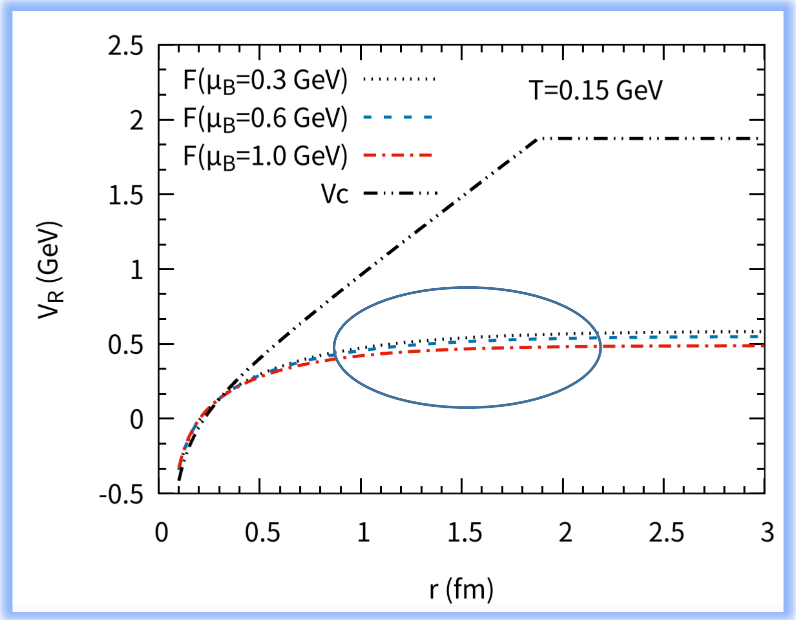
$$\tilde{f}(\hat{r}) = 2\int_0^\infty dz \frac{z}{(z^2+1)^2}\left[1-\frac{\sin(z\hat{r})}{z\hat{r}}\right]$$

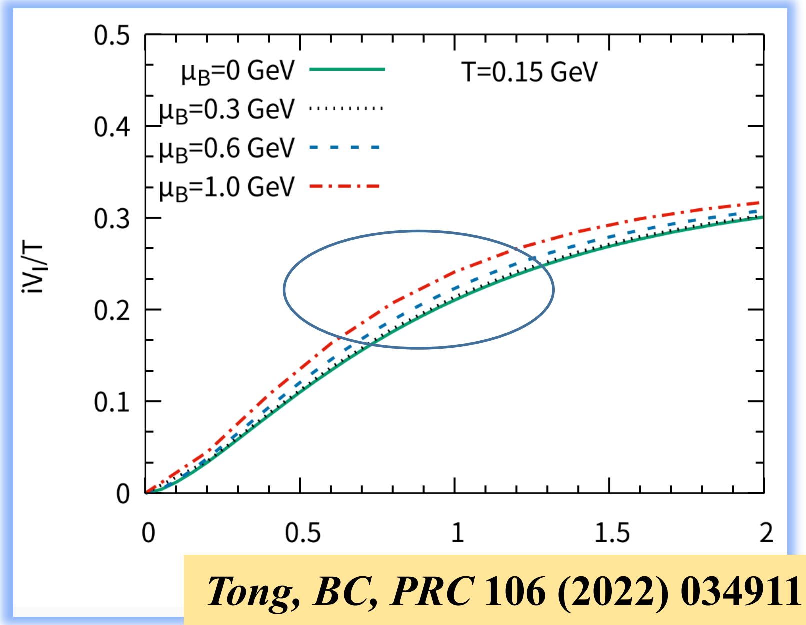
$$m_d(T,\mu_B) = T\sqrt{\frac{4\pi N_c}{3}\alpha\left(1+\frac{N_f}{6}\right)} \times\sqrt{1+\frac{3N_f}{(2N_c+N_f)\pi^2}\left(\frac{\mu_B}{3T}\right)^2}$$

$$\mu_B(\sqrt{s_{NN}}) = \frac{1.3}{1+0.28\sqrt{s_{NN}}}$$

CPC 42, 013103 (2018)

Correction from μ_B not evident.





Tong, BC, PRC **106 (2022) 034911**

3.HQ potential at finite μ_B

Introduce baryon chemical potential in HQ potential

$$V_R(r,T,\mu_B) = -\frac{\alpha}{r}e^{-m_d r} + \frac{\sigma}{m_d}(1-e^{-m_d r})$$

$$V_I(r,T,\mu_B) = -i\frac{g^2 C_F T}{4\pi}\tilde{f}(\hat{r}),$$

$$\tilde{f}(\hat{r}) = 2\int_0^\infty dz \frac{z}{(z^2+1)^2}\left[1-\frac{\sin(z\hat{r})}{z\hat{r}}\right]$$

$$m_d(T,\mu_B) = T\sqrt{\frac{4\pi N_c}{3}\alpha\left(1+\frac{N_f}{6}\right)} \times\sqrt{1+\frac{3N_f}{(2N_c+N_f)\pi^2}\left(\frac{\mu_B}{3T}\right)^2}$$

$$\mu_B(\sqrt{s_{NN}}) = \frac{1.3}{1+0.28\sqrt{s_{NN}}}$$

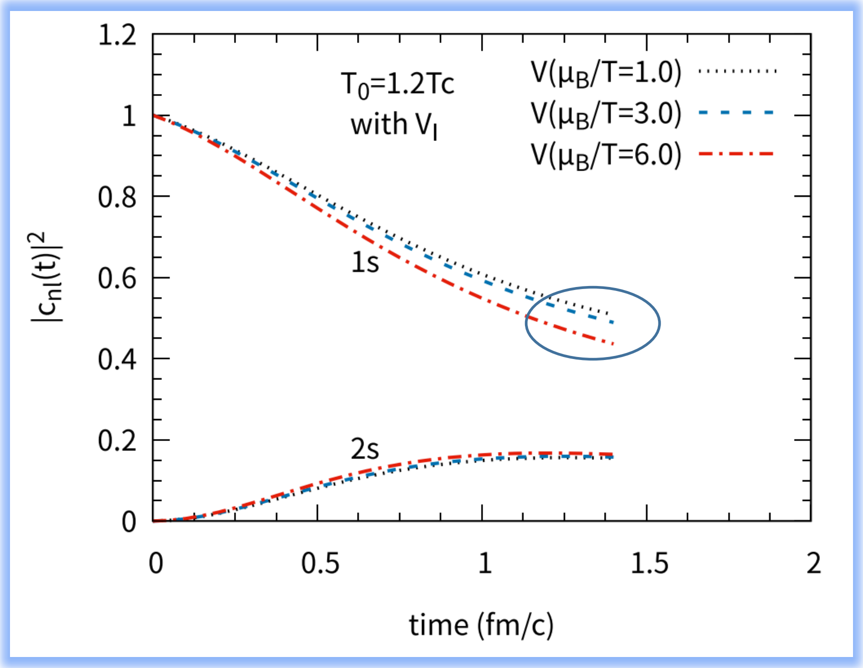
CPC 42, 013103 (2018)

Correction from μ_B not evident.

