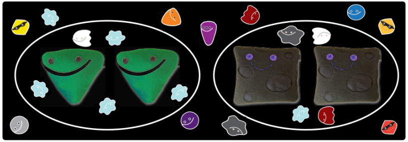

Quarkonia Meet Dark Matter

Kavli IPMU, Kashiwa, Japan, June 16, 2021 (Online)

Nuclear modification of open heavy flavor and quarkonia production in heavy ion collisions

Weiyao Ke (UCB & LBNL)

Based on: Xiaojun Yao, WK, Yingru Xu, Steffen Bass, and Berndt Müller, JHEP01(2021)046
WK, Yingru Xu, Steffen Bass PRC 98, 064901, PRC 100, 064911

WK is supported by the UCB-CCNU Collaboration Grant and NSF No. ACI-1550228.

1. A space-time picture of plasma formation in nuclear collisions

2. Dynamics of heavy quarks in the QGP

3. In-medium dynamics of quarkonia and interplay with heavy quark

4. Summary

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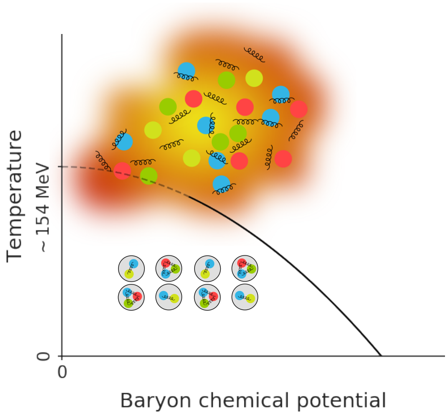
The space-time picture of plasma formation in nuclear collisions



- Hadronic matter undergoes color-deconfinement "phase transition" at $T \sim 155$ MeV and the quark-gluon plasma (QGP) is formed.

The space-time picture of plasma formation in nuclear collisions

Nuclear collisions

$\sqrt{s} \gg M$

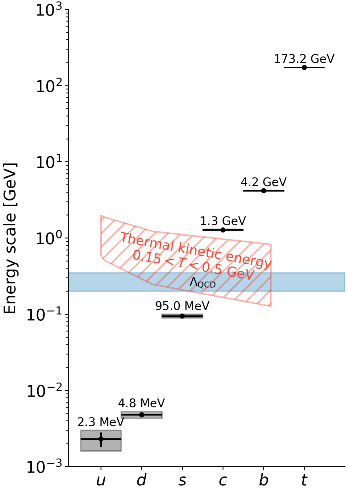
Energy depostion

Longitudinal and transvese expansion

Chemical and kinetic freeze-out of particle production

- Hadronic matter undergoes color-deconfinement “phase transition” at $T \sim 155$ MeV and the quark-gluon plasma (QGP) is formed.
- Besides thermodynamics, non-equilibrium evolution is important to understand the QGP created in labs.
    - Extremely hot initial state $T_0 > 500$ MeV.
    - Cools down fast due to expansion, $\tau_{QGP} \sim 10$ fm$/c$.
    - We only observes particles from freeze-out.

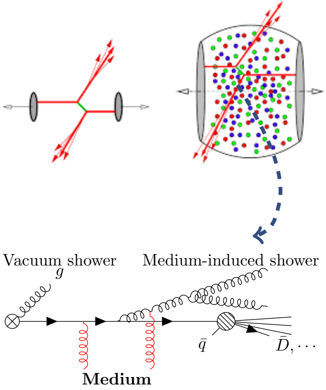
Heavy quarks and quarkonia in medium



- $M_{c,b} > T, \Lambda_{\mathrm{QCD}}$, perturbative produced at early-time hard collisions $\tau \sim 1/(2M)$.
- Heavy quarks and quarkonia introduce a hierarchy of relaxation times $\tau_{R,c} \ll \tau_{R,b} < \tau_{R,\mathrm{bottomia}}$ and binding energies E_{nL} that measure properties of medium.
  - $\tau_{R;b,c} \sim \frac{M_{c,b}}{\alpha_s^2 T^2}$ from collisional process B Svetitsky PRD 37, 2484, E Braaten, MH Thoma PRD 1991.
  - Bound states: interaction rate further reduced due to small size of the dipole.

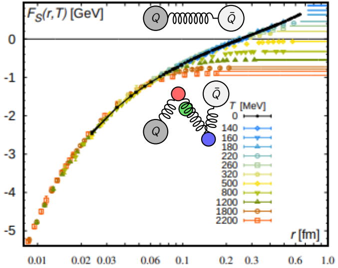
Rich dynamics of heavy quarks and quarkonia in the QGP

- A more complete picture of heavy quark energy loss & diffusion



Collisional + radiative processes

- Plasma screens color potential. Quarkonia melting temperatures is a “thermometer” of a QGP brick T Matsui, H Satz, PLB 178 (1986) 416.



TUMQCD collaboration, PRD 98, 054511 (2018)

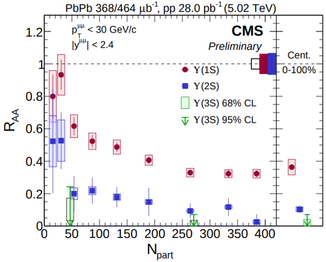
- Dynamical effects: dissociation & regeneration induced by collision with thermal parton.
- Non-equilibrium evolution in a finite-size & time medium.

