Nonperturbative Nature of QCD via Heavy Quark Dynamics in AA, pA and eA collisions

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Advancing the Understanding of Non-Perturbative QCD Using Energy Flows
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- Transport of heavy quarks in QGP

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- Transport of quarkonia in QGP

  - Open quantum system approach, Lindblad equation

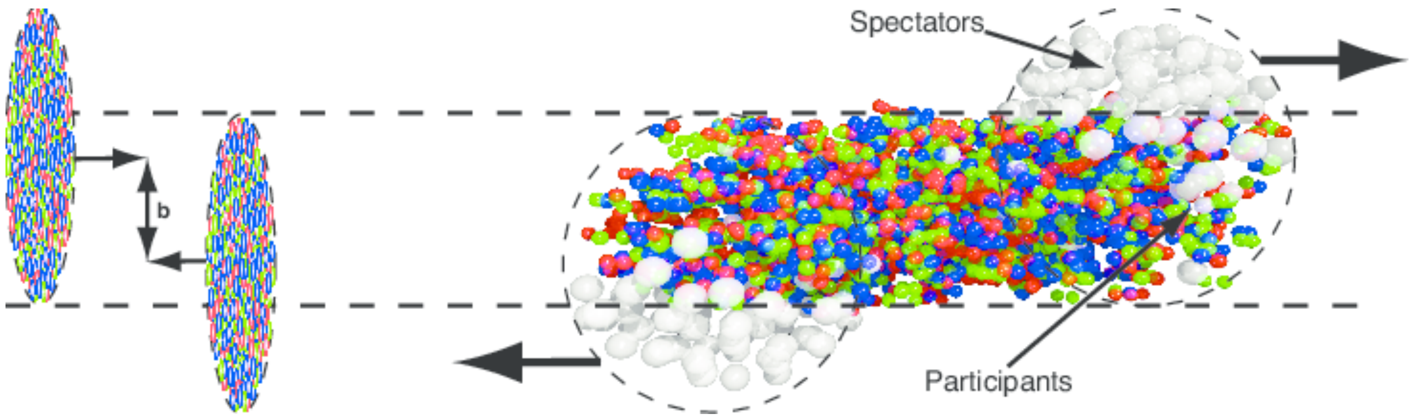
  - Novel transport coefficient v.s. heavy quark diffusion coefficient

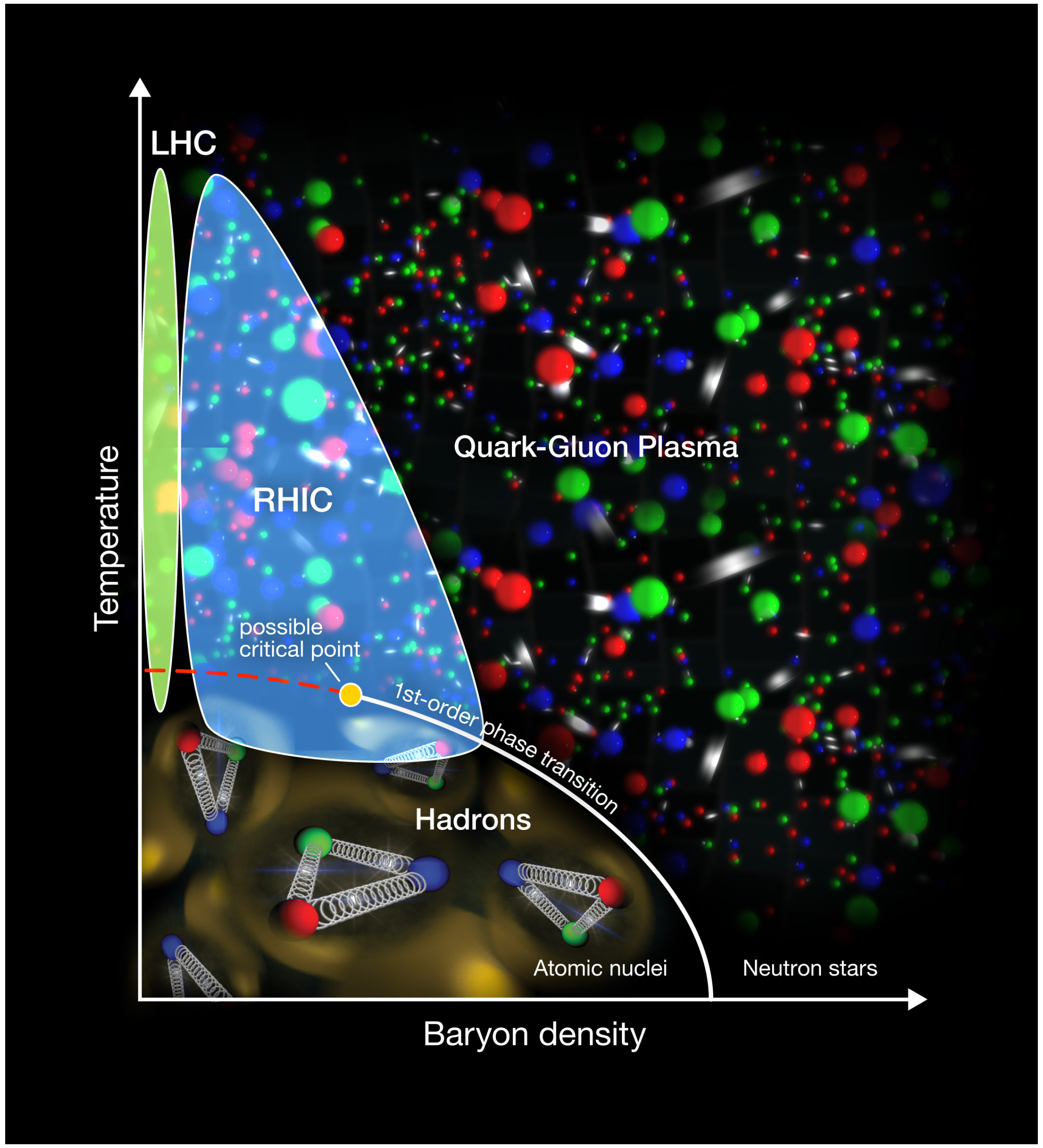
- Transport in cold nuclear matter in pA and eA collisions