- Charmonium evolution in Bjorken medium With a fixed μ_B/T

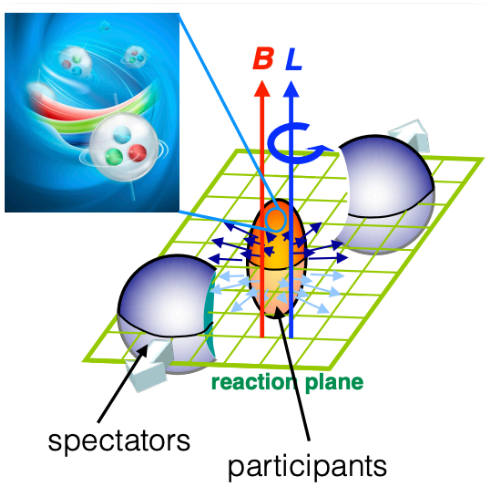
$$\frac{T(t)}{T(t_0)} = \left(\frac{t_0}{t}\right)^{1/3}$$

- The effect of μ_B on charmonium suppression Is weak at $\mu_B/T = 1.0$



Tong, BC, PRC **106 (2022) 034911**

Regeneration: Heavy quark coupled with QGP



- **Rotational QGP: HF are strongly coupled with the rotational QGP.**
  HF carry the collective motion, and their spin polarization affected by the vortical field ?

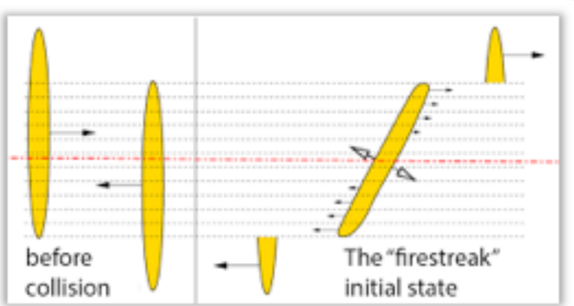
HQ detect the transverse profiles of QGP, via sizable v_1, v_2, v_3

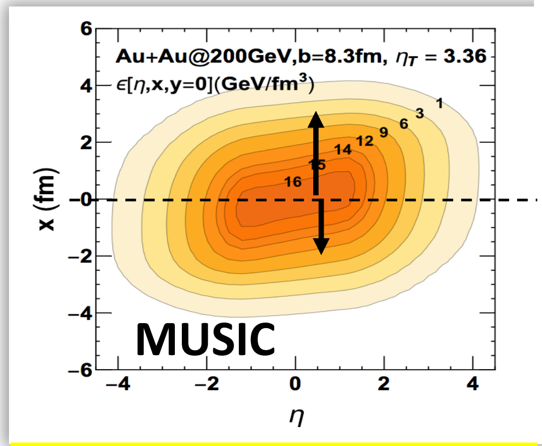
Charm directed flow:
Phys.Rev.Lett. 120 (2018) 19, 192301

$$s(\tau_0, x, y, \eta_{\|}) = s_0\{\alpha N_{\rm coll} + (1-\alpha)[N^{+}_{\rm part} f_{+}(\eta_{\|}) + N^{-}_{\rm part} f_{-}(\eta_{\|})]\} f(\eta_{\|}),$$

$$f(\eta_{\|}) = \exp\left(-\theta(|\eta_{\|}| - \eta^0_{\|}) \frac{(|\eta_{\|}| - \eta^0_{\|})^2}{2\sigma^2}\right)$$

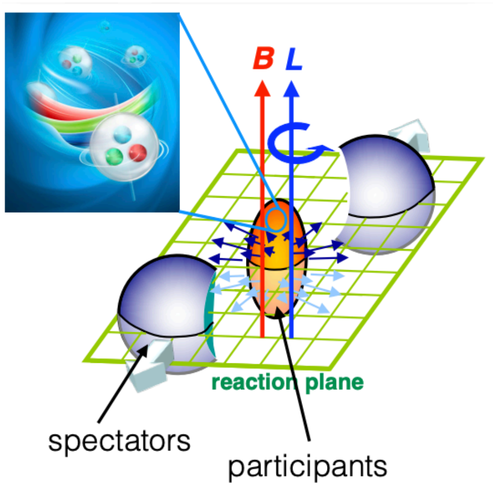
$$f_{+}(\eta_{\|}) = \begin{cases} 0 & \eta_{\|} < -\eta_T \\ \frac{\eta_T + \eta_{\|}}{2\eta_T} & -\eta_T \le \eta_{\|} \le \eta_T \\ 1 & \eta_{\|} > \eta_T, \end{cases}$$





Rapidity-odd distribution

Regeneration: Heavy quark coupled with QGP



- **Rotational QGP: HF are strongly coupled with the rotational QGP.**

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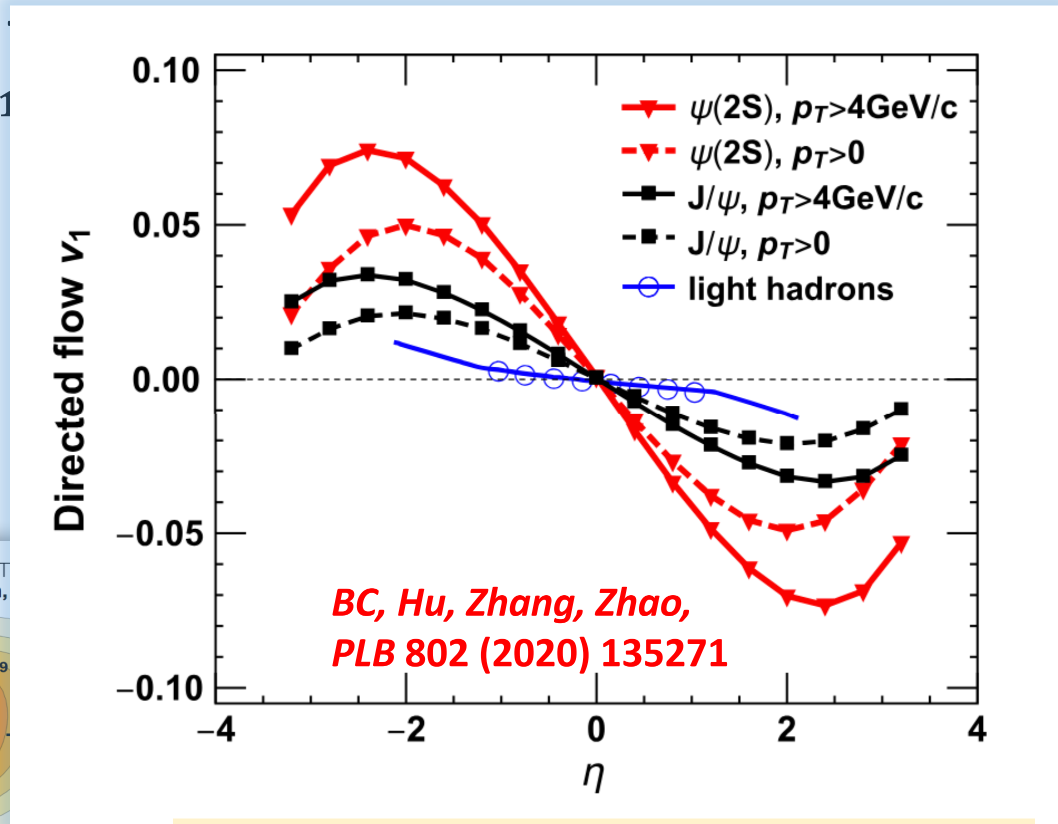
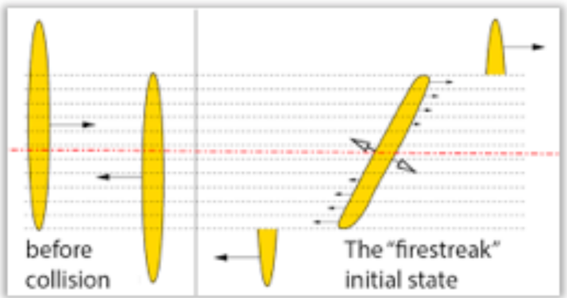
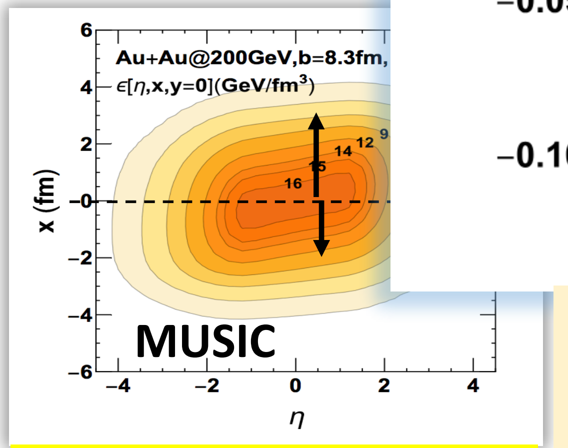
Phys.Rev.Lett. 120 (2018) 19, 192301

