Traces of nonequilibrium effects in the charm observables & quarkonia

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outline

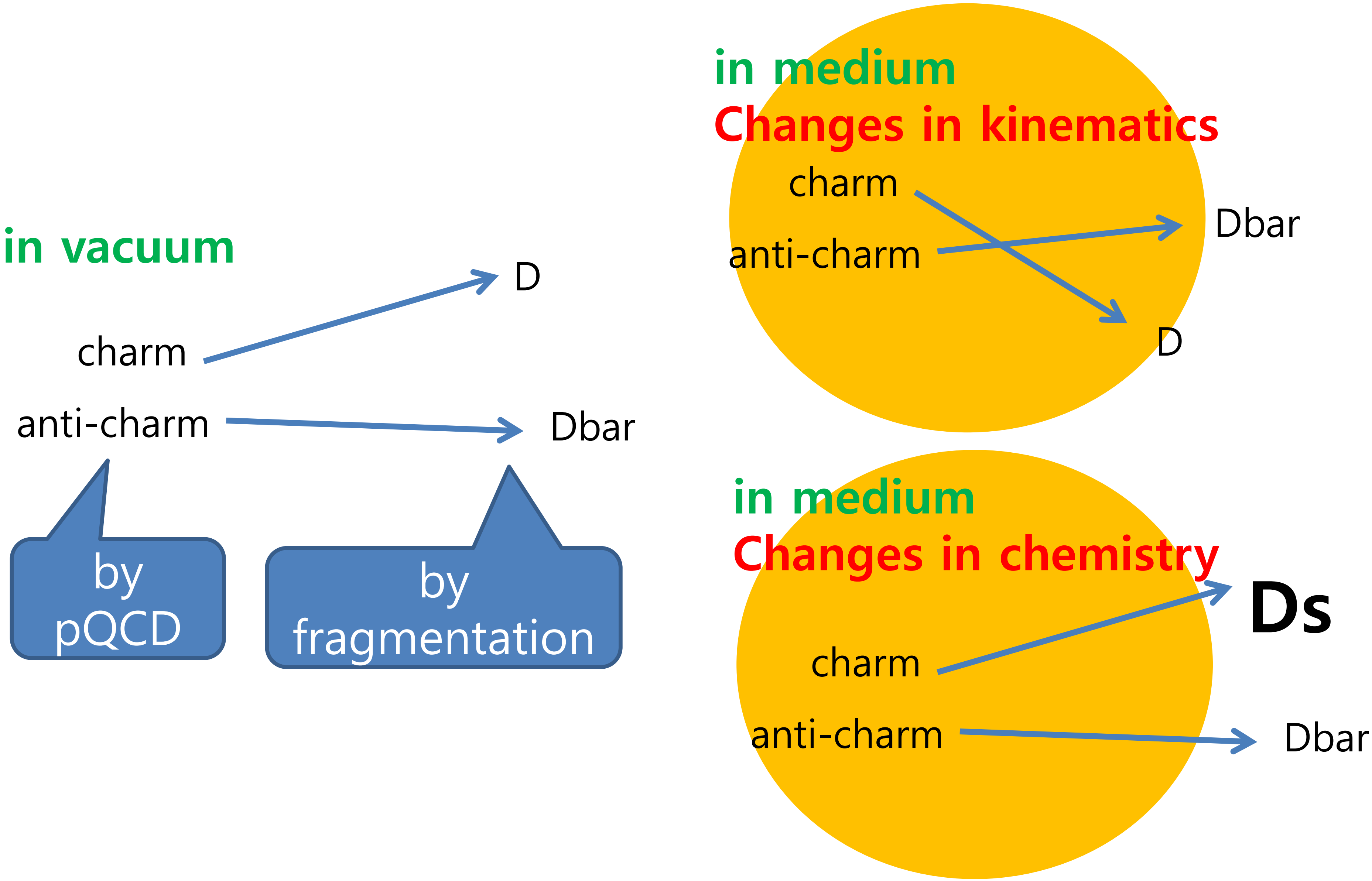
- 1. introduction
- 2. PHSD (parton-hadron-string dynamics)
- 3. Coarse graining and linearized Boltzmann approach tried in PHSD
- 4. Quarkonium production/dissociation in PHSD
- 5. Summary

1. introduction

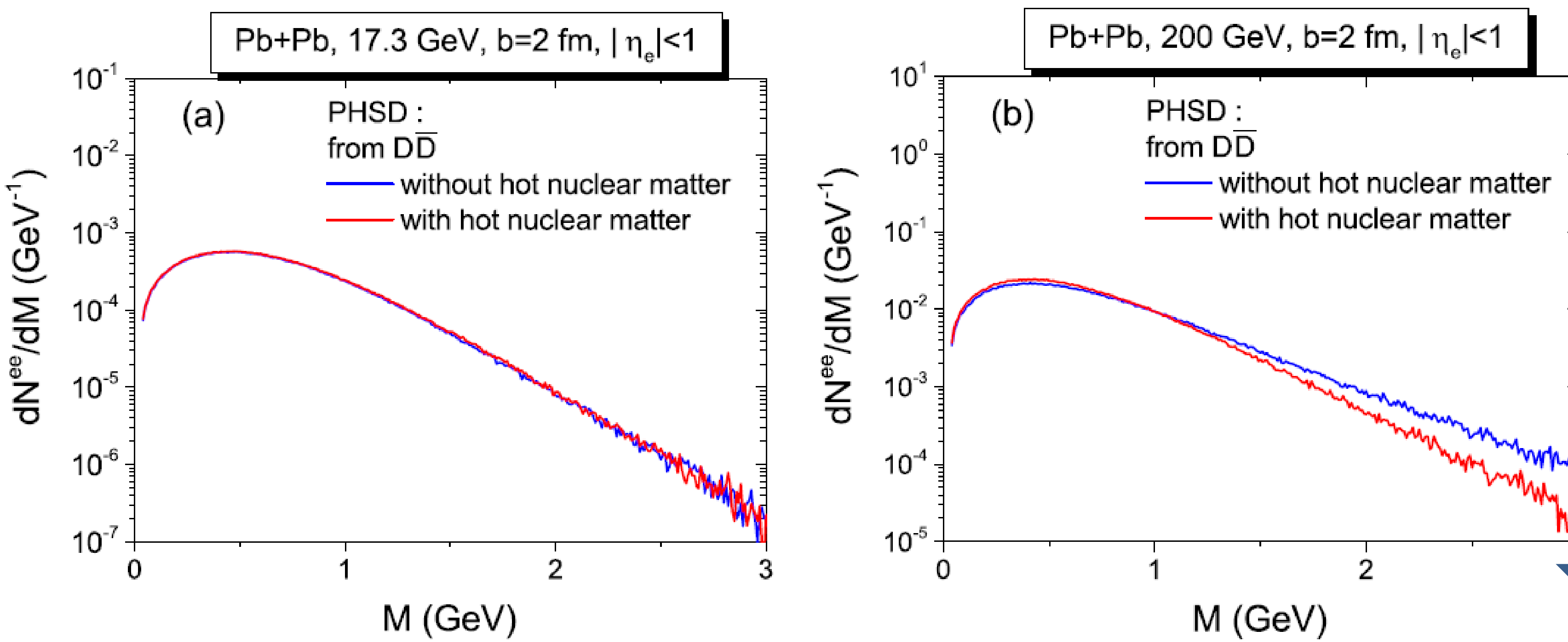
Advantages of heavy flavor

- Heavy flavor is a good probe particle for a hot dense nuclear matter created in heavy-ion collisions (HIC)
- Early produced → probes the matter from the initial stage of HIC
- The production of heavy flavor needs a large energy-momentum transfer → pQCD is applicable

As a probe particle in HIC



For example, invariant mass spectra of dilepton from DDbar pairs



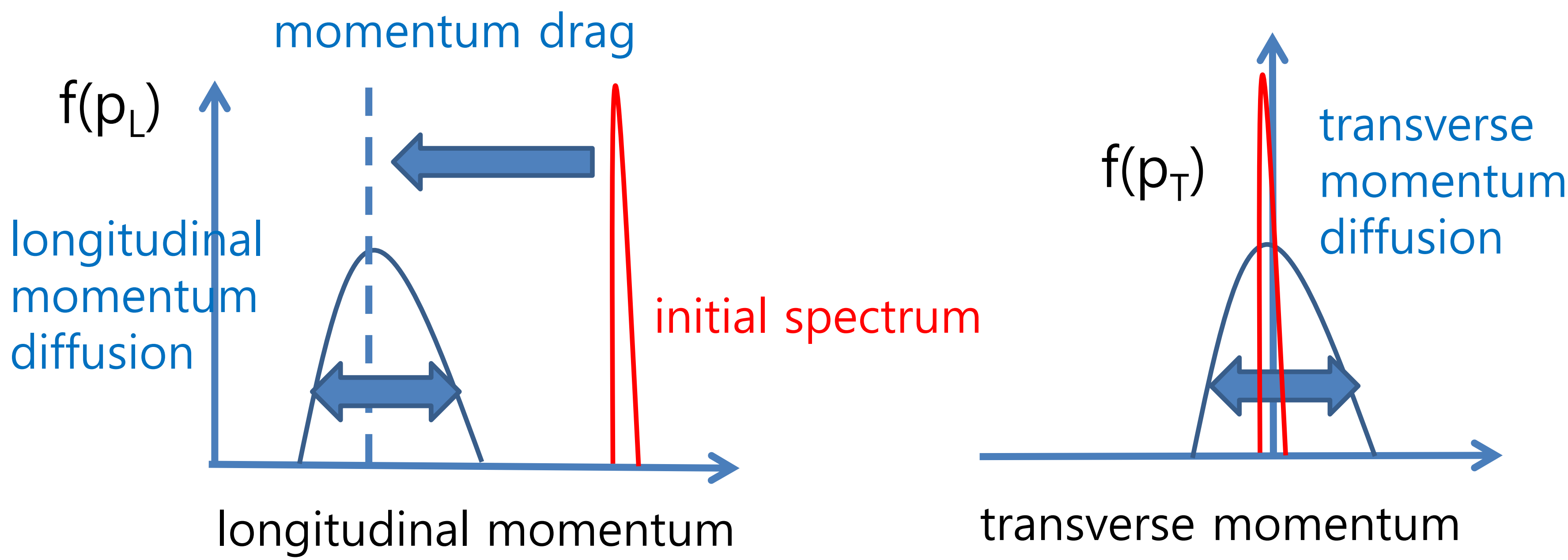
How to describe a nuclear matter

- hydrodynamics:
- macroscopic
- assumes local thermal equilibrium
- solves hydrodynamic equations (energy, momentum conservation of fluid cells)
- EoS is given by p(ε)

- transport approach:
- microscopic
- does not assume local thermal equilibrium
- solves Boltzmann Eqn. (energy, momentum conservation of particles) or Kadanov-Baym Eqn. for off-shell propagation of particles
- EoS is given by the properties of quasiparticles

How to describe heavy flavor in the nuclear matter

- **Solving Langevin Eqn.**



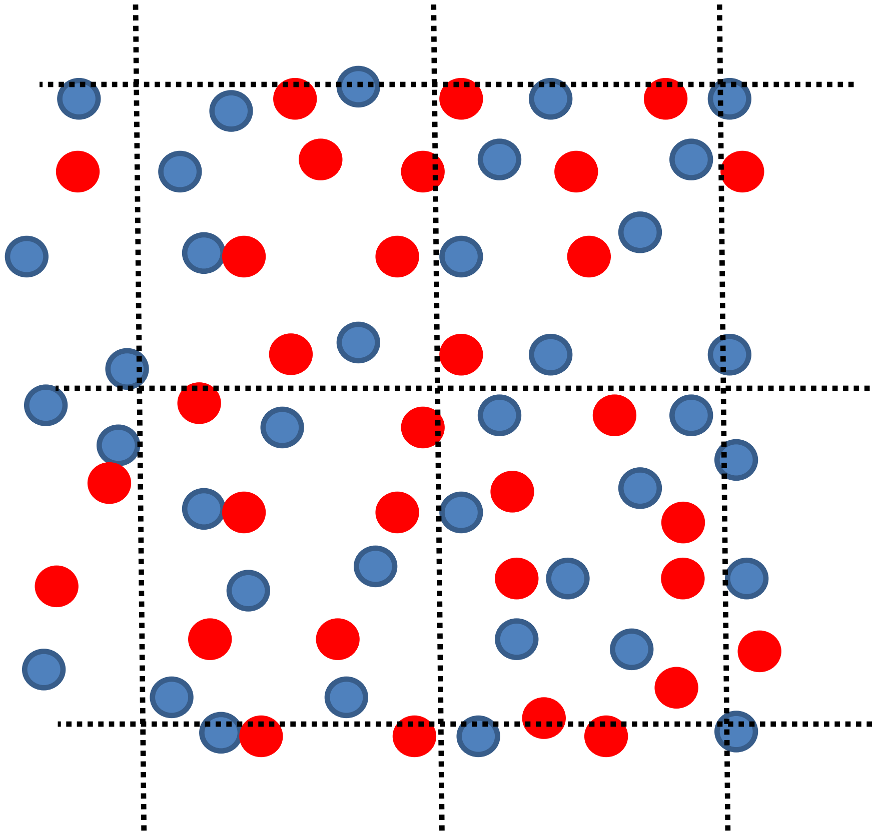
Transport coefficients (drag, diffusion) are pre-calculated as a function of temperature of the matter and heavy quark momentum before simulations

- **Solving Boltzmann Eqn.**
- 1. linearized Boltzmann Eqn.