Quark-Gluon Plasma and Heavy Ion Collision

- Asymptotic freedom —> deconfined phase of QCD matter expected at high temperature / density —> QGP

- Study QGP: heavy ion collision experiments at RHIC and LHC



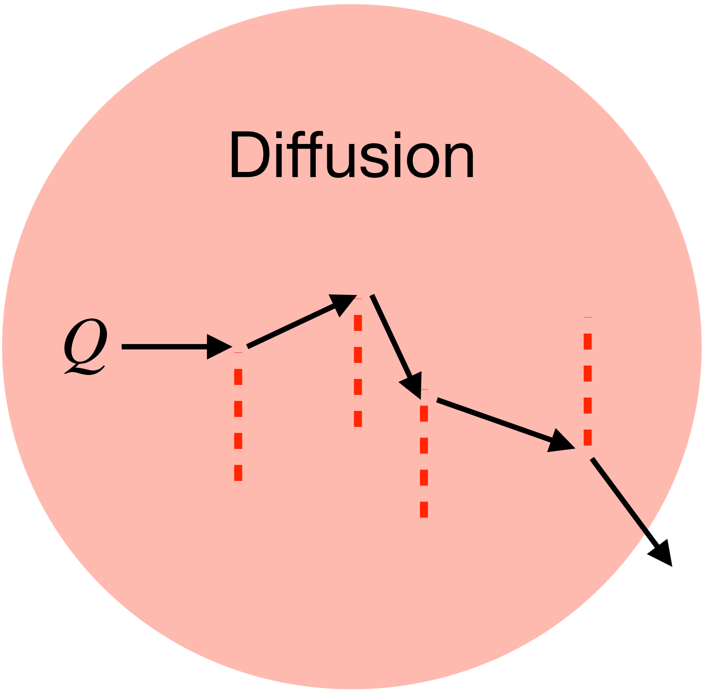


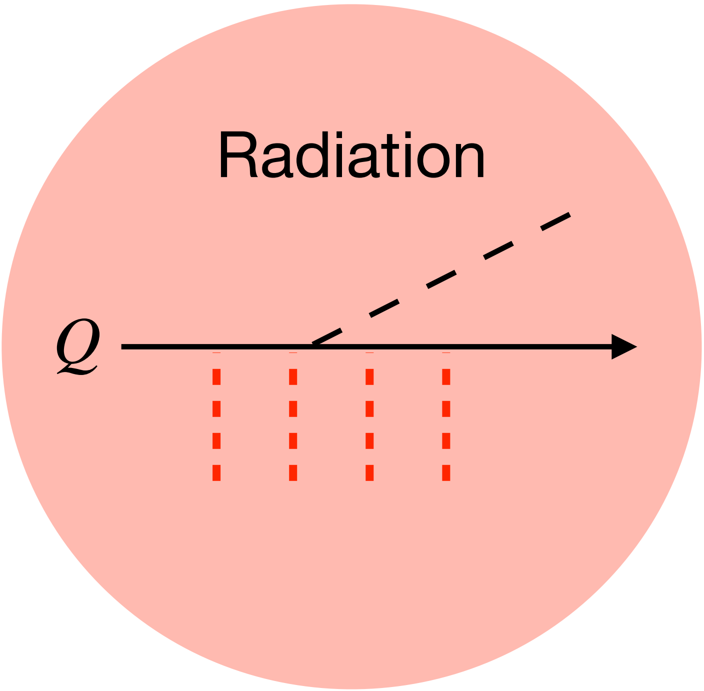
- QGP fireball: strongly coupled, lifetime ~10 fm/c, temperature 150—600 MeV

- Hard probes of QGP: large energy scale, heavy quarks, quarkonia and jets

I. Transport of Heavy Quarks in QGP

Heavy Quark Diffusion and Radiation





- **Modified Langevin equation**

$$\frac{dp_i}{dt} = -\eta_D p_i + \xi_i + f_i^{\mathrm{rad}} \longrightarrow$$ **Radiation, likely to be perturbative**

$$\langle \xi_i(t) \xi_j(0) \rangle = \kappa \delta_{ij} \delta(t)$$ **Fluctuation coefficient**

Drag coefficient

$$\eta_D = \frac{\kappa}{2MT}$$

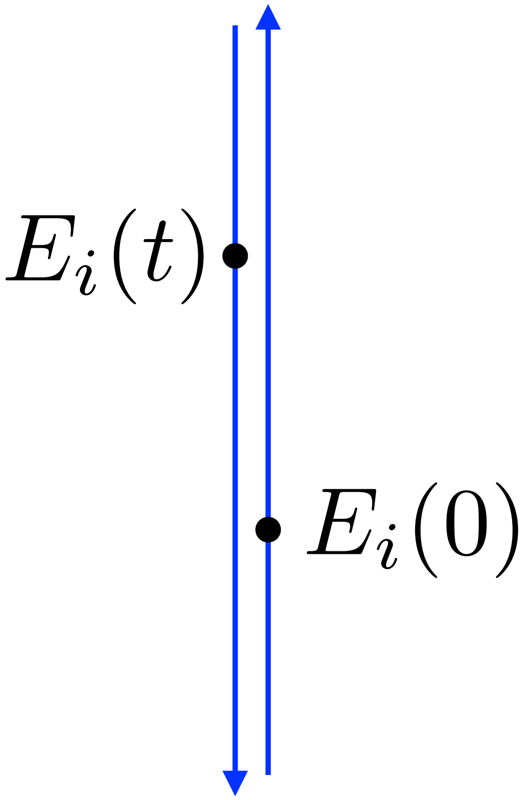
$$D_s = \frac{2T^2}{\kappa}$$ **Diffusion coefficient, likely to be nonperturbative**

Heavy Quark Diffusion Coefficient

$$\frac{dp_i}{dt} = -\eta_D p_i + \xi_i + f_i^{\mathrm{rad}} \qquad \langle \xi_i(t)\xi_j(0)\rangle = \kappa\delta_{ij}\delta(t)$$

- **Field operator definition of heavy quark diffusion coefficient**

$$\kappa = \int dt \left\langle \mathrm{Tr}_c\big(U(-\infty,0)E_i(t)U(t,0)E_i(0)U(0,-\infty)\big) \right\rangle_T$$