Medium imprints on particle spectra, chemistry, and anisotropy

Nuclear modification factor:

$$R_{AA} = \frac{\frac{dN_{AA\to i+X}}{dp_T}}{\langle N_{\mathrm{coll}}\rangle \frac{dN_{pp\to i+X}}{dp_T}}$$

Bottomonium



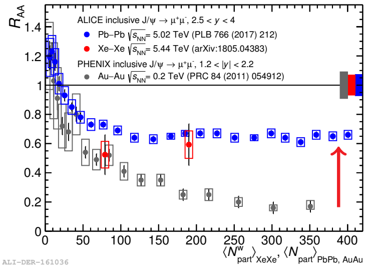
Higher-excited states of bottomnia are more suppressed.

Suppression becomes stronger with increased medium size (N_{part})

Medium imprints on particle spectra, chemistry, and anisotropy

Nuclear modification factor:

$$R_{AA} = \frac{\frac{dN_{AA\to i+X}}{dp_T}}{\langle N_{\rm coll}\rangle \frac{dN_{pp\to i+X}}{dp_T}}$$



Charmonia regeneration becomes important at LHC.

- Moderate increase of medium temperature from $\sqrt{s} = 0.2$ to 5.02 TeV.
- A factor of 10 increase in initial $c\bar{c}$ production.

Medium imprints on particle spectra, chemistry, and anisotropy

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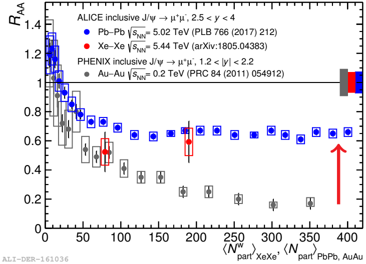

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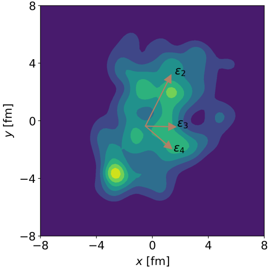
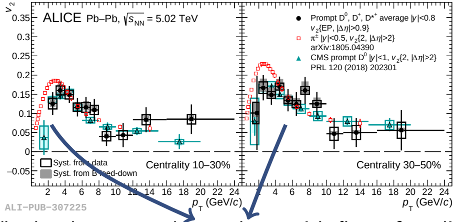
Momentum anisotropy from path-length dependent energy loss & coupling to anisotropic flow of medium

$$v_n = \langle \cos(n(\phi - \Psi_n))\rangle$$



v_2 of pions and charmed mesons



Whether heavy quarks catch up with flow of medium

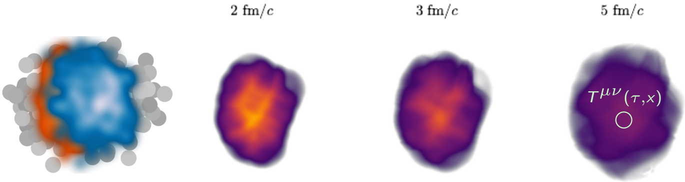
The necessity of a concurrent evolution of HQs and quarkonia

We need a concurrent evolution of HQ + quarkonia, coupled to medium evolution to study non-equilibrium effects:

- Estimate the degree of thermalization before the system freeze out.
- Memory of the initial-state correlations.
- Extract color stopping power and color screening power of the QGP.

Medium evolution

- "Linearized": neglect back reactions from HQ and quarkonia to the medium.
- Medium is described by a multi-stage model:

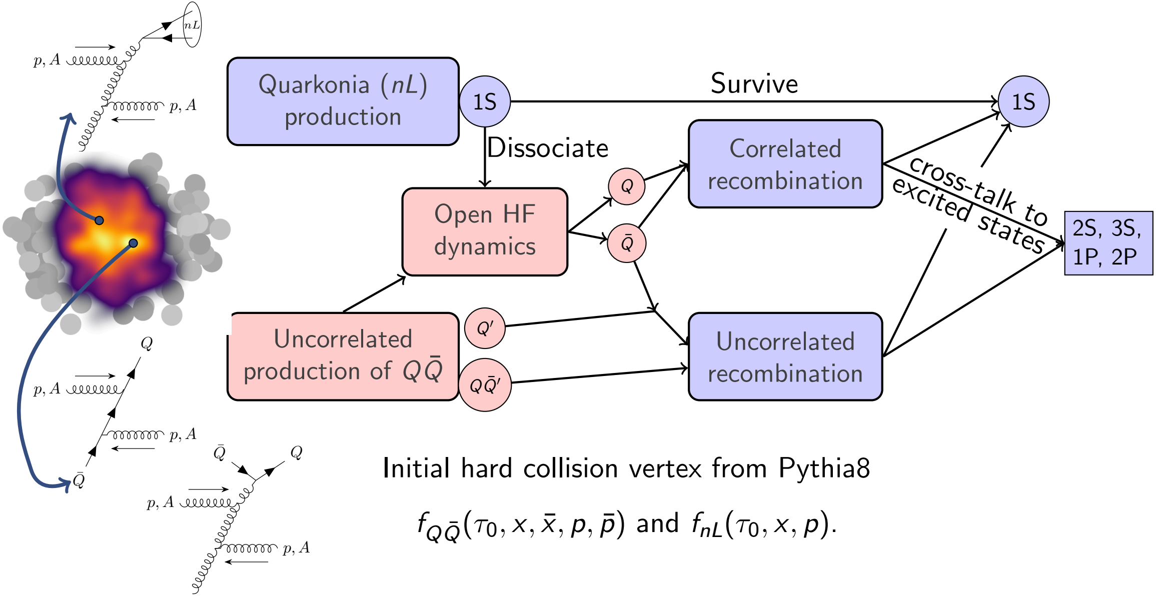


- Provides medium flow velocity and local energy density e, u^μ.
- Approximate the color charges follow the Boltzmann distribution $f_q, f_g = e^{-p\cdot u/T(e)}$

Medium parameters are calibrated to light hadron productions.
JE Bernhard JS Moreland, SA Bass, Nat. Phys. 15, 1113-1117

- Initial condition for collision geometry (TRENTo model, JS Moreland, JE Bernhard, SA Bass)
- Pre-equilibrium dynamics at early time (the free-streaming model by U Heinz, J Liu)
- 2+1D viscous hydro equations QGP expansion (VISHNew, H Song, U Heinz, Z Qiu, C Shen, J Liu)
- Hadron produced by particlization at $T = 154$ MeV. Hadronic rescatterings (using UrQMD) until chemical and kinetic freeze out.