Coarse graining; assumes local thermal Equilibrium

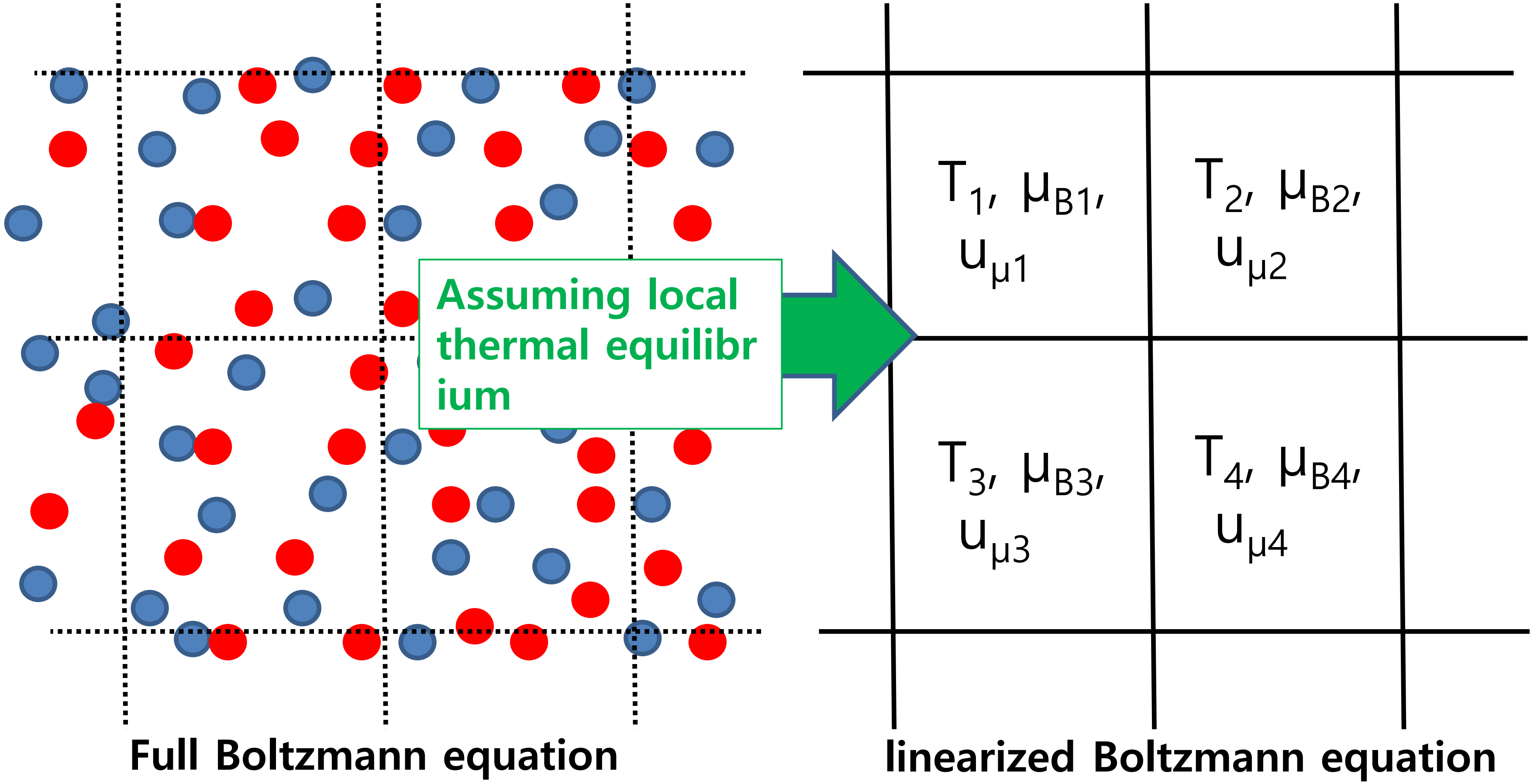
- 2. Full Boltzmann Eqn.

coarse graining



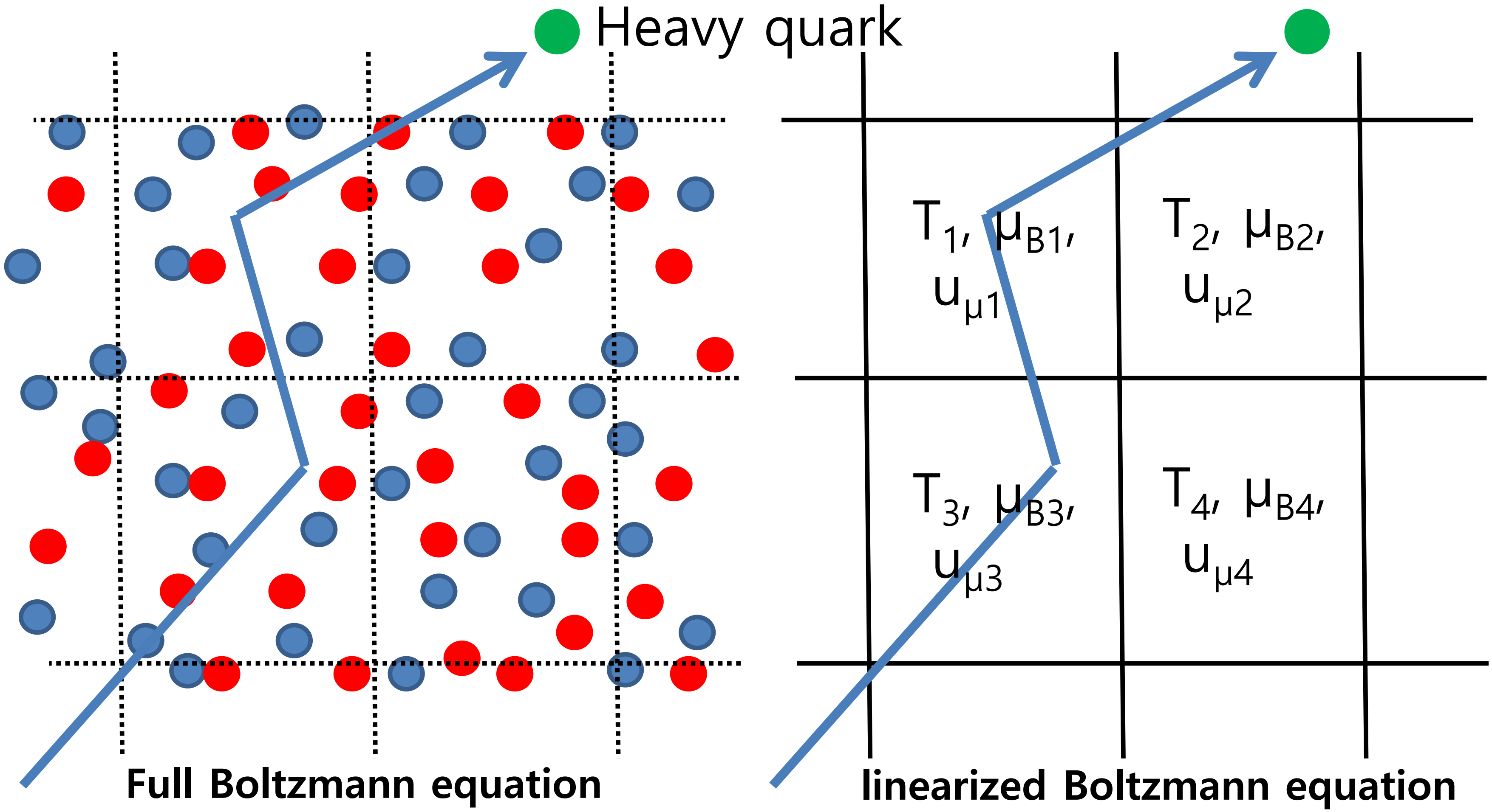
Full Boltzmann equation

- Grid is introduced
- Energy-momentum tensor, baryon current are calculated in each grid cell
- Diagonalizing the energy-momentum tensor, flow velocity & energy density, pressure, and baryon charge density in cell-rest frame are obtained
- Assuming local thermal equilibrium, local T, μ_B are given



Energy density, flow velocity, and baryon charge are exactly same in both figures,

but the left is in non-equilibrium and the right in equilibrium



By comparing
heavy flavor dynamics in **full Boltzmann Eqn.** and those in **linearized Boltzmann Eqn.,**
one can study the effects of non-equilibrium matter on heavy flavor in heavy-ion collisions

2. Parton-Hadron-String Dynamics (PHSD)

Dynamical Quasi-Particle Model (DQPM)

Quark/gluon masses and widths from HTL calculations at high T limit

- quarks:

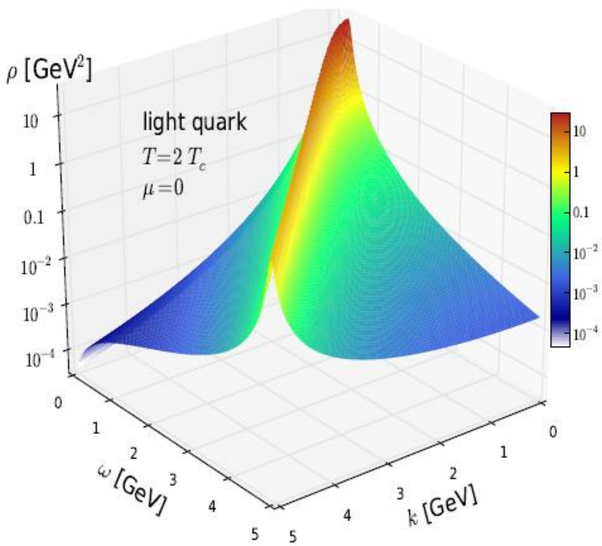
mass: $$M^2_{q(\bar{q})}(T,\mu_B) = \frac{N_c^2-1}{8N_c} g^2(T,\mu_B)\left(T^2+\frac{\mu_q^2}{\pi^2}\right)$$

width: $$\gamma_{q(\bar{q})}(T,\mu_B) = \frac{1}{3}\frac{N_c^2-1}{2N_c}\frac{g^2(T,\mu_B)T}{8\pi}\ln\left[\frac{2c}{g^2(T,\mu_B)}+1\right],$$

- gluons:

mass: $$M_g^2(T,\mu_B) = \frac{g^2(T,\mu_B)}{6}\left[\left(N_c+\frac{1}{2}N_f\right)T^2+\frac{N_c}{2}\sum_q\frac{\mu_q^2}{\pi^2}\right]$$

width: $$\gamma_g(T,\mu_B) = \frac{1}{3}N_c\frac{g^2(T,\mu_B)T}{8\pi}\ln\left[\frac{2c}{g^2(T,\mu_B)}+1\right],$$



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$$\rho_j(\omega,\mathbf{p}) = \frac{\gamma_j}{\tilde{E}_j}\left(\frac{1}{(\omega-\tilde{E}_j)^2+\gamma_j^2}-\frac{1}{(\omega+\tilde{E}_j)^2+\gamma_j^2}\right)$$

$$\equiv \frac{4\omega\gamma_j}{\left(\omega^2-\mathbf{p}^2-M_j^2\right)^2+4\gamma_j^2\omega^2}$$

Pole mass

Spectral width

Dynamical Quasi-Particle Model (DQPM)