HQ detect
sizable v_1



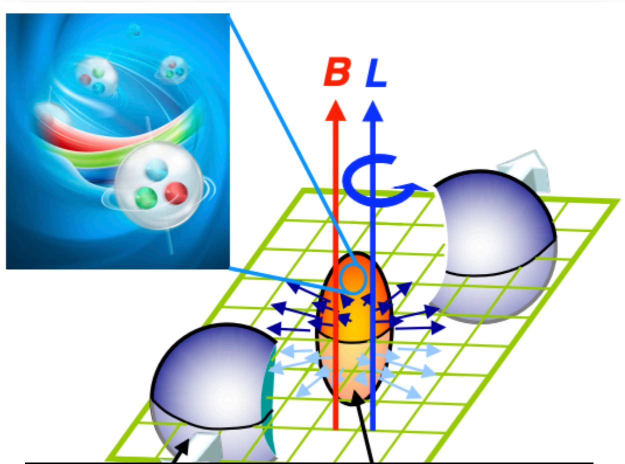


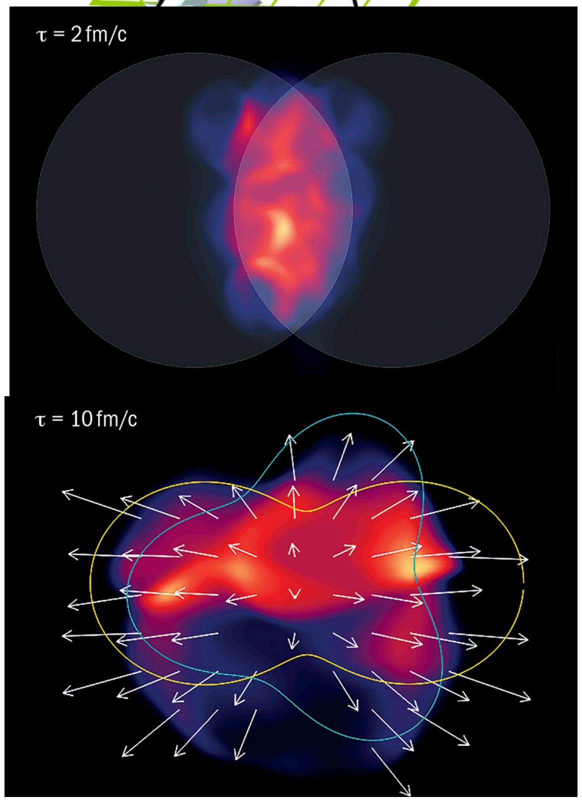


Rapidity-odd distribution

Charmonium v_1 expected to be larger than light hadron

Regeneration: Heavy quark coupled with QGP





- **Rotational QGP: HF are strongly coupled with the rotational QGP.**

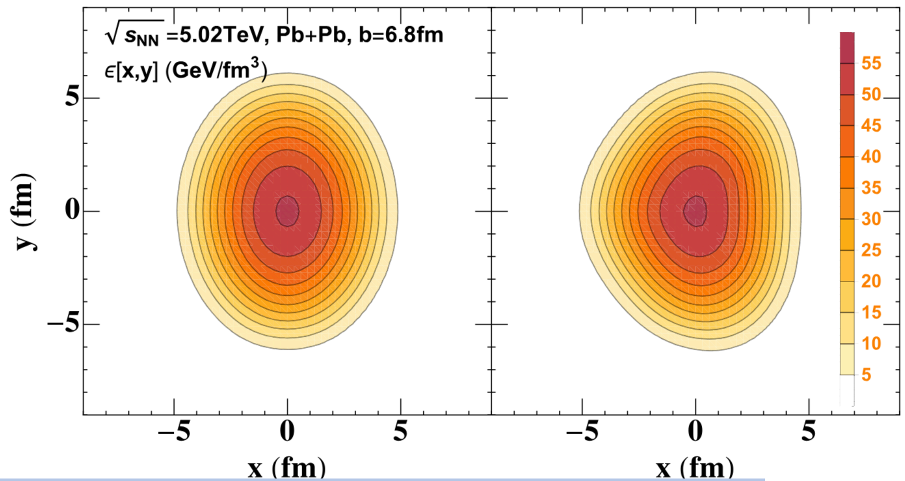
  HF carry the collective motion, and their spin polarization affected by the vortical field ?

HQ detect the transverse profiles of QGP, via sizable v_1, v_2, v_3

Introduce Fluctuations in initial energy density

$$\epsilon(\boldsymbol{x},\, \tau_0|\boldsymbol{b}) \rightarrow \epsilon(\tilde{\boldsymbol{x}},\, \tau_0|\boldsymbol{b})$$

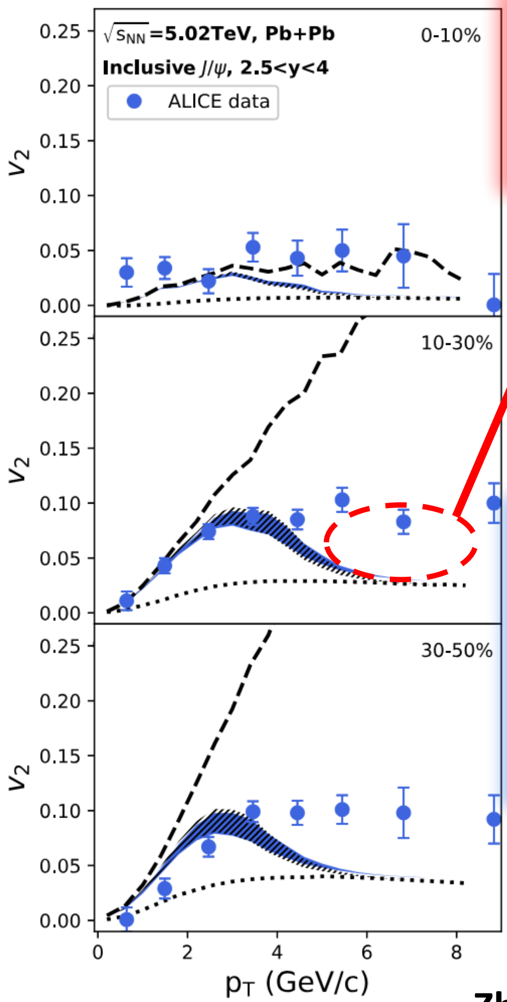
$$\tilde{\boldsymbol{x}}=(x_T\sqrt{1+\varepsilon_3\cos[3(\phi_s-\Psi_3)]},$$