A coupled evolution of HQ and quarkonia



Quarkonia (nL) production

1S

Survive

1S

Dissociate

Open HF dynamics

Q

$\bar{Q}$

Correlated recombination

cross-talk to excited states

2S, 3S, 1P, 2P

Uncorrelated production of $Q\bar{Q}$

Q'

$Q\bar{Q}'$

Uncorrelated recombination

Initial hard collision vertex from Pythia8

$f_{Q\bar{Q}}(\tau_0, x, \bar{x}, p, \bar{p})$ and $f_{nL}(\tau_0, x, p)$.

A coupled evolution of open and hidden flavors

Space-time evolution X Yao et al JHEP01(2021)046:

$$\begin{aligned} \underbrace{\frac{d}{dt} f_{Q\bar{Q}}(t, x, \bar{x}, p, \bar{p}) + \mathcal{C}_Q[f_{Q\bar{Q}}] + \mathcal{C}_{\bar{Q}}[f_{Q\bar{Q}}]}_{\text{Open HF transport}} &= -\mathcal{R}[f_{Q\bar{Q}}] + \mathcal{D}[f_{nL}], \\ \frac{d}{dt} f_{nL}(t, x, p) &= \underbrace{-\mathcal{D}[f_{nL}]}_{\text{Dissociation}} + \underbrace{\mathcal{R}[f_{Q\bar{Q}}]}_{\text{Regeneration}} . \end{aligned}$$

Requirement for a semi-classical transport equation:

- Well-defined quasi-particles.
- Localized few-body collisions: $\tau_{D,\mathrm{coll}} \ll \lambda_{\mathrm{coll}}$

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Dynamics of heavy quarks in the QGP[1]

- Collisions with medium are dominated by frequent an soft momentum transfer $q^2 \sim m_D^2 < M^2$. A Brownian motion characterized by spatial (or momentum) transport coefficients D_s (or $\kappa = 2T^2/D_s, \eta_D = \kappa/(2ET)$).

$$C_Q \supset C_{\mathrm{diff}} = -\nabla_p \left[\eta_D \mathbf{p} + \frac{1}{2}\kappa\nabla_p\right], \text{ Fokker–Planck term}$$

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[1] Heavy quark transport part of the model WK, Y Xu. SA Bass, PRC 98 064901 (2018), PRC 100 064911 (2019).

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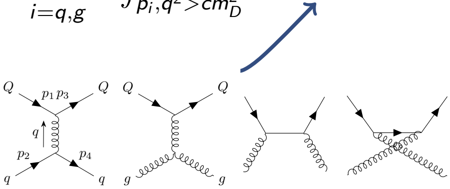
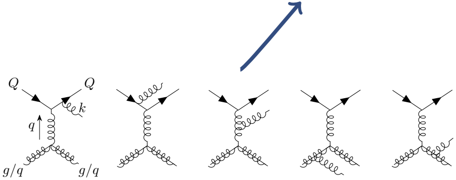
$$C_Q \supset C_{\rm diff} = -\nabla_p \left[\eta_D \mathbf{p} + \frac{1}{2}\kappa \nabla_p\right], \text{ Fokker–Planck term}$$

- Intermediate p_T: phase-space allows harder & inelastic collisions.

$$C_Q \supset \sum_{i=q,g} g_i \int_{p_i, q^2 > c m_D^2} |v_{\rm rel}| d\sigma_i^{\rm el} f_0(p_i) \left[f_Q(p) - f_Q(p-q)\right] + [\text{emission \& absorption}]$$





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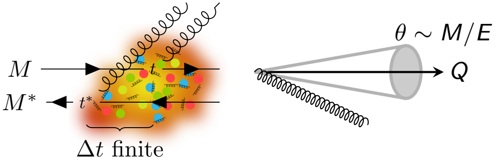
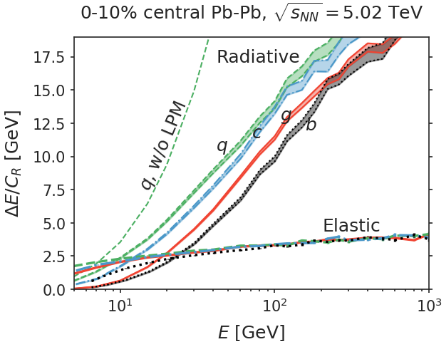
Dynamics of heavy quarks in the QGP[1]

- High-p_T energy loss of heavy quarks are dominated by induced gluon radiation.
- Nonlinear L-dependent E-loss due to interference $\Delta E \propto L^2$ for short path.





WK, XN Wang 2010.13680

- Mass hierarchy of energy loss from a "dead-cone" effect $\Delta E_q^{\rm rad} > \Delta E_c^{\rm rad} > \Delta E_b^{\rm rad}$
- Elastic collisions dominates for $p_T^c \lesssim 10$ GeV and $p_T^b \lesssim 25$ GeV.