T-dependent running coupling

$$g^2(s/s_{SB}) = d((s/s_{SB})^e - 1)^f$$

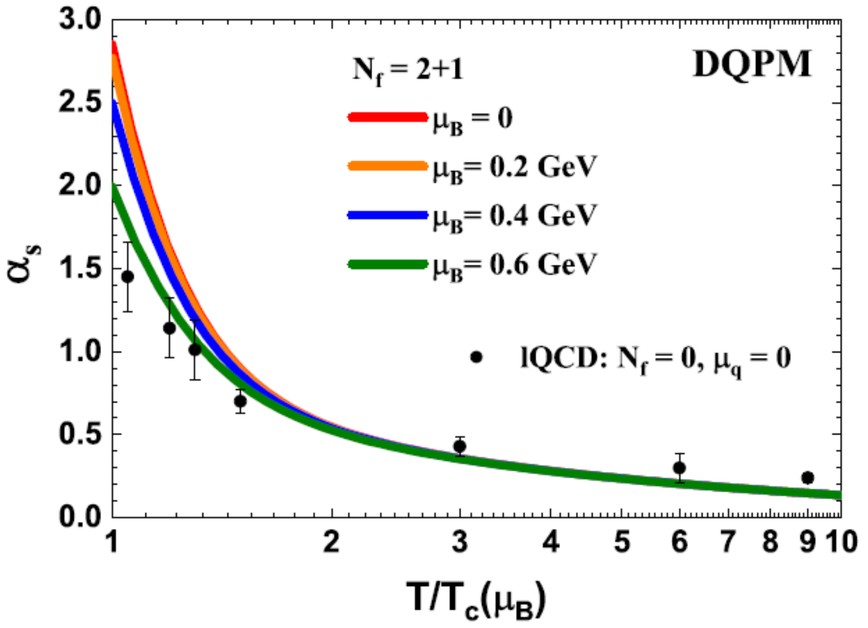
s: entropy density
$s_{SB} = 19/9\pi^2 T^3$: Stefan-Boltzmann entropy density
d=169.934, e=-0.178434, f=1.14631

(T,μ)-dependent running coupling

$$g^2(T/T_c, \mu_B) = g^2(T^*/T_c(\mu_B), \mu_B = 0)$$

$$T^* = \sqrt{T^2 + \mu_q^2/\pi^2}\ ,\ T_c(\mu_B) = T_c\sqrt{1 - \alpha\mu_B^2}$$

α=0.974 GeV^{-2}



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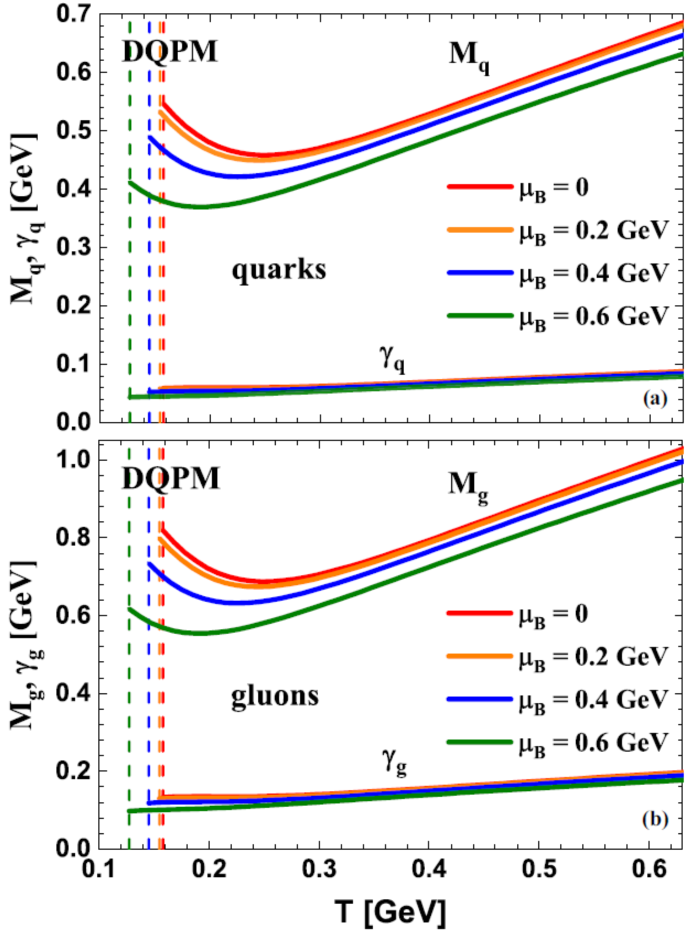
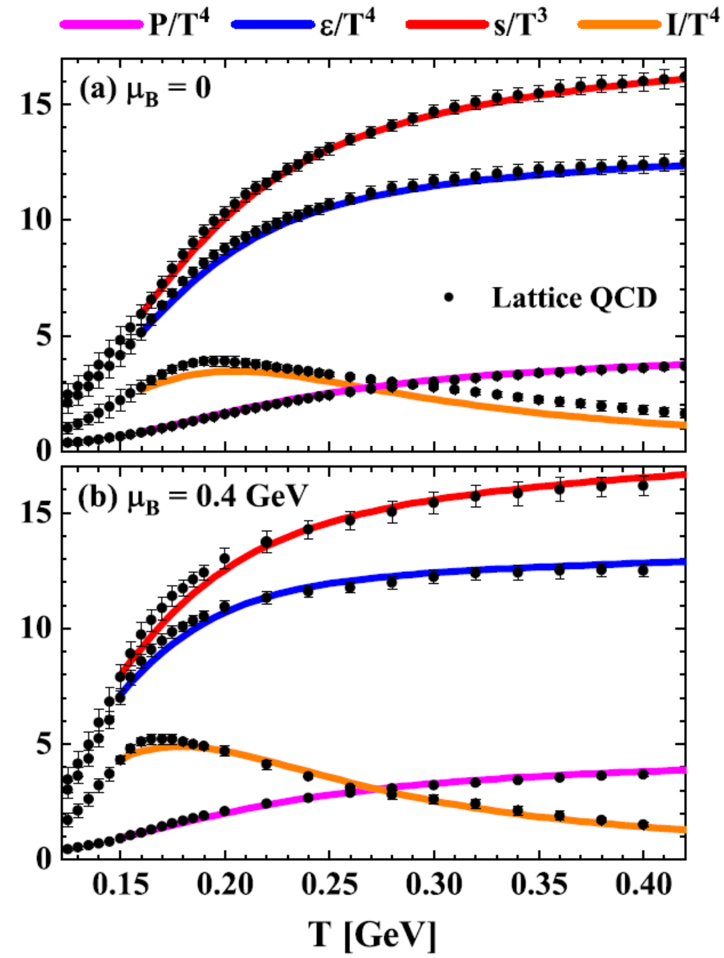
Dynamical Quasi-Particle Model (DQPM)

Lattice EOS is well reproduced both at $\mu_B = 0$ and $\mu_B \neq 0$





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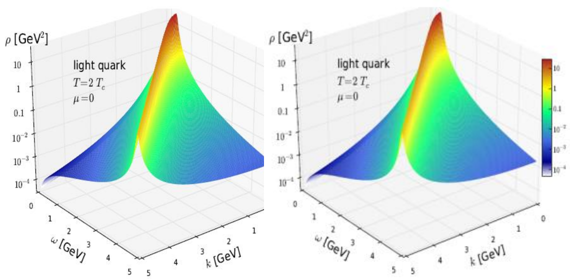
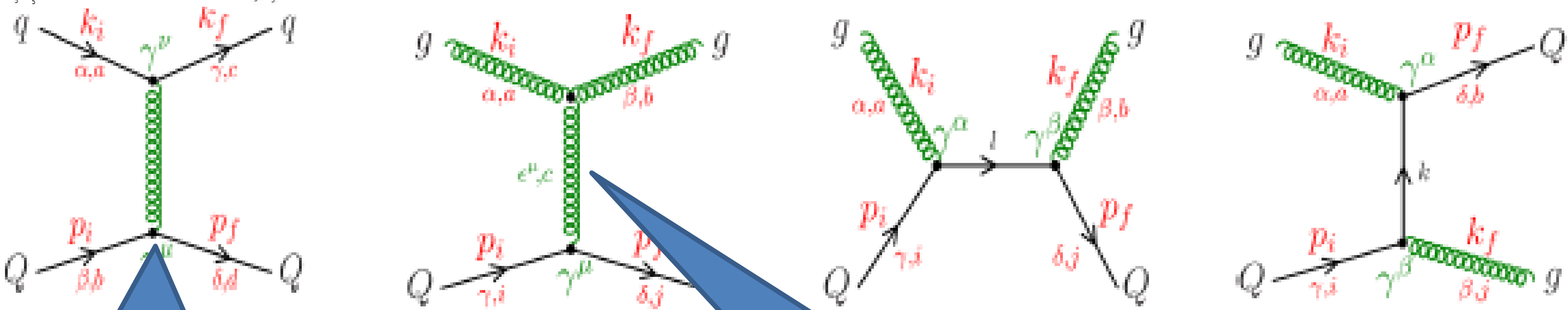
Heavy quark scattering in the QGP (DQPM)



HQ interacts with off-shell massive quark/gluon



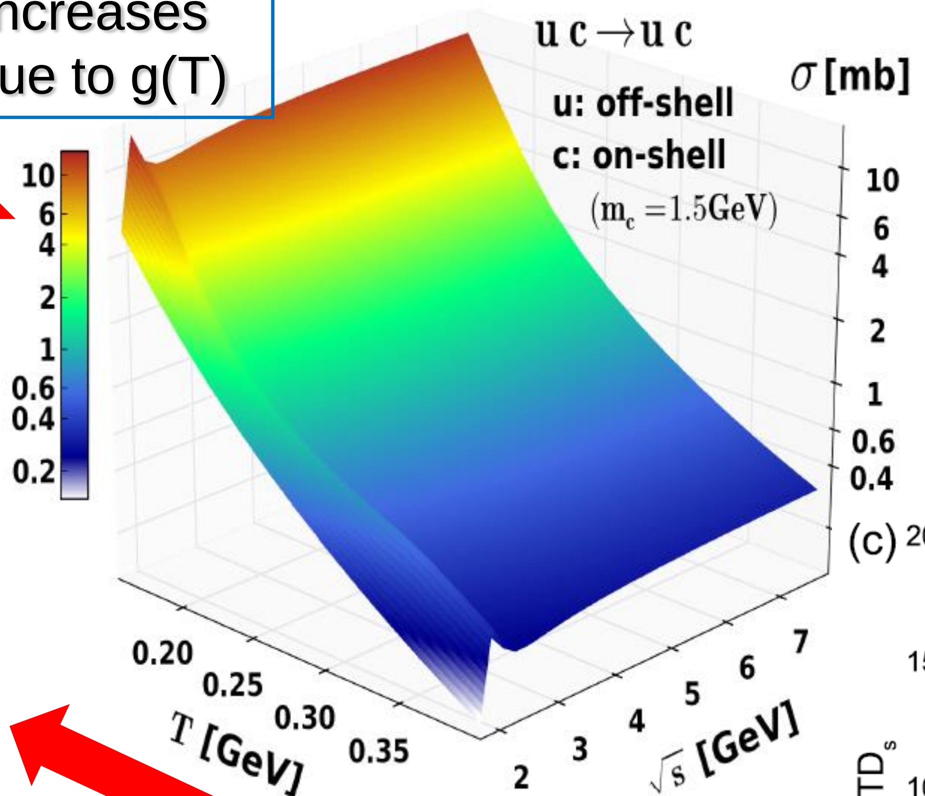
Temperature-dependent strong coupling

Off-shell massive gluon is exchanged: divergence-free without introducing a screening mass

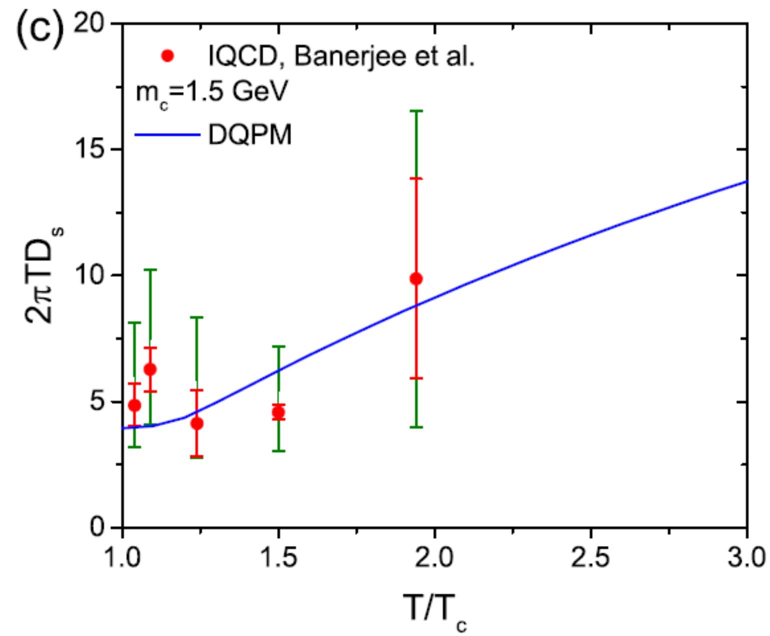
H. Berrehrah et al, PRC 89 (2014) 054901; PRC 90 (2014) 051901; PRC90 (2014) 064906