- Figure from MUSIC: 1209.6330

Zhao, BC, Zhuang, PRC 105 (2022) 034902

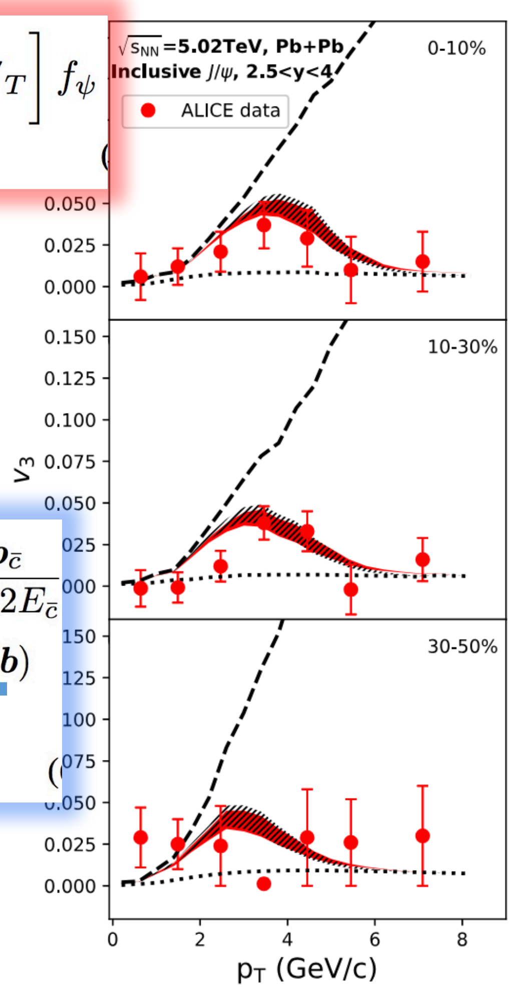
Quarkonium triangular flow v_3



$$
\left[\cosh(y-\eta)\partial_\tau + \frac{\sinh(y-\eta)}{\tau}\partial_\eta + \boldsymbol{v}_T\cdot\nabla_T\right] f_\psi = -\alpha f_\psi + \beta,
$$

Due to charm non-thermal distribution.

$$
\begin{aligned}
\beta(\boldsymbol{p},\boldsymbol{x},\tau|\boldsymbol{b}) = \frac{1}{2E_T}\int & \frac{d^3\boldsymbol{p}_g}{(2\pi)^3 2E_g}\frac{d^3\boldsymbol{p}_c}{(2\pi)^3 2E_c}\frac{d^3\boldsymbol{p}_{\bar{c}}}{(2\pi)^3 2E_{\bar{c}}} \\
& \times W_{c\bar{c}}^{g\psi}(s) f_c(\boldsymbol{p}_c,\boldsymbol{x},\tau|\boldsymbol{b}) f_{\bar{c}}(\boldsymbol{p}_{\bar{c}},\boldsymbol{x},\tau|\boldsymbol{b}) \\
& \times (2\pi)^4\delta^{(4)}(p+p_g-p_c-p_{\bar{c}}) \\
& \times \Theta(T(\boldsymbol{x},\tau|\boldsymbol{b})-T_c),
\end{aligned}
$$



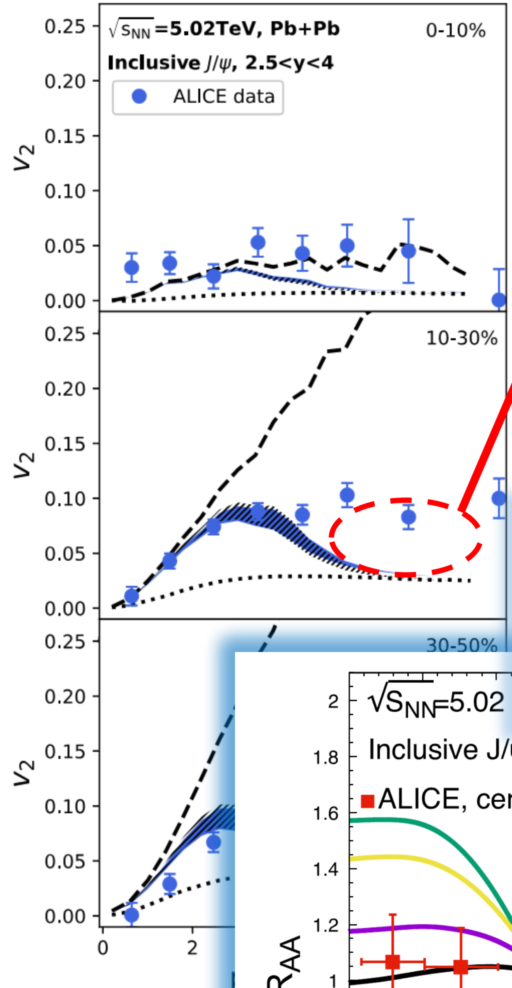
<u>Zhao, BC, Zhuang, PRC 105 (2022) 034902</u>

Triangular flows

Weak dependence on centrality.

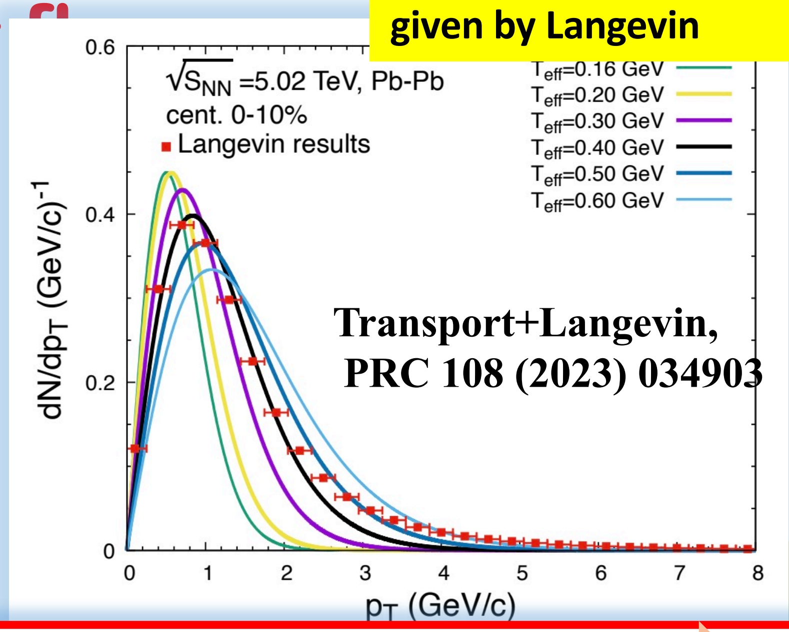
It seems that HQ and quarkonium may be one of promising probes to detect the initial rotations of QGP. The degree of HQ spin polarization by this QGP rotation deserves further studies.