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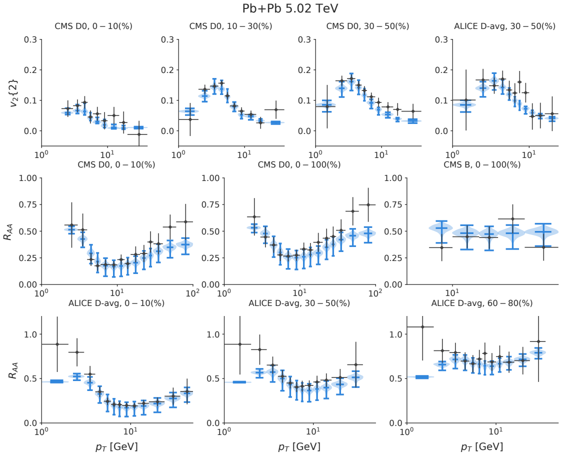
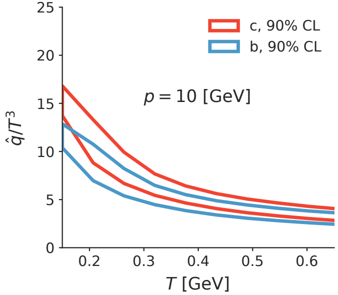
[1] Heavy quark transport part of the model WK, Y Xu. SA Bass, PRC 98 064901 (2018), PRC 100 064911 (2019).

Calibrate the heavy-quark coupling to the medium

- A calibrated in-medium evolution of charm and bottom quarks WK, Y Xu, SA Bass, PRC 98, 064901 (2018).
- Temperature and momentum-dependent transport parameters are reverse engineered from heavy meson R_{AA} and v_n.





$$\hat{q}_Q = 2\kappa(T, p)$$

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Quarkonia screening, dissociation, and recombination

Framework for static screening + dynamical processes of quarkonia in medium: potential Non-Relativistic QCD (pNRQCD) + open-quantum system X Yao, B Müller PRD100, 014008 (2019), X Yao, T Mehen, PRD99, 096028 (2019), X Yao 2102.01736 $\xrightarrow{\text{semi-classical}}$ reduce to Boltzmann equation

- Non-relativistic: $v \ll 1$, $M \gg \underbrace{Mv}_{p_{\rm rel}} \gg \underbrace{Mv^2}_{E_{nl}}$, potential treatment of Q-$\bar{Q}$ interaction.

  $v_b \sim \alpha_s(\alpha_s m_b) \sim 0.34$ (✓), $v_c \sim \alpha_s(\alpha_s m_c) \sim 0.52$ (?).
- Weakly-coupled plasma: $3T > m_D \sim g_{\rm med} T$.
- Limit to well-defined resonance[2]: $E_{nl} > \Gamma$.
- Non-relativistic motion of bound states in the medium $\frac{\gamma_T 3T}{\alpha_s M} \lesssim 1$
  - Charmonia: $p_T \lesssim 3$ GeV.
  - Bottomnia: $p_T \lesssim 10$ GeV.

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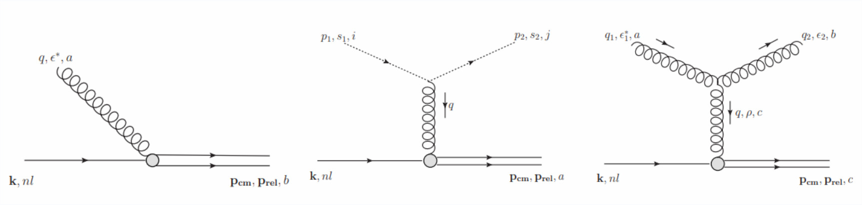
[2] In the current study, excited states initially created in A-A dissociate so fast that they are effectively not present in initial condition

Quarkonia dissociation and recombination

$\mathcal{S}$: color singlet (bound states); $\mathcal{O}$: color octet (unbound pair); $\mathbf{r}\cdot\mathbf{E}$: color-dipole interaction

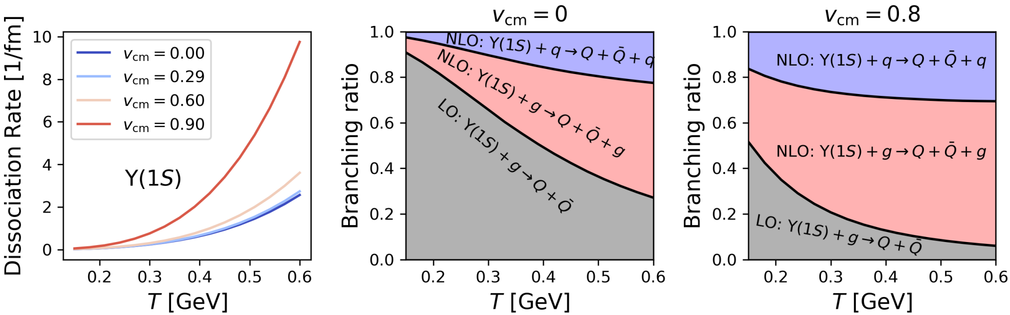
$$\mathcal{L} = \int dr^3 \mathrm{Tr}\left[S^\dagger(i\partial_0 - H_s)S + O^\dagger(iD_0 - H_o)O + gV_A(O^\dagger \mathbf{r}\cdot\mathbf{E}S + h.c.) + gV_B O^\dagger\{\mathbf{r}\cdot\mathbf{E}, O\}\right]$$



X Yao, B Müller PRD100, 014008 (2019)