Elastic cross section uc→uc

cross section rapidly increases near T_c due to g(T)



Spatial diffusion coefficients from lattice QCD are well reproduced

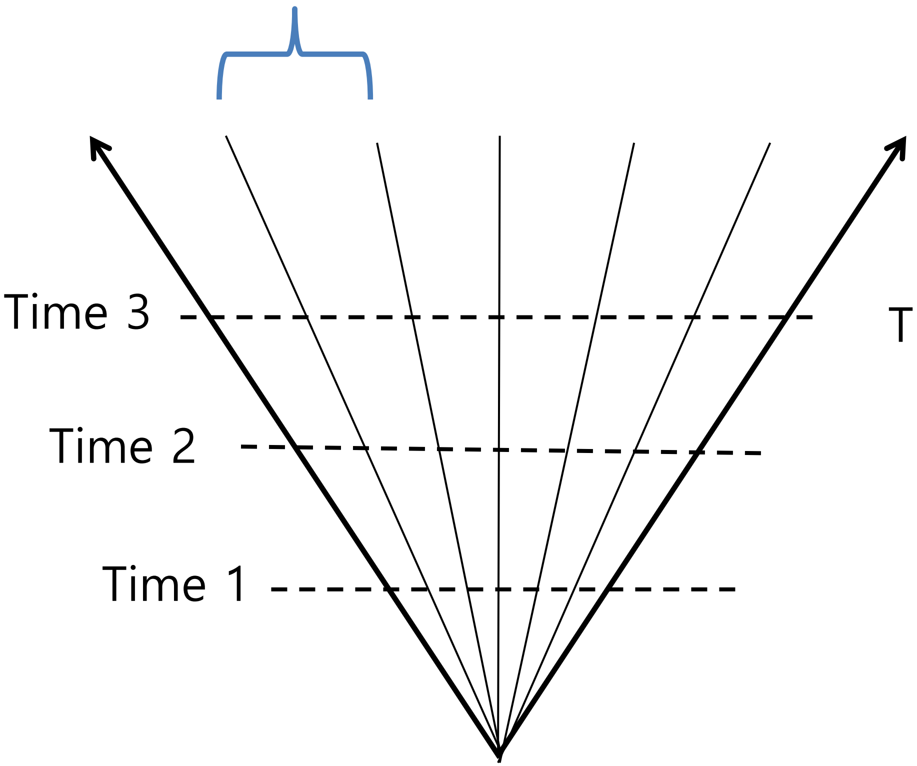


H. Berrehrah et al, PRC 89 (2014) 054901;
PRC 90 (2014) 051901; PRC90 (2014) 064906

3. Coarse grainings and linearized Boltzmann approach tried in PHSD

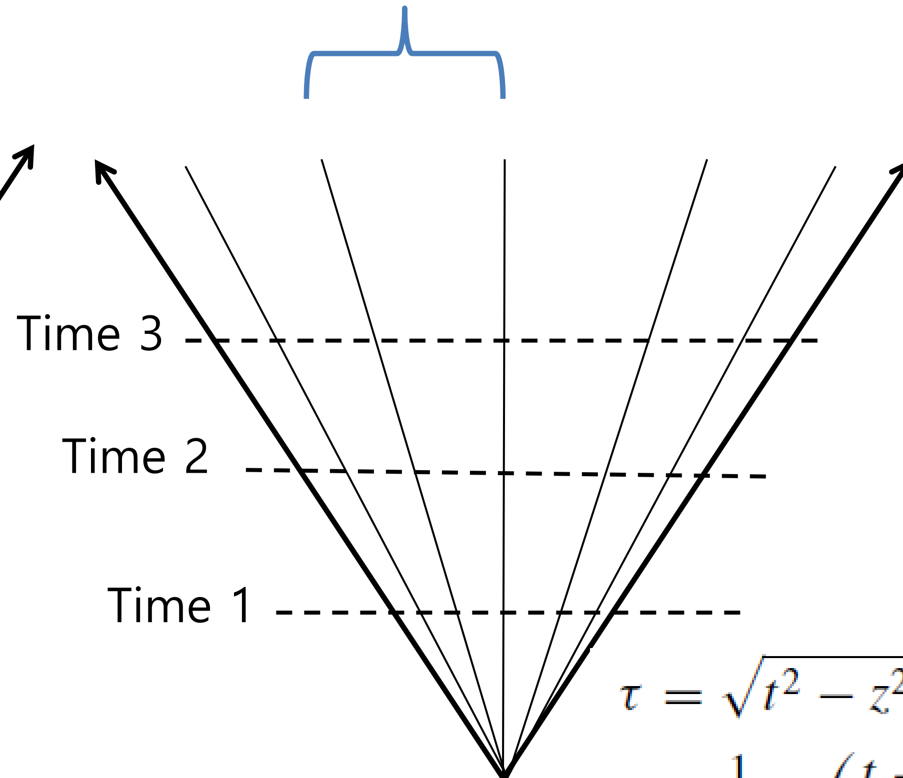
Coarse grainings tried in PHSD

constant dz



dz increases with time, but dz is constant at each time step

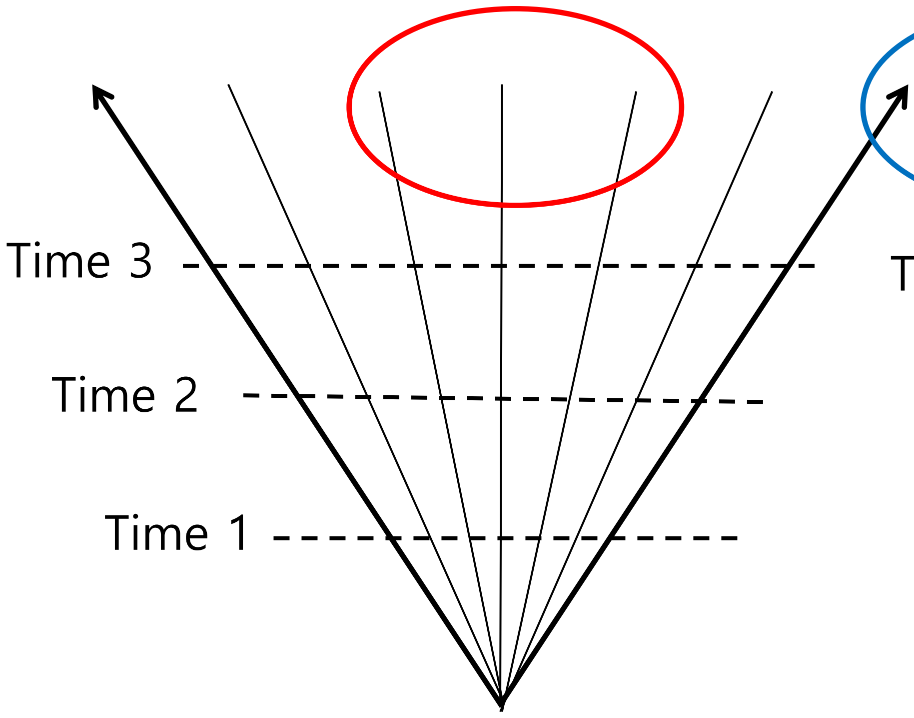
constant dη
(spatial pseudorapidity)



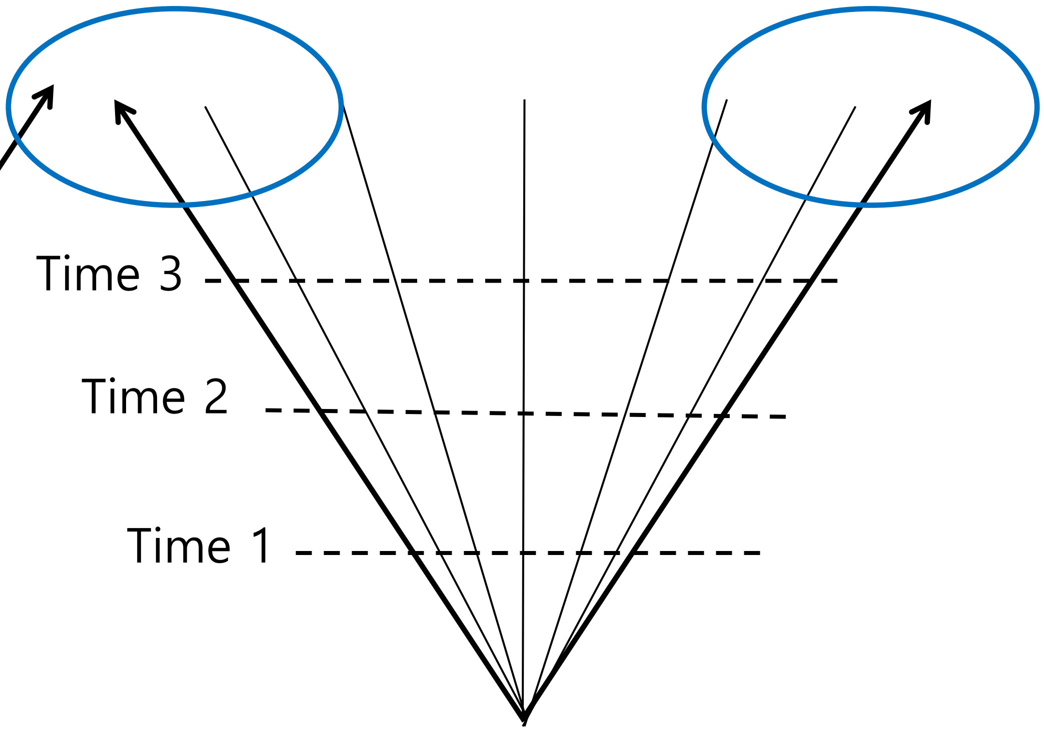
$$\tau = \sqrt{t^2 - z^2},$$
$$\eta = \frac{1}{2}\ln\left(\frac{t+z}{t-z}\right).$$