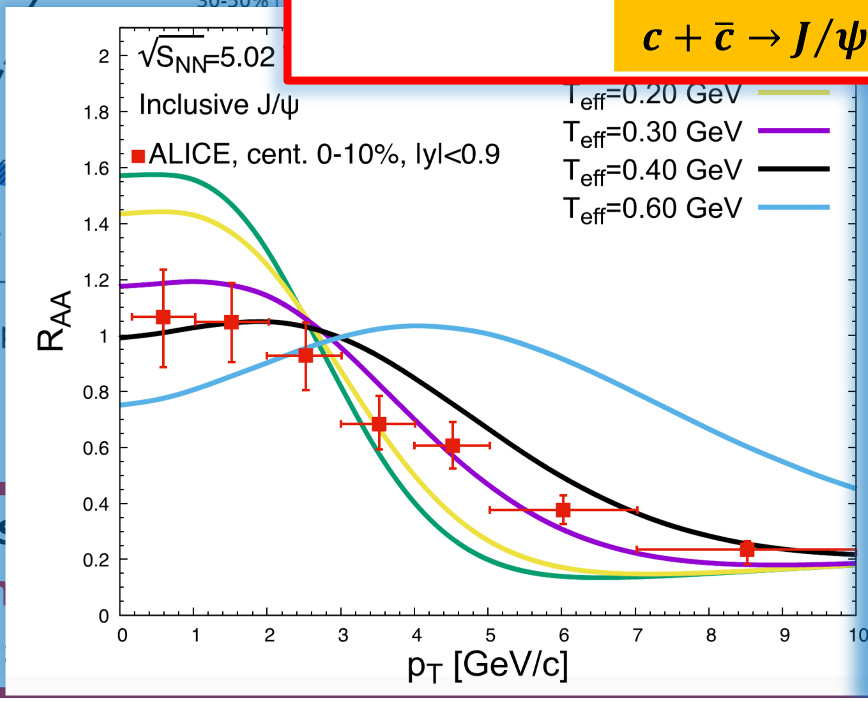
Quarkonium triangular fl

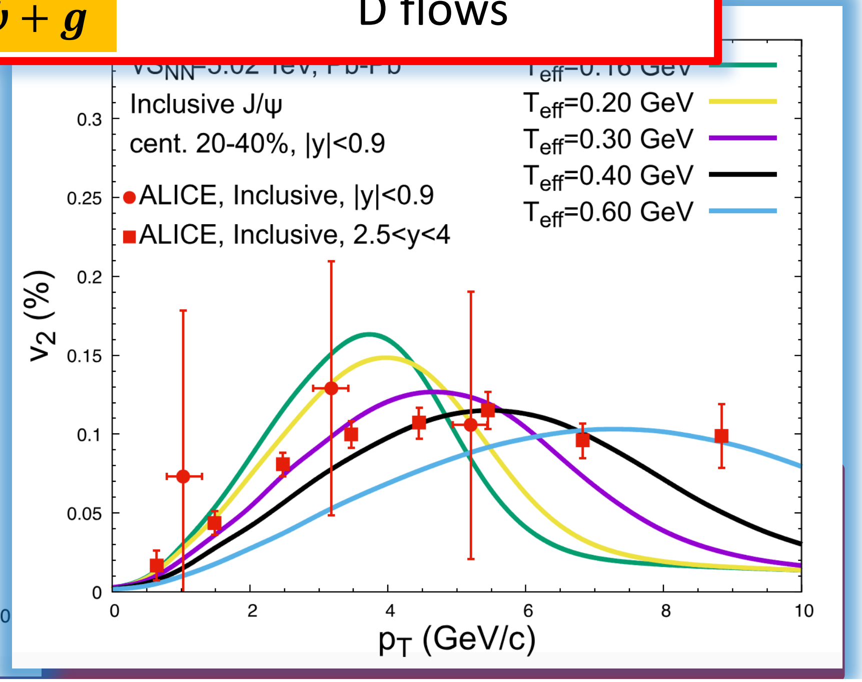


Due to charm non-thermal distribution.

Charm non-thermal distribution given by Langevin







It seems
rotation
further

J/ψ polarization

J/ψ polarization including both initial production and regeneration:

Tsinghua transport model

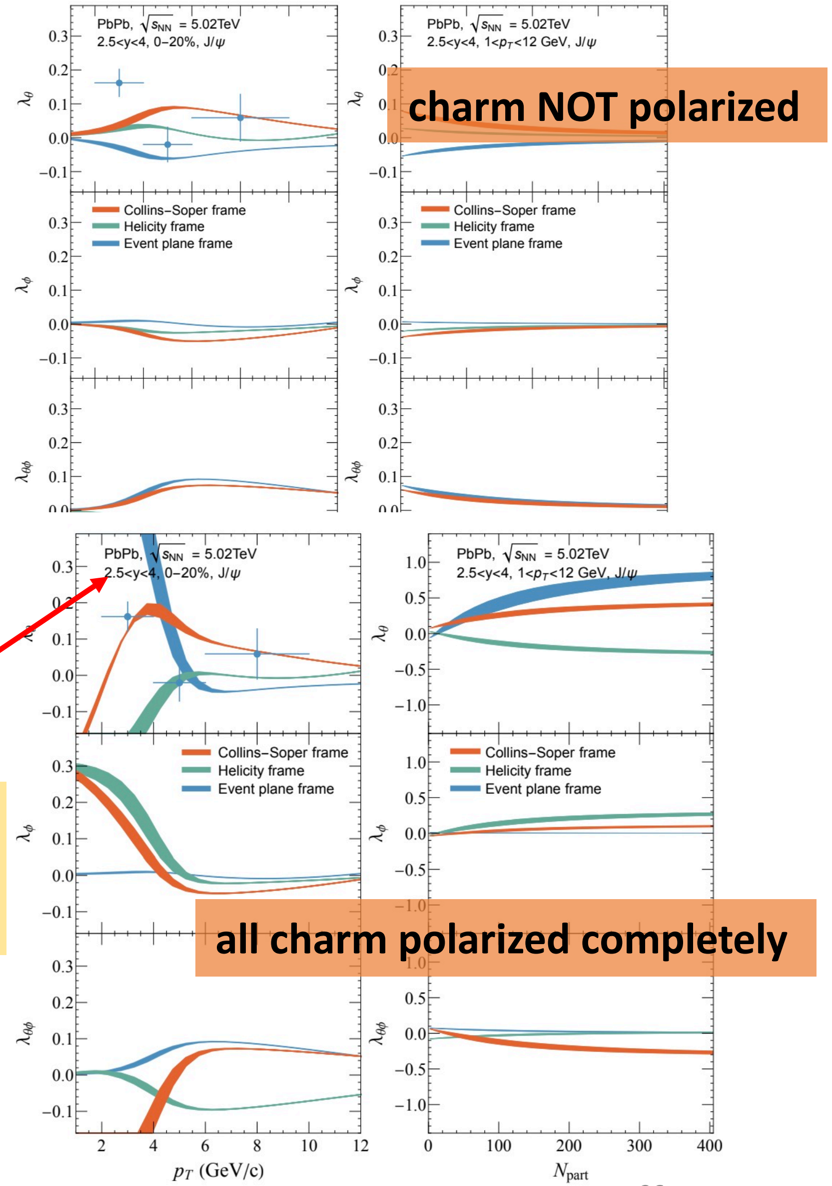
[Zhao, BC, Eur.Phys.J.C 84 (2024) 8, 875]

$$\left[\cosh(y-\eta)\partial_\tau + \frac{\sinh(y-\eta)}{\tau}\partial_\eta + \boldsymbol{v}_T\cdot\nabla_T\right] f_\psi$$
$$= \quad -\alpha f_\psi + \beta,$$

$$\alpha(\boldsymbol{p},\boldsymbol{x},\tau|\mathbf{b}) = \frac{1}{2E_T}\int \frac{d^3\boldsymbol{p}_g}{(2\pi)^3 2E_g} W_{g\psi}^{c\bar{c}}(s) f_g(\boldsymbol{p}_g,\boldsymbol{x},\tau) \times\Theta(T(\boldsymbol{x},\tau|\mathbf{b})-T_c),$$