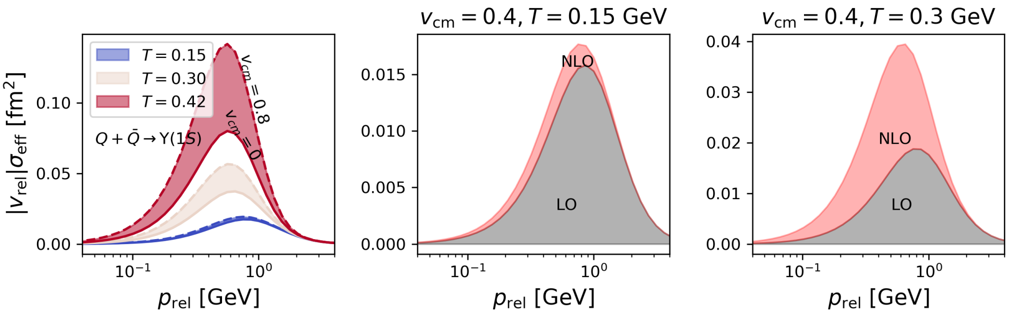
- Leading order (LO): on-shell gluon induced $[nL] + g \leftrightarrow Q + \bar{Q}$
- Next-to-leading order (NLO): virtual gluon induced $[nL] + g/q \leftrightarrow Q + \bar{Q} + g/q$.
- Further simplifications:
  - Bound-state (unbound) wave-functions are assumed to be Coulomb (Coulomb scattering wave). Explicit static screening to be included in the future.
  - Neglect diffusion of quarkonia in QGP, parametrically small compared to that of HQ.

Quarkonia dissociation rates



- Dissociation rates increase rapidly with temperature and velocity. Effectively, bound states cannot exist in the simulation when its lifetime $\ll 1$ fm$/c$.
- NLO processes are increasingly important at high temperature and velocity.

Effective regeneration cross-section (integrate out light partons)



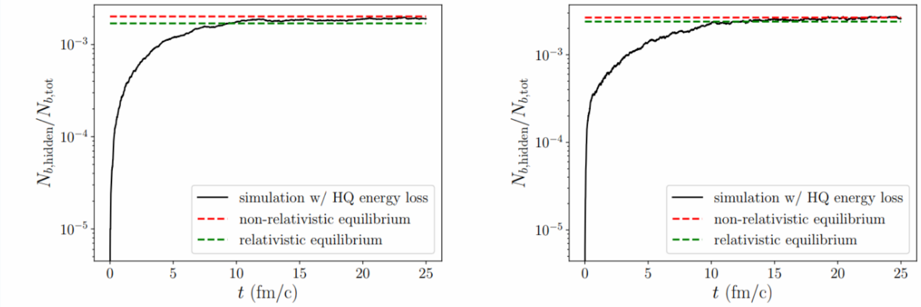
- From Boltzmann equation to particle based simulation: bound states occupy finite volume of phase-space: $\Delta p \Delta x \sim nh$, $\Delta x \sim$ Bohr radius a_B.

$$\Delta f_{nL}(x_{\rm cm}, p_{\rm cm}) \quad = \quad \cdots + \int_{p_{\rm rel}} \Delta t |v| \sigma_{\rm eff}^{nL} f_{Q\bar{Q}}(x,\bar{x};p,\bar{p}) \rightarrow \sum_{ij} \underbrace{\frac{\Delta t |v_{ij}|\sigma_{\rm eff}(p_{\rm rel,ij})}{(2\pi\langle\Delta x^2\rangle)^{3/2}} e^{-\frac{(x_i-x_j)^2}{2\langle\Delta x^2\rangle}}}_{\text{pairwise recombination probability}}$$

taking $\sqrt{\langle\Delta x^2\rangle}_{1S} = a_B$ and $\sqrt{\langle\Delta x^2\rangle}_{2S,2P} = 2a_B$

Equlibration of quarkonia in a static medium

Initial condition: $f(p) = \frac{N_0}{L^3 p_0^3} \prod_{i=x,y,z} \Theta(p_0 - p_i)$, $p_0 = 3$ GeV, $N_0 = 50$, $L = 10$ fm.

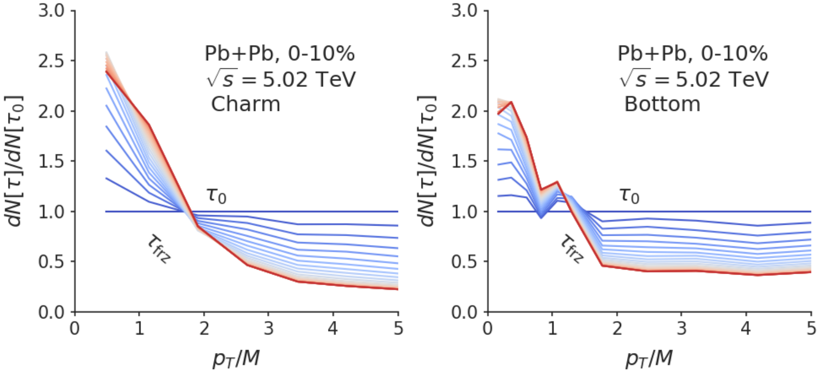


(a) Case 1: $\Upsilon(1S)$ in a 300 MeV QGP box.

(b) Case 2: $\Upsilon(2S)$ in a 180 MeV QGP box.

- Chemical equilibrium: $\lambda_b \lambda_{\bar{b}} = \lambda_\Upsilon$, $N_i = \lambda_i g_i L^3 \int_p e^{-E_i/T}$, $E = \sqrt{M^2 + p^2} \approx M + \frac{p^2}{2M}$
- Diffusion + detailed balance of $\Upsilon \leftrightarrow b, \bar{b}$ rapidly bring the system to chemical equilibrium.