Coarse graining tried in PHSD

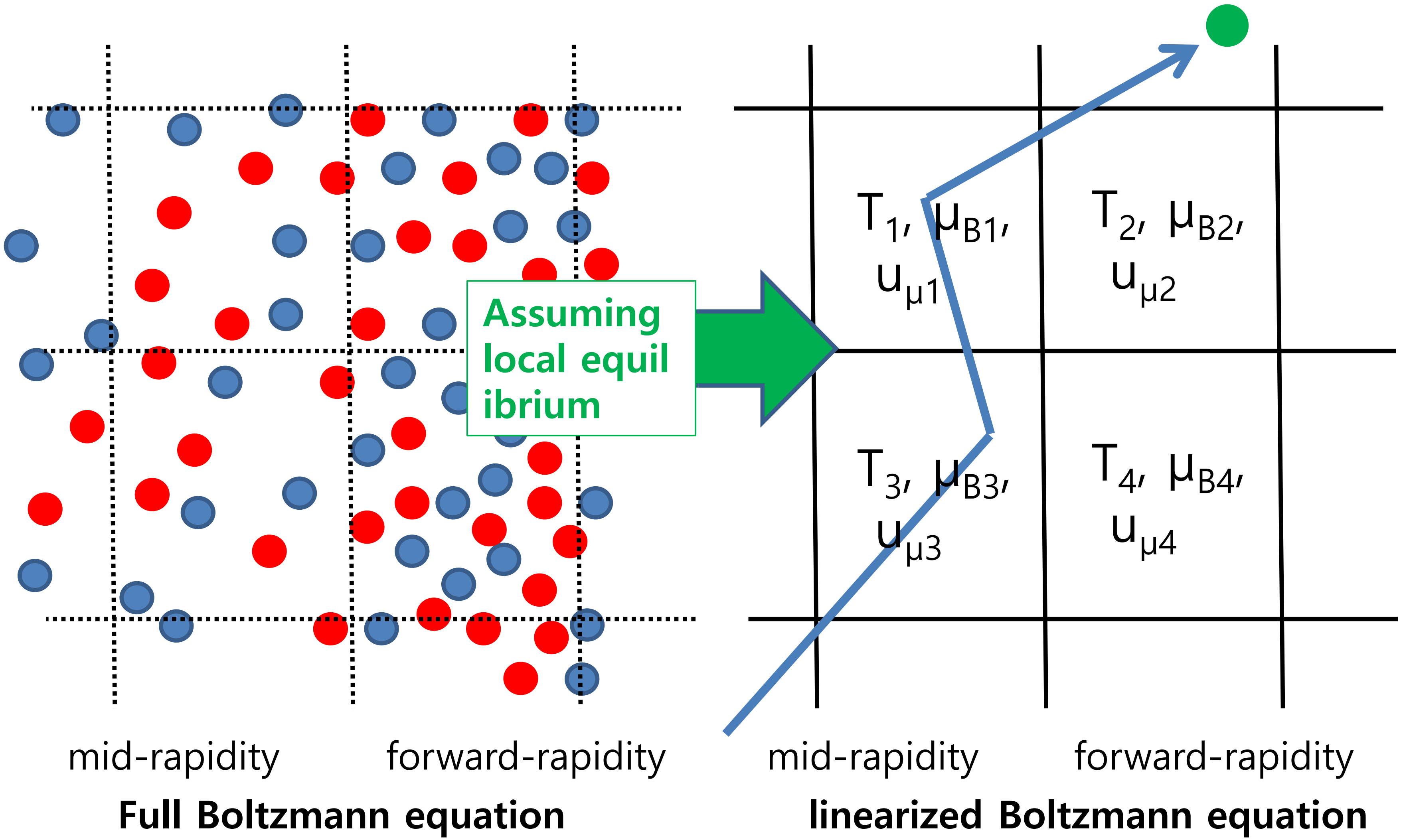
Good resolution at mid-rapidity



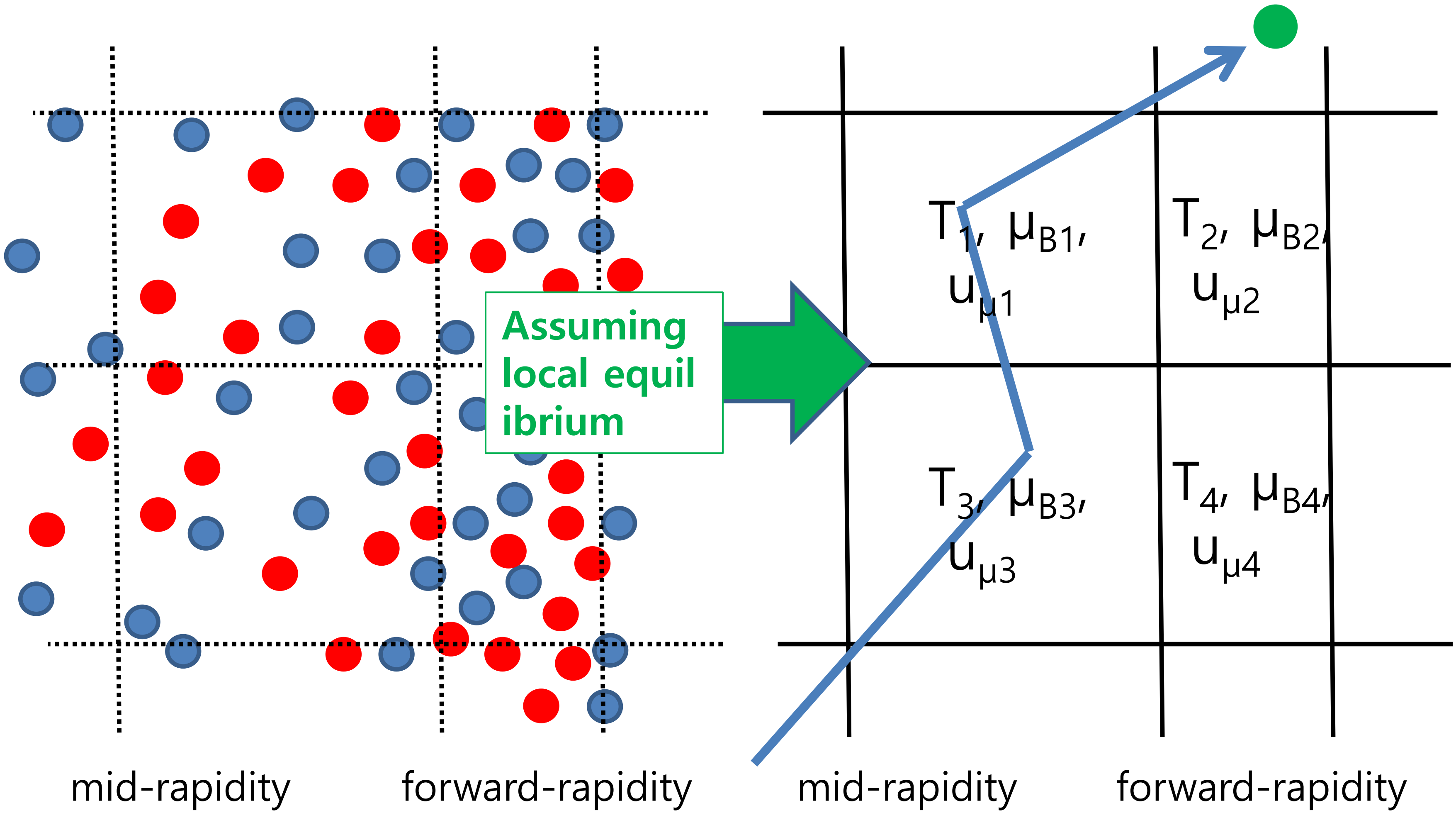
Good resolution at forward/backward-rapidity



coarse graining 1 (constant dz)

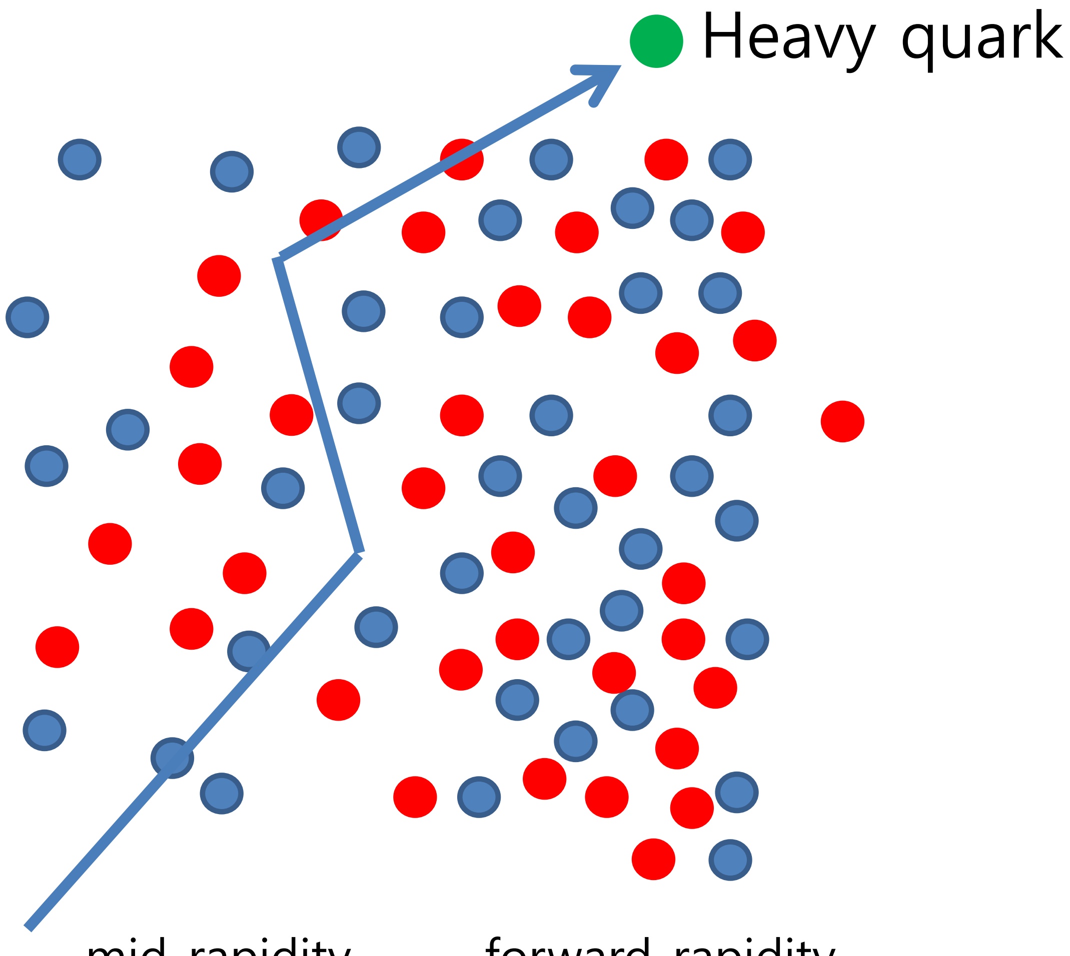


coarse graining 2 (constant dη)