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

$$\partial_\mu(\rho_c u^\mu) = 0$$



Significant polarization of J/ψ at low p_T due to the regeneration

Angular distribution of dilepton decay products

$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi)(p_T) + \lambda_{\theta\phi}\sin 2\theta\cos\phi),$$

$(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$ =(-1/+1, 0, 0) for longitudinal/transverse polarization

Heavy quark polarization in B-field

- **Landau-Lifshitz-Gilbert (LLG) equation**

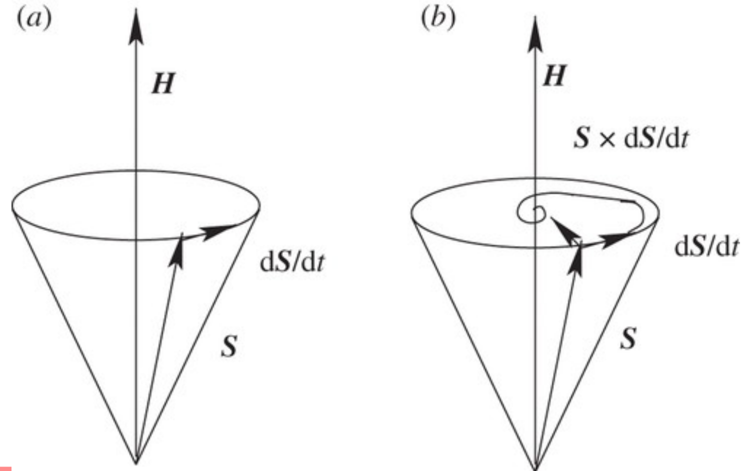
PRB 83, 134418 (2011)

$$\frac{d\vec{S}}{dt} = -\frac{\gamma}{1+\alpha^2}[\vec{S}\times(\vec{H}+\overrightarrow{H_{th}})] - \frac{\alpha\gamma}{1+\alpha^2}\vec{S}\times[\vec{S}\times(\vec{H}+\overrightarrow{H_{th}})]$$

$\vec{S} = \vec{s}/|\vec{s}|$

Unit vector

Polarization of heavy quark is induced by:
spin-magnetic field interaction
+ particle-particle interaction



Momentum evolution: $\frac{d\mathbf{p}}{dt} = -\eta(p)\mathbf{p} + \xi + \mathbf{f}_g + \frac{\mathbf{p}}{E_Q} \times (q\mathbf{B})$

Can be studied with Linear Response Theory
Tianyang, Anping, Baoyi, released soon..

$\alpha \cong 0.1$ **Damping factor**

$\gamma = \mathrm{g}\frac{Q}{2m}$ → Electric charge

Langevin white-noise term

$$\langle H_{th,i}(t)\rangle = 0$$

$$\langle H_{th,i}(t)H_{th,j}(t')\rangle = \frac{2\alpha T}{|\mu|\gamma}\delta_{ij}\delta(t-t').$$

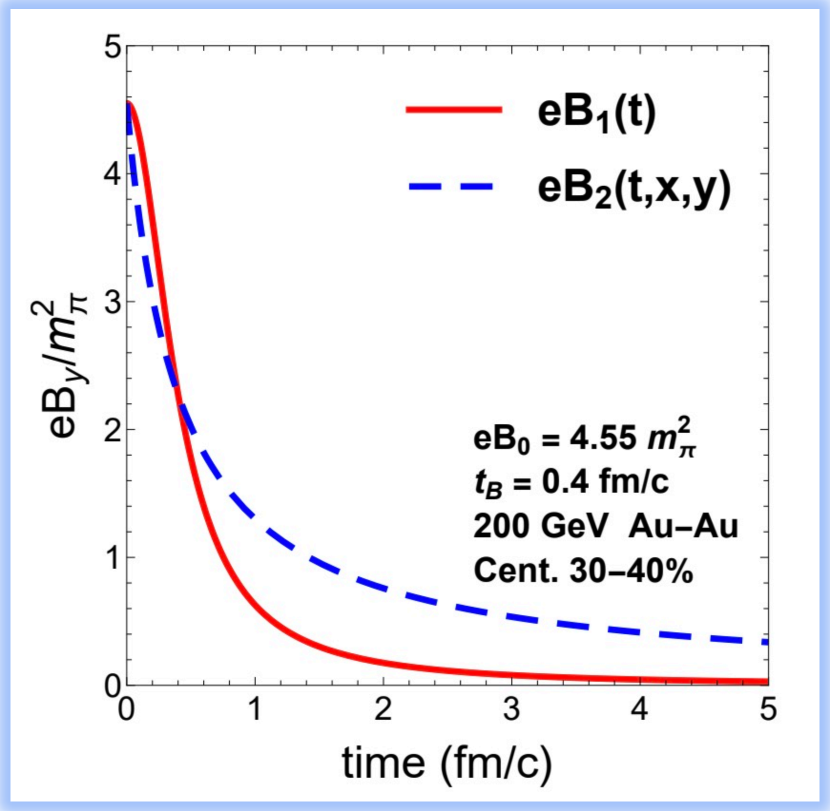
Heavy quark polarization in B-field

In-medium magnetic field

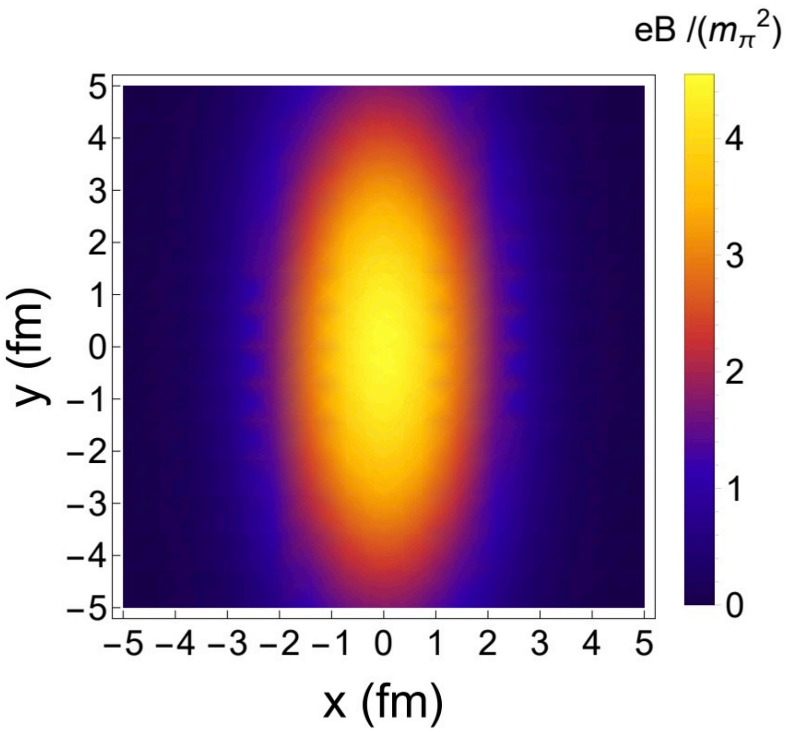
$$eB_1(t) = \frac{eB_0}{1+(\frac{t}{t_B})^2}$$

$$eB_2(t,x,y) = \frac{eB_0}{1+(\frac{t}{t_B})}\exp(-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2})$$