Relaxization of heavy-quark spectra in heavy-ion collisions



- Energy loss: soften spectra of $Q\bar{Q}$ and increase the chance of regeneration.
- A small spatial diffusion constant: $Q\bar{Q}$ pairs diffuses apart slower than free streaming: $\langle x^2 \rangle = 2D_s t$ v.s. $x = |v_{\rm rel}| t$

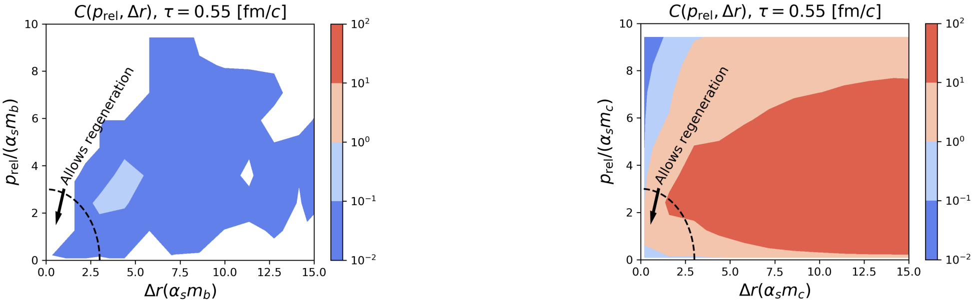
Effect of diffusion on the evolution of Q-$\bar{Q}$ correlation

Trace the evolution of open $Q\bar{Q}$ correlation from τ_0

$$C(\tau, \Delta r, p_{\rm rel}) = \int_{x,\bar{x},p,\bar{p}} \delta(\Delta r - |\mathbf{x} - \bar{\mathbf{x}}|)\delta(p_{\rm rel} - \sqrt{(p+\bar{p})^2 - 4M^2}) f(\tau; x, \bar{x}; p, \bar{p})$$

$b\bar{b}$: effectively one pair of $Q\bar{Q}$.

$c\bar{c}$: larger population O(10) pairs.



Initially, $b\bar{b}$ are close in phase-space; $c\bar{c}$ receive large contribution from uncorrelated pairs. But temperature is too high for long-lived bound states.

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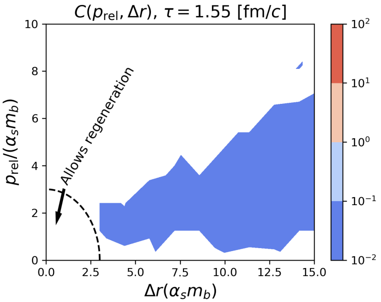
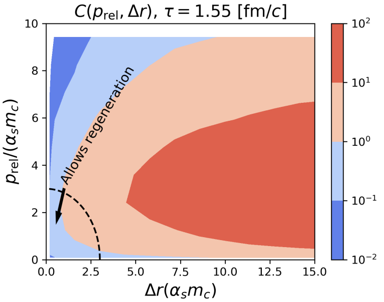


$c\bar{c}$: larger population O(10) pairs.



At latter time, temperature drops down, but bottom pairs are too far apart in phase space to recombine. Close charm pairs are abundant to allow recombination.

Effect of diffusion on the evolution of Q-$\bar{Q}$ correlation

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$$C(\tau, \Delta r, p_{\rm rel}) = \int_{x,\bar{x},p,\bar{p}} \delta(\Delta r - |\mathbf{x} - \bar{\mathbf{x}}|)\delta(p_{\rm rel} - \sqrt{(p+\bar{p})^2 - 4M^2})f(\tau; x, \bar{x}; p, \bar{p})$$

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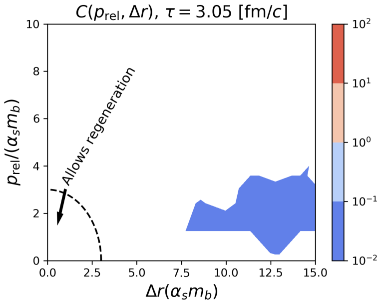
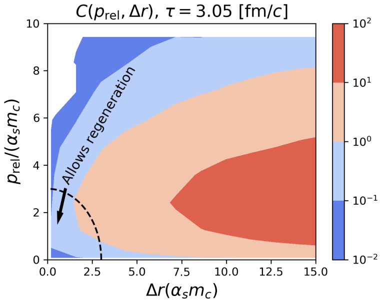
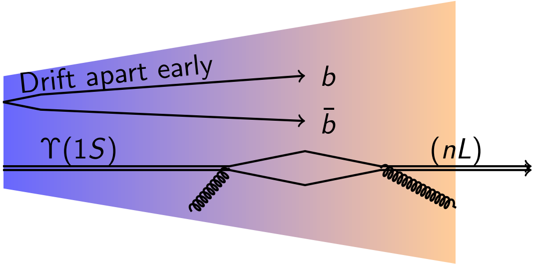




However, recombination does play a role in the evolution of initially produced bottomonia via cross-talk recombination.

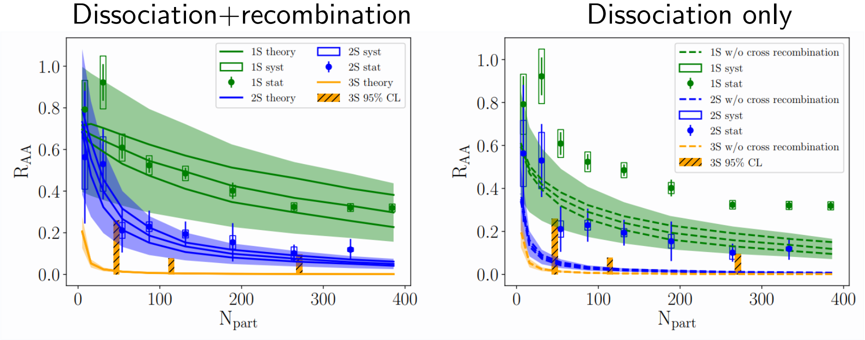
"Cross-talk" recombination



- Dissociated $\Upsilon(1S)$ provides correlated $Q\bar{Q}$ pairs in cooler medium at later time.
- They can recombine into states (nL). Classical in-medium transition $(n'L') \to (nL)$; populate excited states.