Full Boltzmann equation **linearized Boltzmann equation**

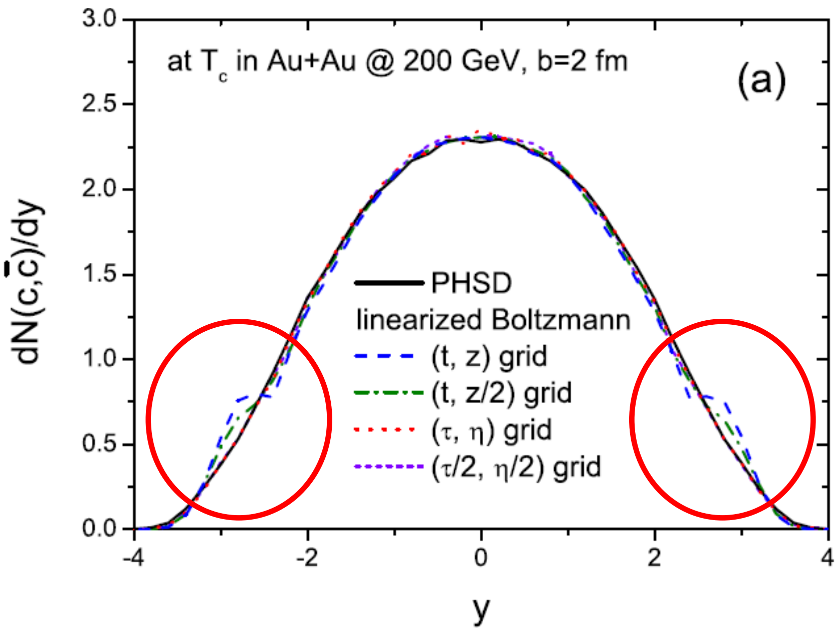
Original PHSD



Full Boltzmann equation

Comparison of PHSD & coarse grainings

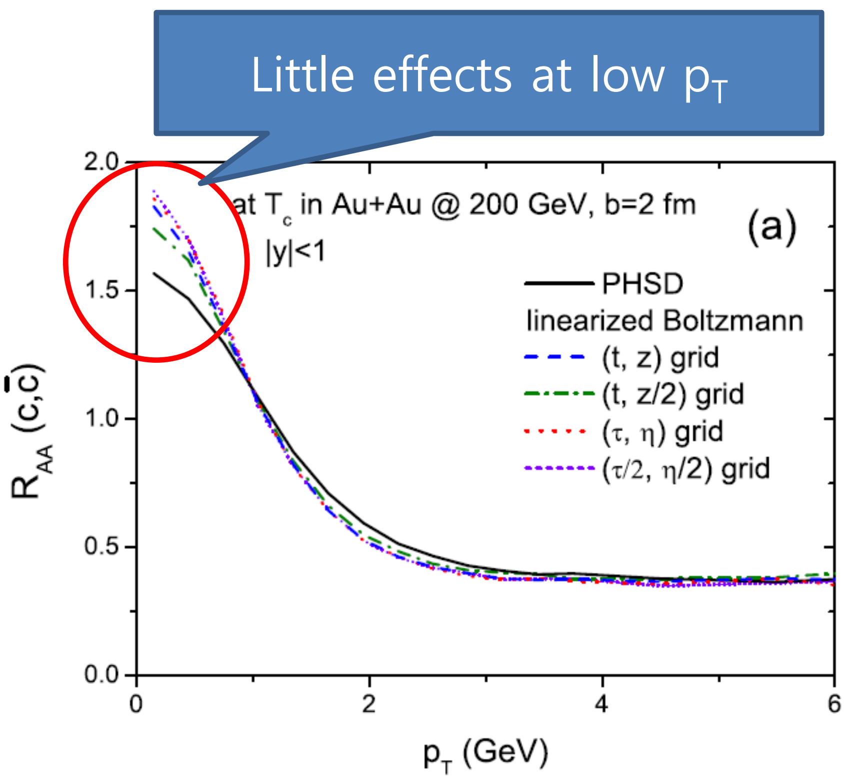
dN/dy of charm at Tc



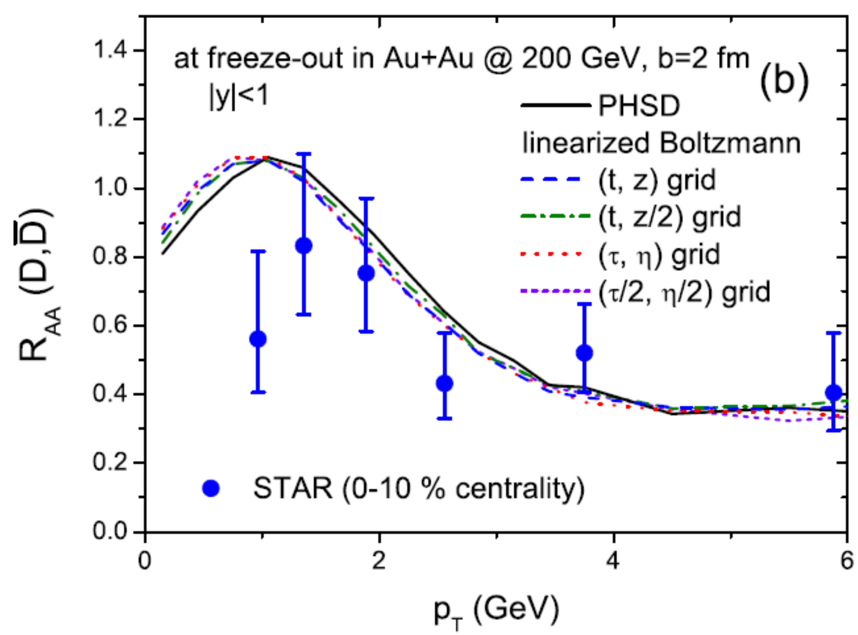
- At mid-y no significant differences in rapidity distributions between PHSD (fully nonequilibrium) and linearized Boltzmann (local equilibrium assumed) whether constant dz or constant dη
- Shoulders appear in the case of **constant dz**, which are artifacts from the bad resolution at forward/backward rapidities

Effects on R_{AA} at mid-rapidity

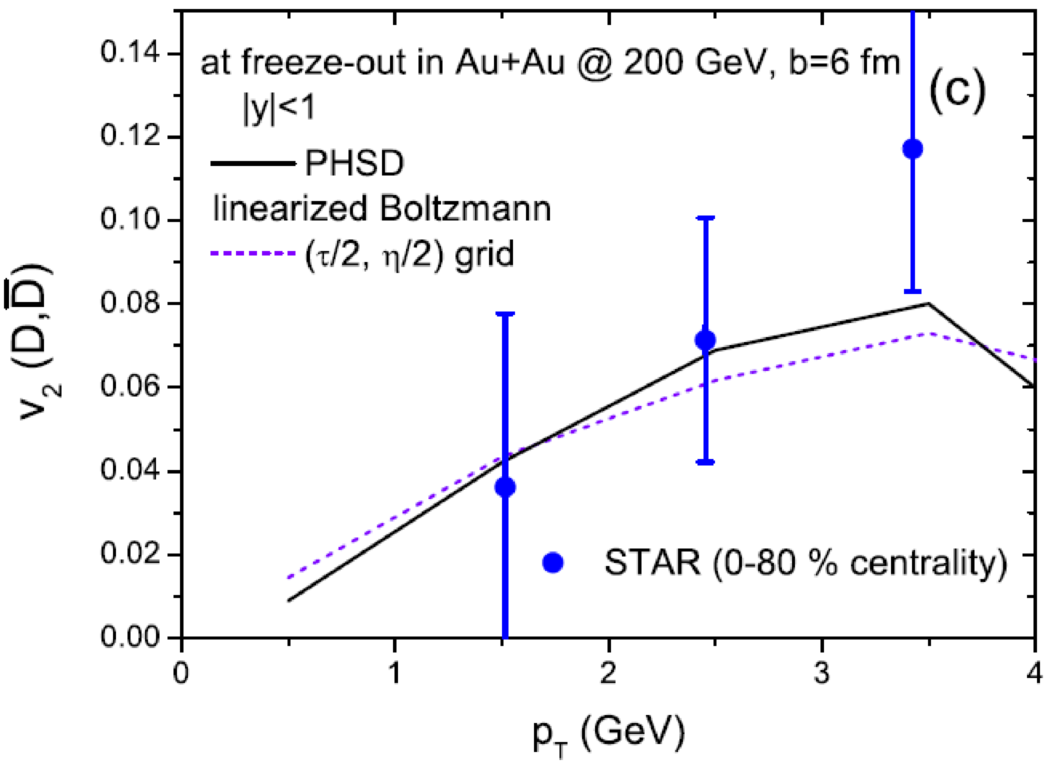
R_{AA} of charm at Tc



R_{AA} of D meson at freeze-out



Effects on v_2 at mid-rapidity

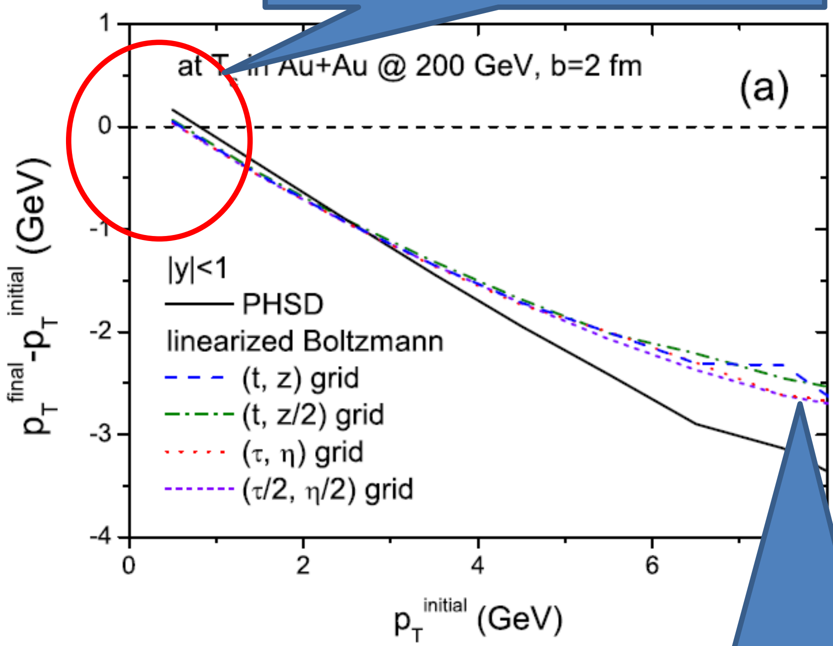


There seems no significant effects of non-equilibrium
But what happens behind?

p_T drag, diffusion

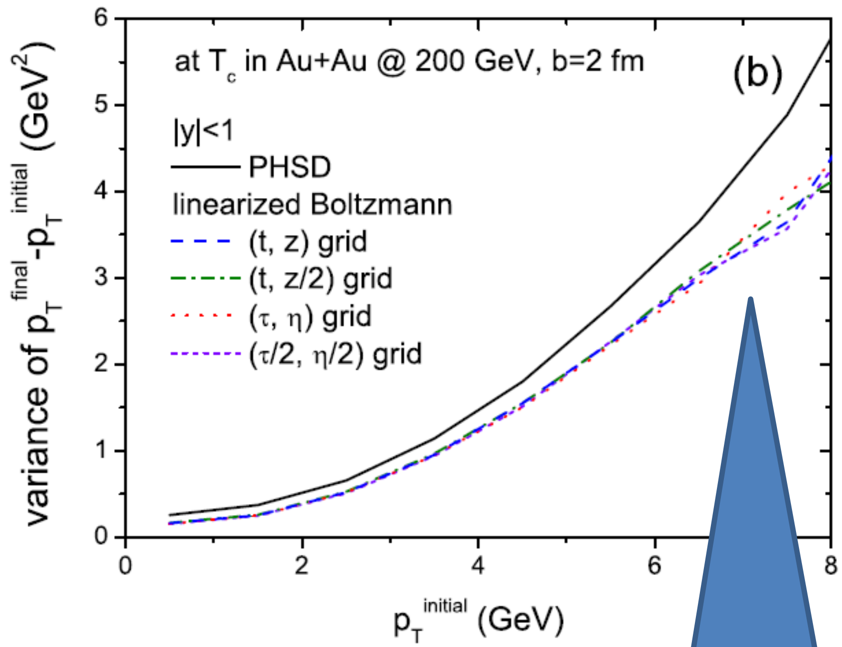
p_T drag

Positive due to transverse flows



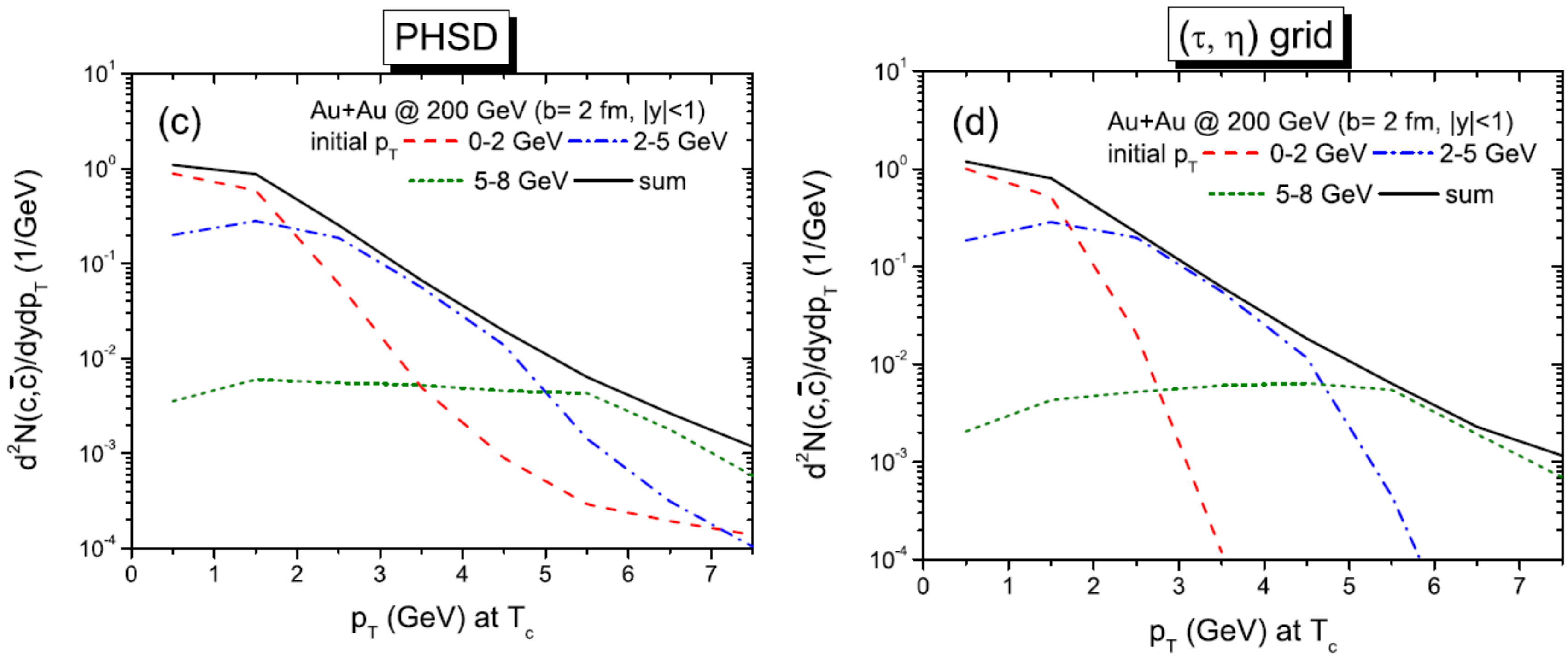
Less drag for linearized Boltzmann at high p_T