- **Z. F. Jiang, S. Cao, W. J. Xing, X. Y. Wu, C. B. Yang and B. W. Zhang, PRC 105, no.5, 054907 (2022)**
- **M. Hongo, Y. Hirono and T. Hirano, PLB 775, 266-270 (2017)**
- **G. K. K, M. Kurian and V. Chandra, PRD 106, no.3, 034008 (2022)**
- **A. Huang, Y. Jiang, S. Shi, J. Liao and P. Zhuang, PLB 777, 177-183 (2018)**

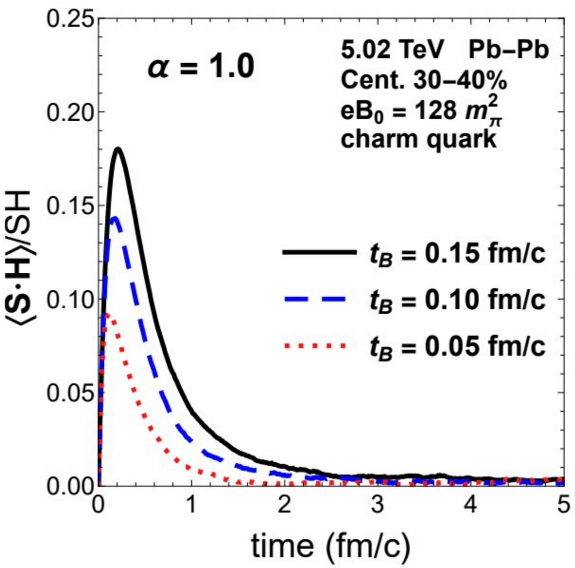


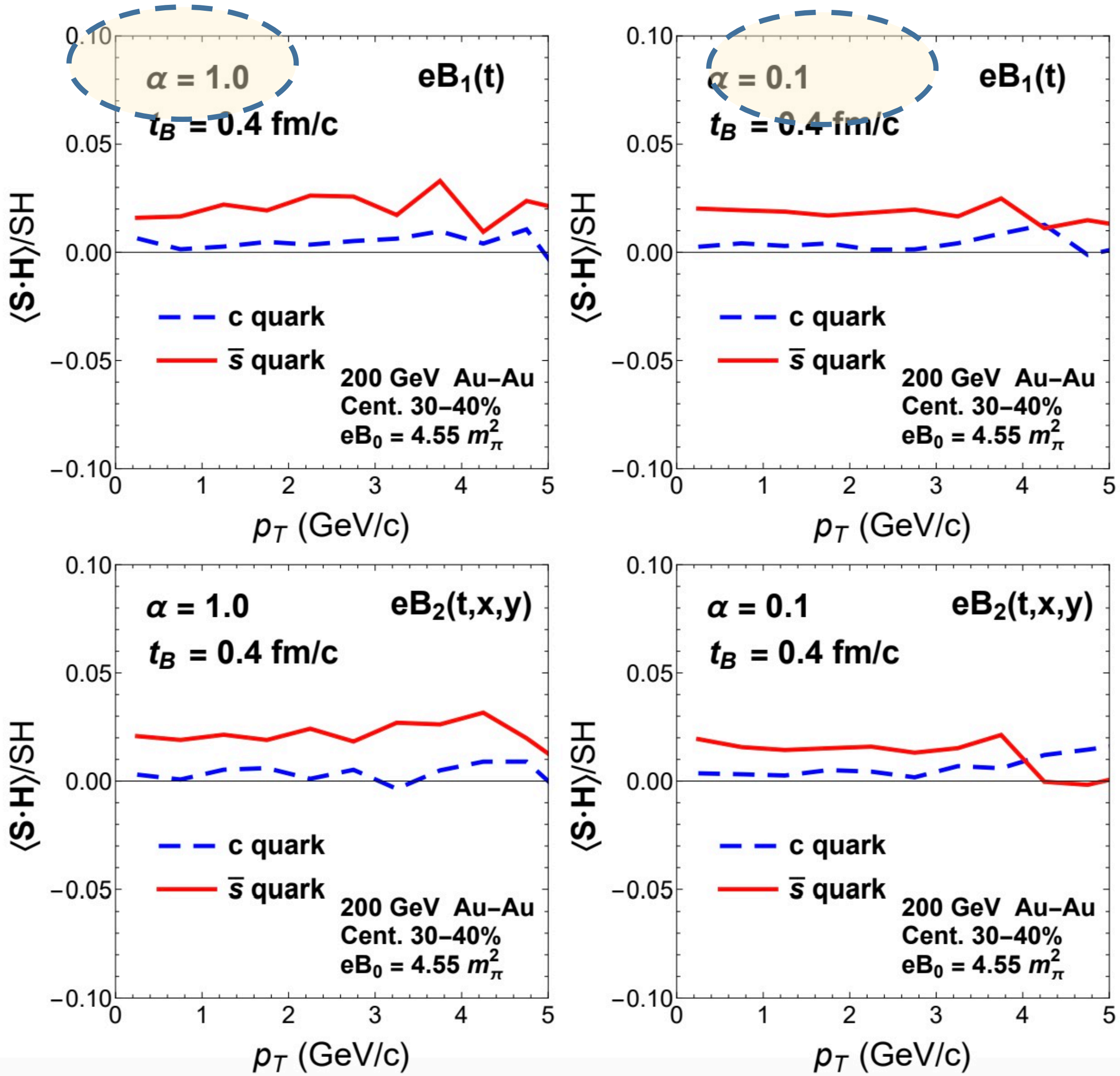
Time evolutions of eB(t)



Liu, et al, BC, PRC110 (2024)034910

Heavy quark polarization in B-field





Liu, Bai, Zheng, Huang, BC, PRC110 (2024)034910

Spin polarization in RHIC: s and c quarks after movig out of QGP

Summary

- We study the **in-medium HQ potentials** from small (pp, pA) to large (Pb-Pb, Au-Au) collision systems with charmonium observables.

  The Color screening effect is expected to be small and imaginary parts of the potential dominates the quarkonium suppression.

- Heavy quarks strongly coupled with the expanding QGP, and HQ is sensitive to the initial profiles of QGP energy density, which makes **HQ carry the information of rotational QGP.**

- The spin-polarization of heavy flavor is discussed.