Dissociation and recombination in bottomonia suppression

- R_{AA} of $\Upsilon(1S), 2S$ (w/ feed-down), $(3S)$ (w/o feed-down) v.s. $N_{\rm part}$ for Pb+Pb @ $\sqrt{s_{NN}} = 5.02$ TeV, calculations are compared to the CMS measurement PLB 790 (2019) 270



Dissociation+recombination

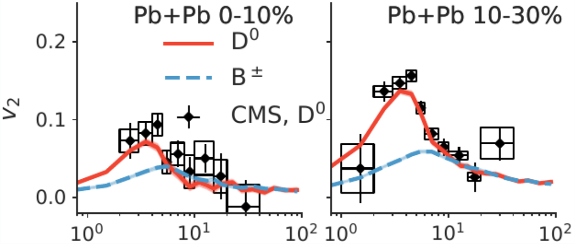
Dissociation only

X Yao et al JHEP01(2021)046

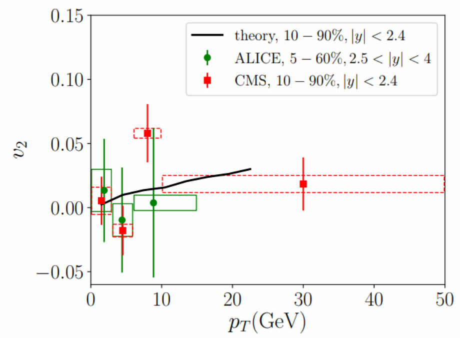
- Cross-talk recombination increases R_{AA} of $\Upsilon(1S)$ and $\Upsilon(2S)$, especially for excited state.
- Lines: $\pm10\%$ variation in α_s. Bands: uncertainty from nuclear parton distribution function (EPPS16 K Eskola et al EPJC 77 (2017) 3, 163).

Momentum anisotropy of bottomonia

v_2 of $c \to D$ and $b \to B$



v_2 of ground-state Bottomonia $\Upsilon(1S)$



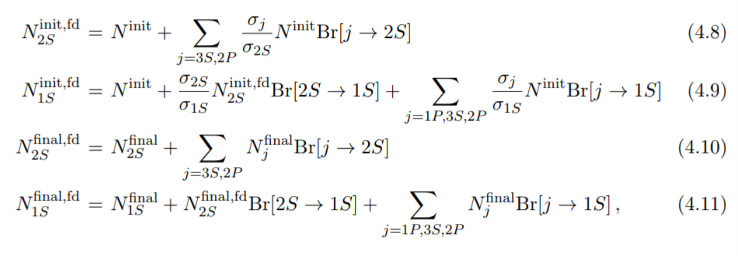
- $v_2^D(p_T = M) \approx 0.1$, $v_2^B(p_T = M) \approx 0.04$. Charm flavor is much closer to local equilibrium than bottom quark.
- v_2 of $\Upsilon(1S)$ in Pb-Pb collisions @ 5.02 TeV is less than 2% for $p_T \lesssim M_\Upsilon$. Calculations are compared to ALICE PRL 123, 19, 192301 (2019) and CMS data 2006.07707.

1. A space-time picture of plasma formation in nuclear collisions
2. Dynamics of heavy quarks in the QGP
3. In-medium dynamics of quarkonia and interplay with heavy quark
4. Summary

Summary

- Heavy-flavor and quarkonia are sensitive to moment transport and color screening of QGP.
- A coupled Boltzmann equation for heavy quark & low-p_T bottomonia is developed to account for the non-equilibrium dynamics in heavy-ion collisions.
- Quarkonia dissociation and recombination from pNRQCD + open-quantum system techniques.
- In-medium transition among ground & excited states is important to describe suppression of bottomonia states.

Initial production & feed-down contributions



$$N_{2S}^{\mathrm{init,fd}} = N^{\mathrm{init}} + \sum_{j=3S,2P} \frac{\sigma_j}{\sigma_{2S}} N^{\mathrm{init}} \mathrm{Br}[j \to 2S] \tag{4.8}$$

$$N_{1S}^{\mathrm{init,fd}} = N^{\mathrm{init}} + \frac{\sigma_{2S}}{\sigma_{1S}} N_{2S}^{\mathrm{init,fd}} \mathrm{Br}[2S \to 1S] + \sum_{j=1P,3S,2P} \frac{\sigma_j}{\sigma_{1S}} N^{\mathrm{init}} \mathrm{Br}[j \to 1S] \tag{4.9}$$

$$N_{2S}^{\mathrm{final,fd}} = N_{2S}^{\mathrm{final}} + \sum_{j=3S,2P} N_j^{\mathrm{final}} \mathrm{Br}[j \to 2S] \tag{4.10}$$

$$N_{1S}^{\mathrm{final,fd}} = N_{1S}^{\mathrm{final}} + N_{2S}^{\mathrm{final,fd}} \mathrm{Br}[2S \to 1S] + \sum_{j=1P,3S,2P} N_j^{\mathrm{final}} \mathrm{Br}[j \to 1S]\,, \tag{4.11}$$

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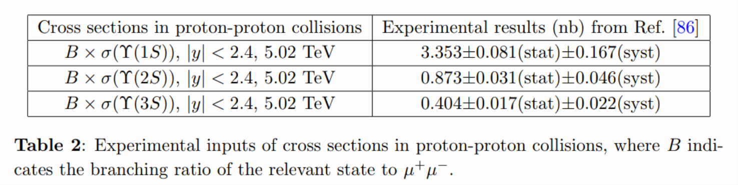
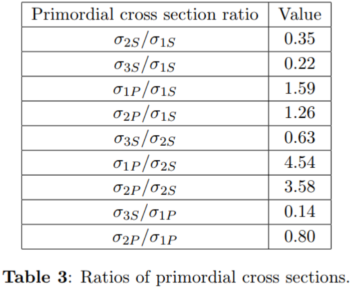