p_T diffusion



Less p_T diffusion for linearized Boltzmann

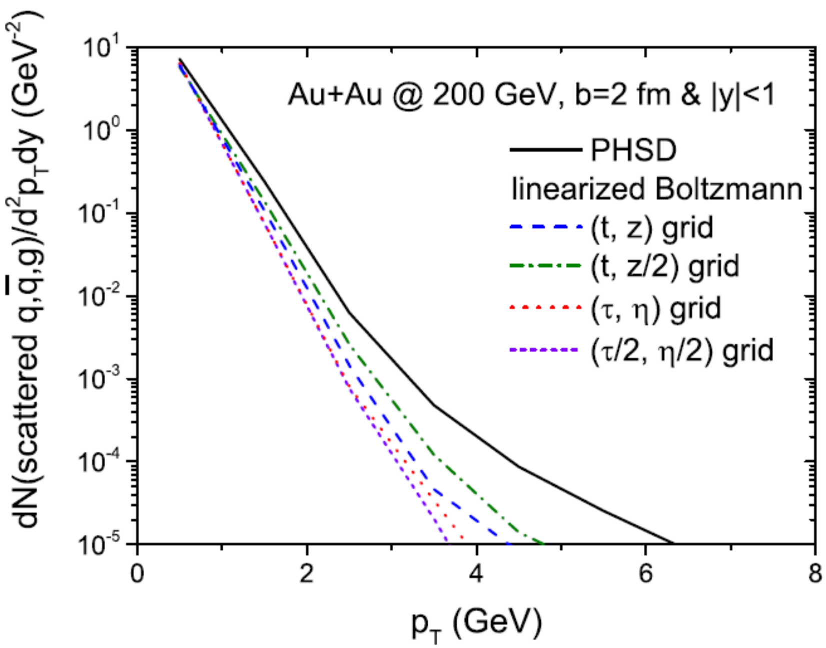
p_T distributions from each initial p_T



However, sums of them (black lines) are similar in PHSD and in linearized Boltzmann due to compensation between larger momentum drag and larger momentum diffusion in PHSD

One possible reason for the non-equilibrium effects

p_T spectra of partons scattered by charm

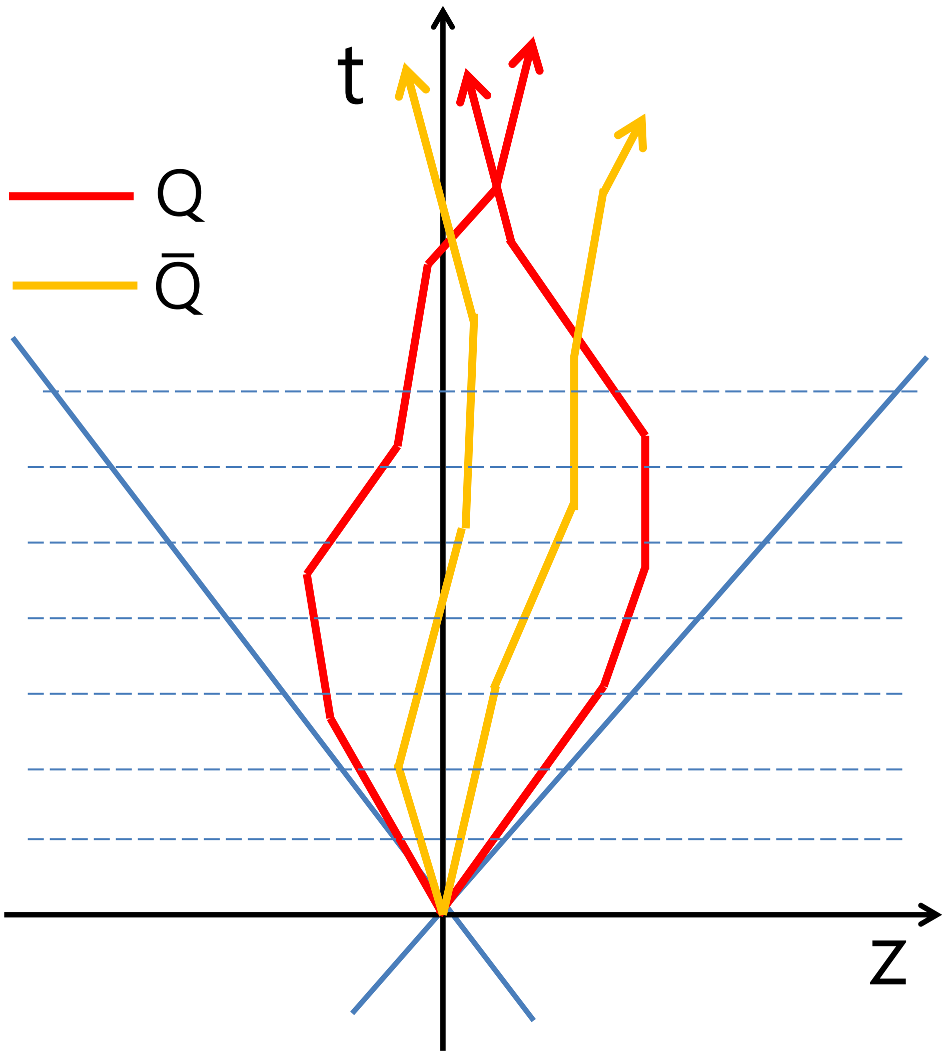


- P_T spectrum of partons scattered by charm is harder in PHSD, compared to that in the linearized Boltzmann, which partly explains the larger drag and diffusion of charm momentum
- However there are hidden & more complicated stories (non-equilibrium in momentum anisotropy, kinetic energy, quasiparticle mass, PRC 101, 044901)

Nonequilibrium effects will be more important at lower collision energies (high μ_B)

4. Quarkonium production/dissociation in PHSD

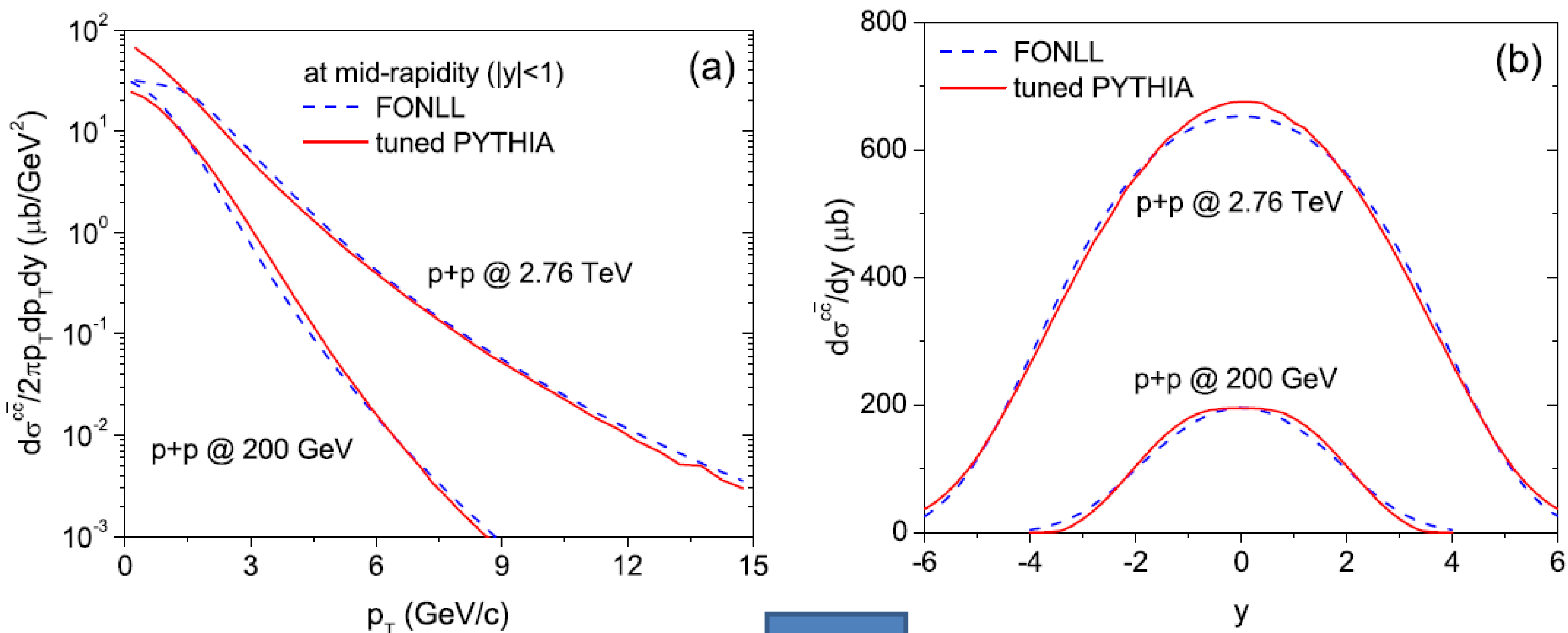
$$[W_{Q\overline{Q}}(t+\epsilon) - W_{Q\overline{Q}}(t-\epsilon)]$$



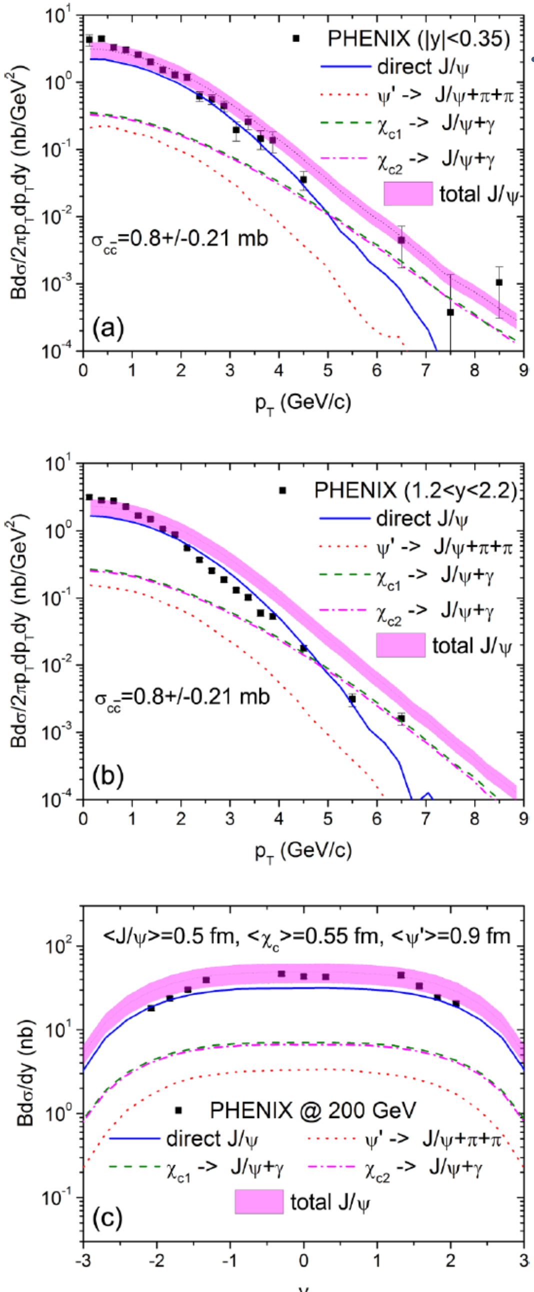
1. Each time step Wigner function is calculated for scattered Q with all existing Qbar and for scattered Qbar with all existing Q before scattering and after scattering.
2. The Wigner function before scattering is subtracted and that after scattering is added (The former is interpreted as the dissociation and the latter as the regeneration of quarkonium, respectively)
3. Considering the energy loss of heavy flavor in heavy-ion collisions, one can expect that Wigner function is enhanced at low pt and suppressed at high pt.