More slides

4. J/ψ polarization in Pb-Pb

The angular distribution of the two decay products of J/ψ reflects the polarization of the quarkonium state in dilepton decays,

$$W(\theta,\phi) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta\cos^2\theta+\lambda_\phi\sin^2\theta\cos 2\phi + \lambda_{\theta\phi}\sin 2\theta\cos\phi),$$

θ and ϕ are the polar and azimuthal angles in a given reference frame

Polarization depending on the chosen frame (three selected frames):

① **Collins-Soper (CS) frame**: the z−axis is defined as the bisector of the angles between the direction of one beam and the opposite of another beam in the rest frame of the J/ψ.

② **helicity frame (HX)**, z−axis is defined as the direction of the J/ψ in the centre of mass frame of two colliding nucleus.

③ **event plane frame (EP)**, z−axis is defined as the direction orthogonal to the event plane

4. J/ψ polarization in Pb-Pb

polarization parameters $(\lambda_\theta, \lambda_\phi, \lambda_{\theta\phi})$ in different frames are connected with

$$\lambda'_\theta = \frac{\lambda_\theta - 3\Lambda}{1+\Lambda},$$

$$\lambda'_\phi = \frac{\lambda_\phi + \Lambda}{1+\Lambda},$$

$$\lambda'_{\theta\phi} = \frac{\lambda_{\theta\phi}\cos 2\delta - (\lambda_\theta - \lambda_\phi)/2\sin 2\delta}{1+\Lambda},$$

Zhao, BC,
Eur.Phys.J.C 84 (2024) 8, 875

With $\Lambda = (\lambda_\theta - \lambda_\phi)/2\sin^2\delta - \lambda_{\theta\phi}/2\sin 2\delta$

And δ to be the angle between two polarization axis.

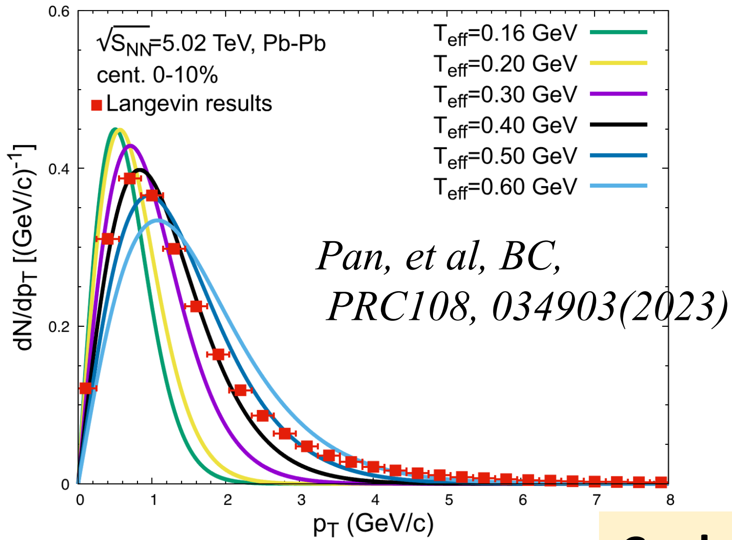
$$\delta_{\mathrm{CS}\to\mathrm{HX}} = \arccos\left(\frac{m_{J/\psi}\sinh y}{\sqrt{p_T^2 + E_T^2\sinh^2 y}}\right)$$

$$\delta_{\mathrm{HX}\to\mathrm{EP}} = \arccos\left(\frac{p_T\sin\phi}{\sqrt{p_T^2 + E_T^2\sinh^2 y}}\right)$$

Averaged polarization in total production

$$\lambda_\theta(p_T) = \frac{N_{\mathrm{ini}}(p_T)\lambda_\theta^{\mathrm{ini}}(p_T) + N_{\mathrm{reg}}(p_T)\lambda_\theta^{\mathrm{reg}}(p_T)}{N_{\mathrm{ini}}(p_T) + N_{\mathrm{reg}}(p_T)}$$

Charm diffusions



Pan, et al, BC, PRC108, 034903(2023)

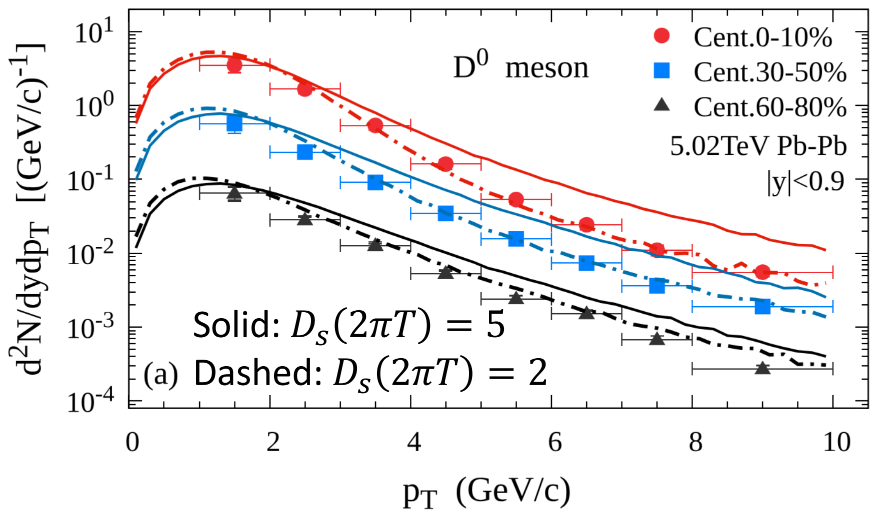
Hydro: 2+1 d ideal hydro

Initial maximum temperature : 510 MeV.

Charm momentum distribution at the hypersurface of a fixed temperature

$$\mathcal{P}_{c+\bar{q}\to D}(\mathbf{p}_D, \mathbf{x}_D) = \mathcal{H}_{c\to D}\int \frac{d\mathbf{p}_c d\mathbf{x}_c}{(2\pi)^3}\frac{d\mathbf{p}_{\bar{q}}}{(2\pi)^3}\frac{dN_c}{d\mathbf{p}_c d\mathbf{x}_c}\frac{dN_{\bar{q}}}{d\mathbf{p}_{\bar{q}}} \times f_D^W(\mathbf{p}_c, \mathbf{p}_{\bar{q}})\delta^{(3)}(\mathbf{p}_D - \mathbf{p}_c - \mathbf{p}_{\bar{q}}), \times \delta^{(3)}(\mathbf{x}_D - \mathbf{x}_c),$$

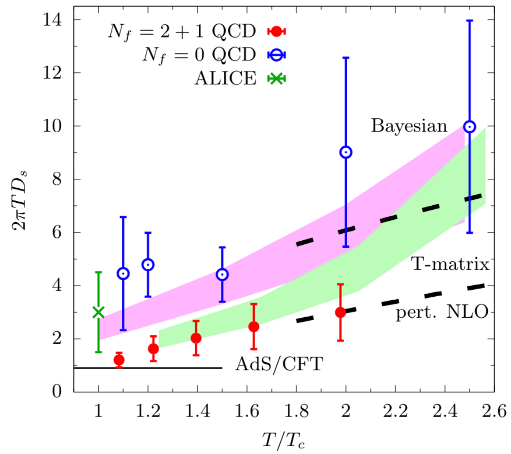
Coalescence process for charm hadronization into D-meson



***BC, Jiang, Liu, et al, PRC* 105 (2022) 054901**

Final momentum distribution of D-meson from Langevin equation

Well describe the data at small p_T



Much stronger coupling between HQ and QGP

HotQCD PRL 130 (2023) 231902