Cross sections in proton-proton collisions	Experimental results (nb) from Ref. [86]
$B \times \sigma(\Upsilon(1S))$, $\lvert y\rvert < 2.4$, 5.02 TeV	3.353±0.081(stat)±0.167(syst)
$B \times \sigma(\Upsilon(2S))$, $\lvert y\rvert < 2.4$, 5.02 TeV	0.873±0.031(stat)±0.046(syst)
$B \times \sigma(\Upsilon(3S))$, $\lvert y\rvert < 2.4$, 5.02 TeV	0.404±0.017(stat)±0.022(syst)

Table 2: Experimental inputs of cross sections in proton-proton collisions, where B indicates the branching ratio of the relevant state to $\mu^+\mu^-$.

CMS PLB 790, 270 (2019)

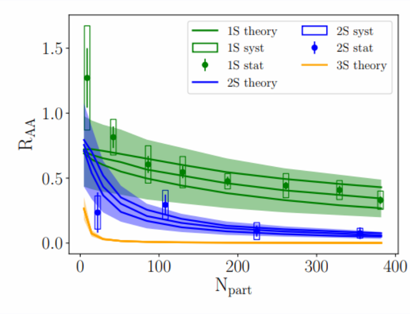


Primordial cross section ratio	Value
σ_{2S}/σ_{1S}	0.35
σ_{3S}/σ_{1S}	0.22
σ_{1P}/σ_{1S}	1.59
σ_{2P}/σ_{1S}	1.26
σ_{3S}/σ_{2S}	0.63
σ_{1P}/σ_{2S}	4.54
σ_{2P}/σ_{2S}	3.58
σ_{3S}/σ_{1P}	0.14
σ_{2P}/σ_{1P}	0.80

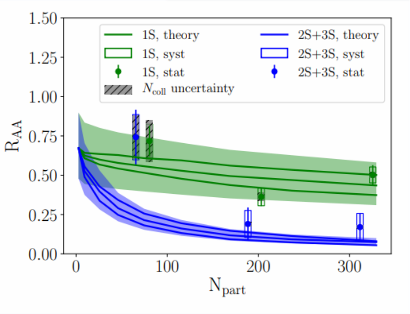
Table 3: Ratios of primordial cross sections.

Beam energy dependence of bottomonia suppression

Pb-Pb @ 2.76 TeV



Au-Au @ 0.2 TeV

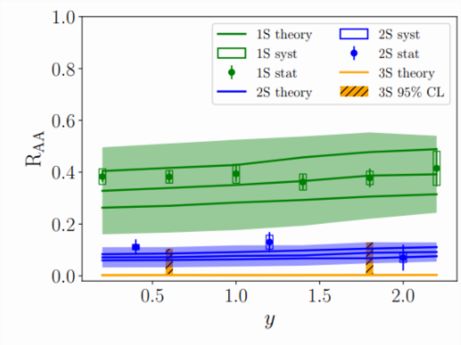


- Beam energy dependence of bottomonia suppression, comparing to CMS data @ 2.76 TeV PLB 770, 357 (2017) and STAR data @ 0.2 TeV NPA 982, 723 (2019).

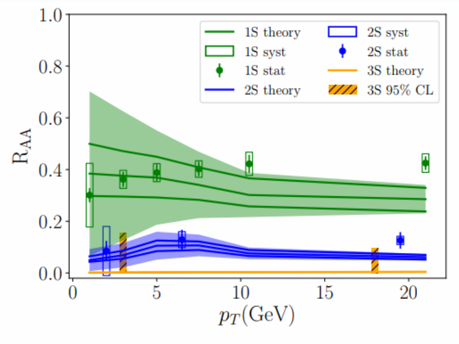
Rapidity and p_T dependence of bottomonia suppression

- R_{AA} of 1S, 2S, 3S v.s. y and p_T in Pb+Pb collisions @ $\sqrt{s_{NN}} = 5.02$ TeV, Calculations are compared to the CMS measurement PLB 790 (2019) 270

$R_{AA}(y)$

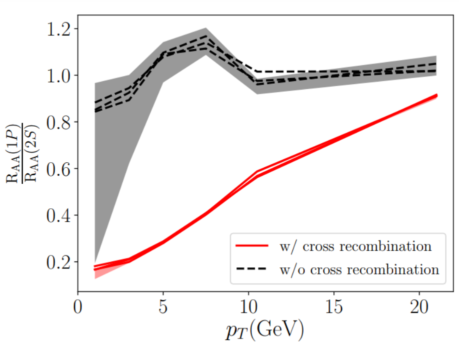


$R_{AA}(p_T)$



- The flat R_{AA} as function of rapidity is reproduced.
- p_T-dependent R_{AA} starts to deviate from trend of data at larger p_T. Suggest relativistic corrections be important at high-p_T.

Double ratios and unique consequence of recombination



- Transitions due to cross-talk recombination leaves a unique signal in $R_{AA}(1P)/R_{AA}(2S)$.
- Initially, 4-5 times more $(1P)$ produced than $(2S)$.
- $(1P) \xleftrightarrow{\text{similar rates}} (2S)$, eventually more $(1P)$ will turn into $(2S) \rightarrow R_{AA}(1P)/R_{AA}(2S) < 1$.
- Uncertainties are dominated by the nuclear parton distribution function (nPDF). Double ratios like $R_{AA}(1P)/R_{AA}(2S)$ greatly suppress the nPDF uncertainty.