In p+p collisions
(only production without dissociation)

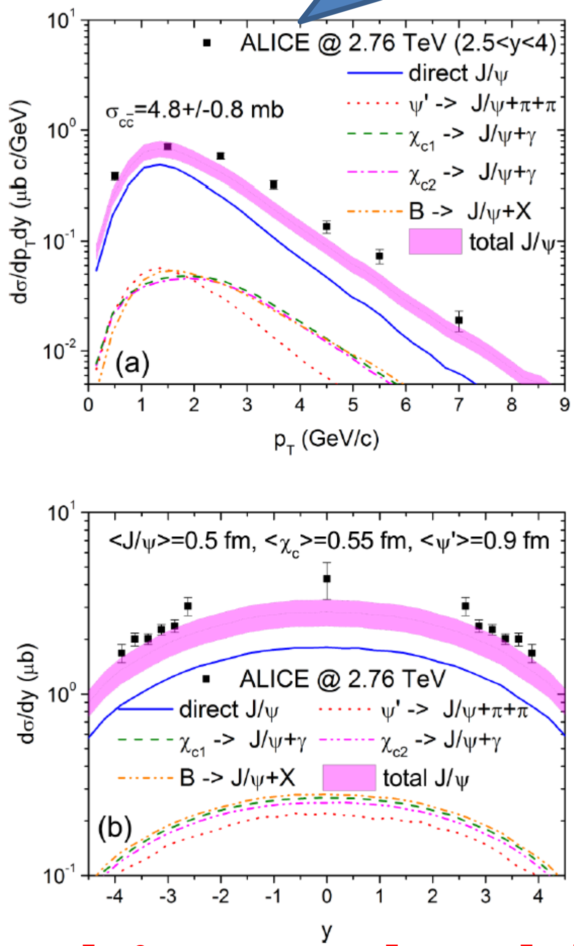
$$[W_{Q\overline{Q}}(t+\epsilon) - \cancel{W_{Q\overline{Q}}(t-\epsilon)}]$$



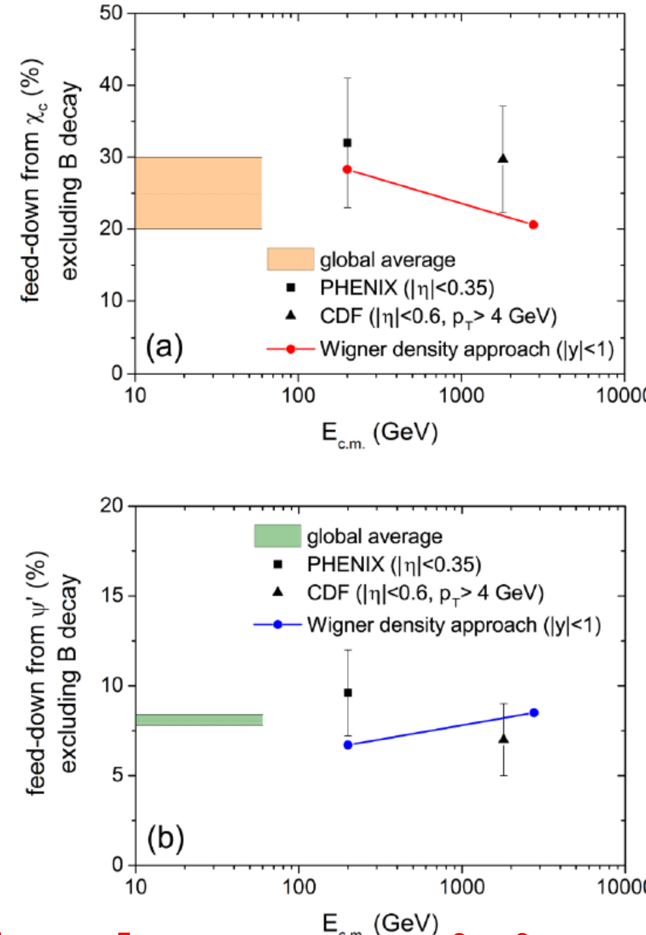
p+p @ RHIC



p+p @ LHC



Feed-down ratio from χ_c, ψ' to J/ψ



This method looks promising

5. Summary

- We have studied non-equilibrium effects on charm by comparing **original PHSD** and **linearized Boltzmann approach introduced in PHSD**
- Assuming local thermal equilibrium, momentum drag and diffusion of charm decrease
- However, at mid-y final spectra are similar because of the compensation between less drag and less diffusion of charm momentum in the linearized Boltzmann approach
- **Nonequilibrium effects will be more important at lower collision energies (high μ_B)**
- Quarkonium production/dissociation in HIC by using the Wigner density function looks promising

Grid size (dt, dz) tried in PHSD

Before heavy-ion collision

Before the two nuclei pass through each other, the grid size along the z direction and the time step are, respectively, given by

$$dz = \frac{1}{\gamma_{\rm cm}}, \quad dt = \frac{dz}{2}, \tag{1}$$

where

$$\gamma^{\rm cm} = \frac{1}{2}\left(\frac{E^{\rm projectile}}{M^{\rm projectile}} + \frac{E^{\rm target}}{M^{\rm target}}\right). \tag{2}$$

We note that dt is taken to be smaller than dz in order not to violate causality. In each nucleus rest frame dz in Eq. (1) is 1 fm, as dx and dy

After heavy-ion collision

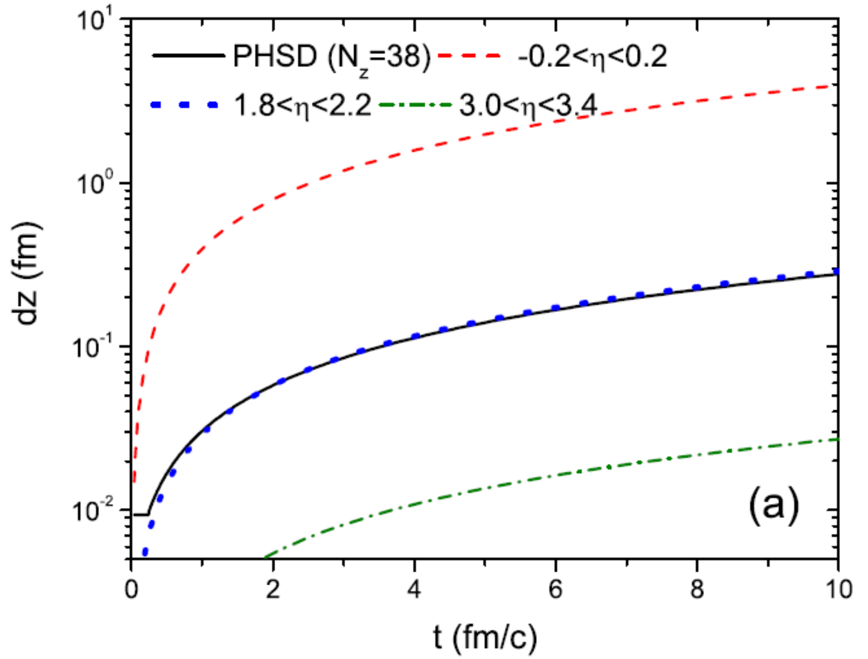
After the passage of the two nuclei, dz grows linearly with time as

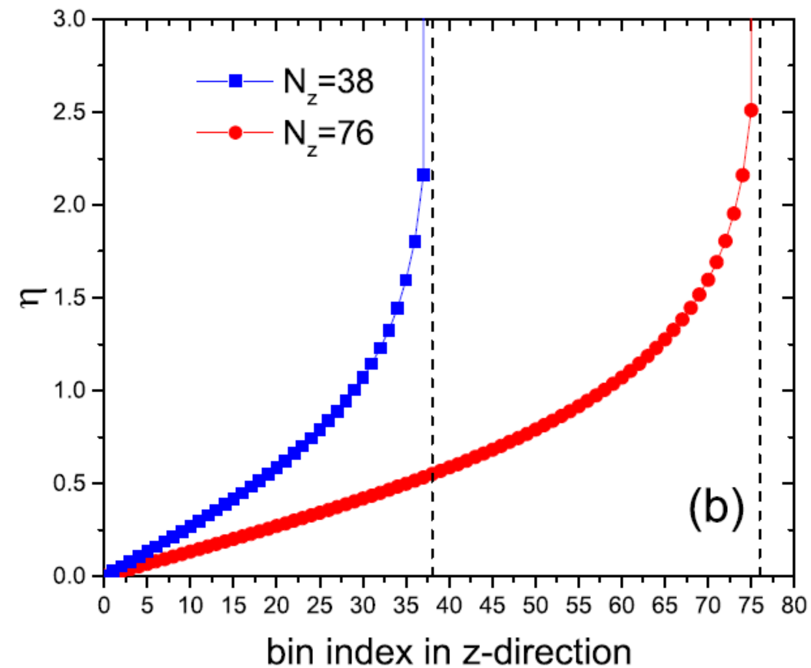
$$dz \approx \frac{1}{N_z}(t - t^*) + \frac{1}{\gamma_{\rm cm}}. \tag{3}$$

t^* is the approximate time which two nuclei need to pass each other and N_z is the number of grid cells in the $+(-)$ z direction. Equation (3) implies that the grid size in the $+(-)$ z direction corresponds to the elapsed time after t^*:

$$z_{\max} = N_z \times dz \approx t - t^*. \tag{4}$$

constant dz vs constant dη





In PHSD there are 38 cells in forward or backward direction, and each cell size is similar to dη=0.4 at η=2

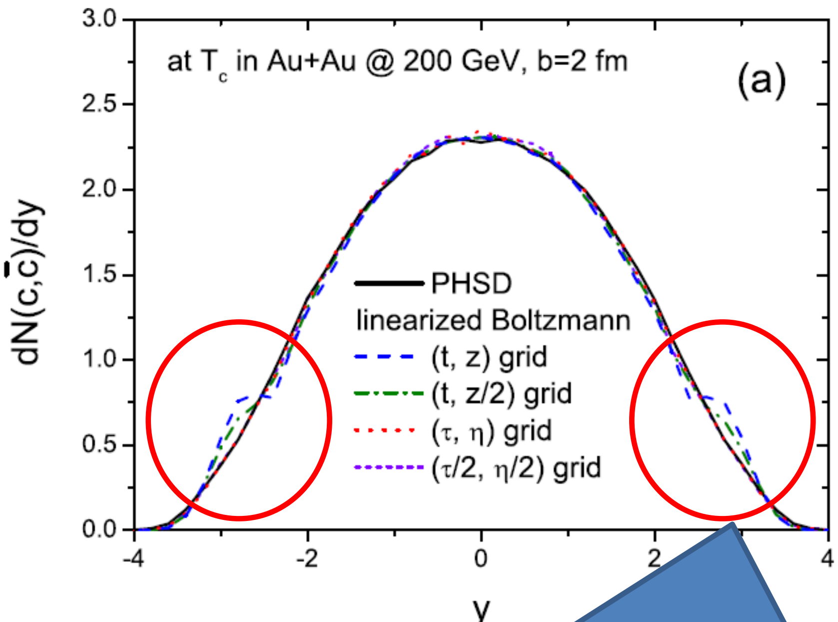
Constant dz has good resolution at mid-rapidity but poor resolution at forward/backward rapidities

For 38 longitudinal cells, the last cell covers 2.2<η<infinity.

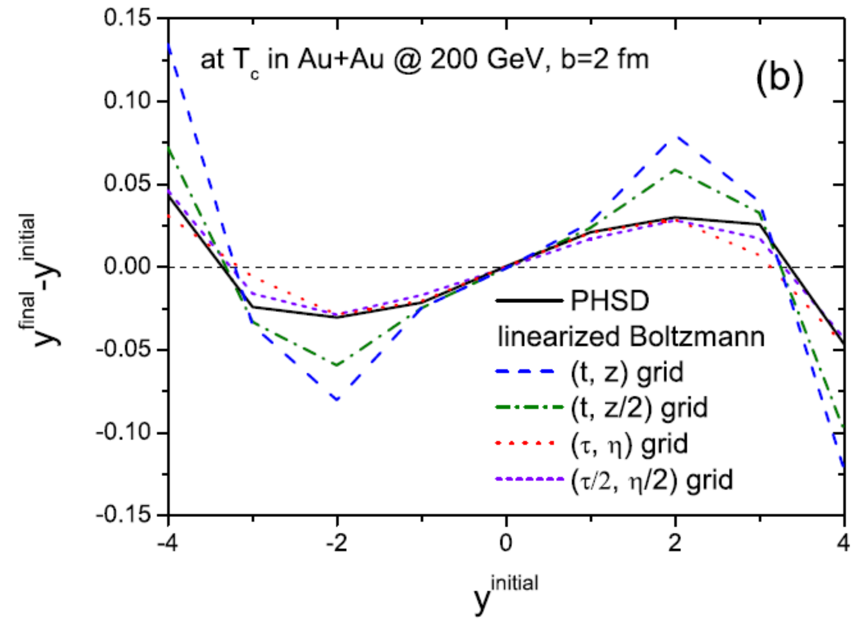
For 76 longitudinal cells, the last cell covers 2.5<η<infinity.

Comparison of coarse grainings

dN/dy of charm at Tc



Rapidity changes



Shoulders appear in the case of constant dz, which are the artifacts from the bad resolution at forward/backward rapidities