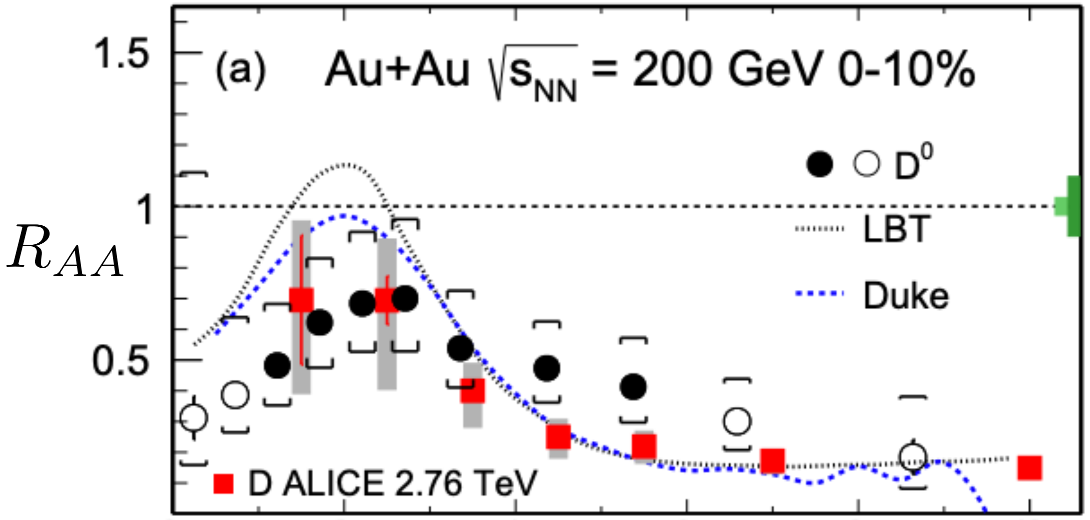


Gauge invariant object—>physical

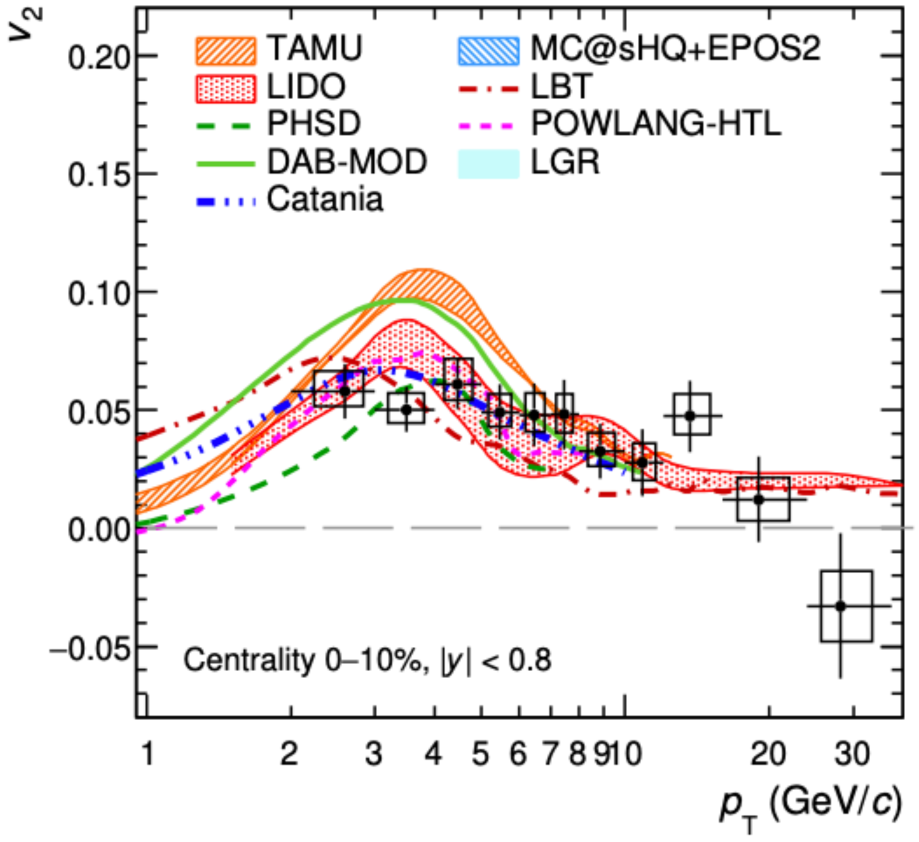
Zero frequency in Fourier transform

J. Casalderrey-Solana, D. Teaney, hep-ph/0605199

Calculation and Extraction of Diffusion Coefficient

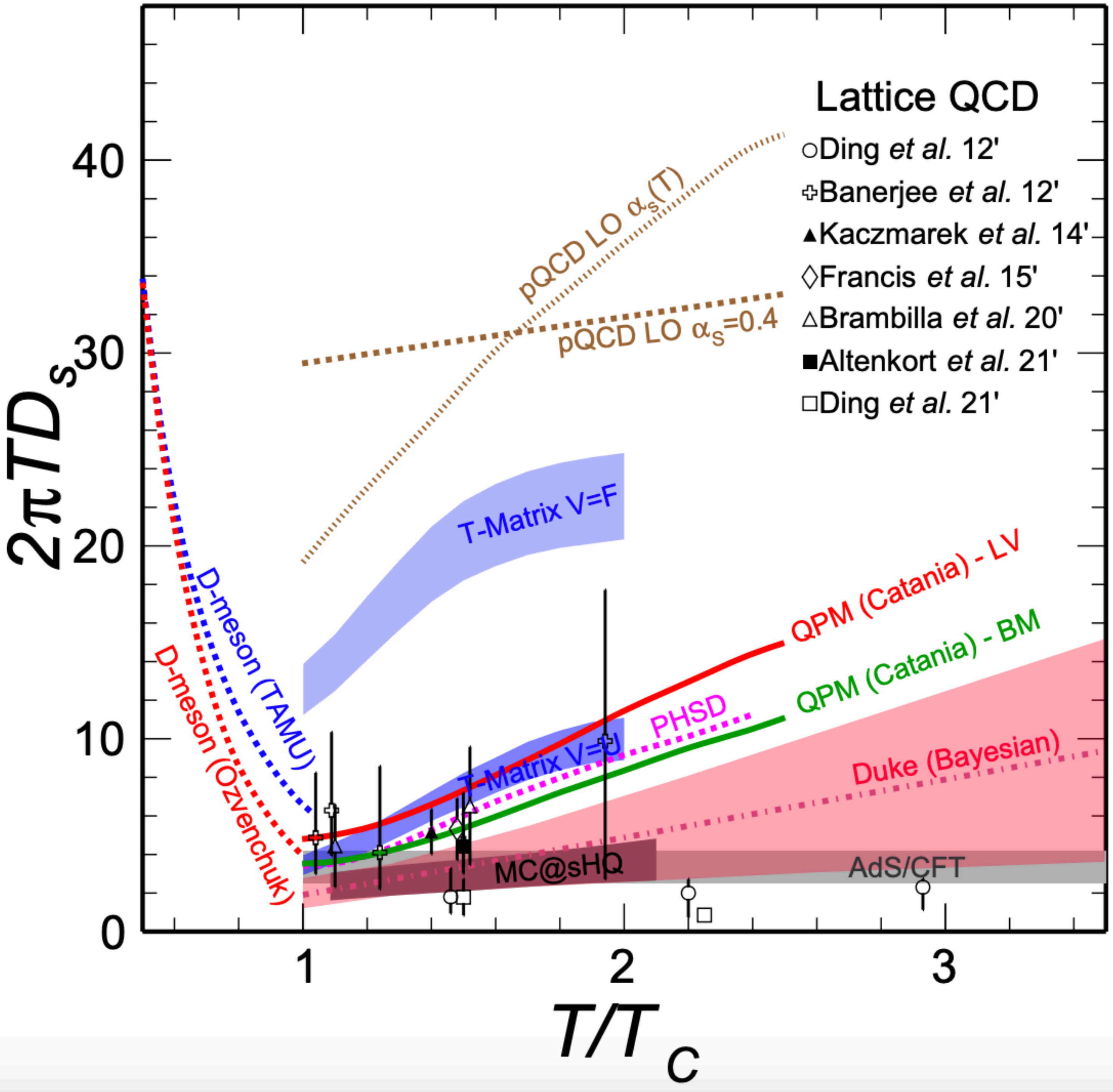


STAR, 1812.10224



ALICE, JHEP01(2022)174

L.Apolinário, Y.J.Lee, M.Winn, 2203.16352



Short Summary for Heavy Quark Dynamics

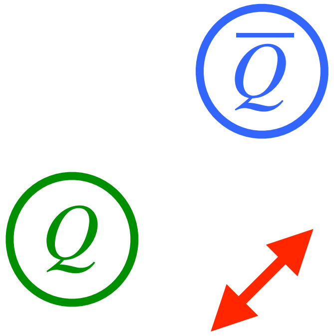
- Perturbative calculation of heavy quark diffusion coefficient probably not applicable; lattice calculations need more precision and go beyond quenched approximation

- Extraction from experimental data has model dependence, need more data, especially at 200 GeV, sPHENIX

II. Transport of Quarkonia in QGP

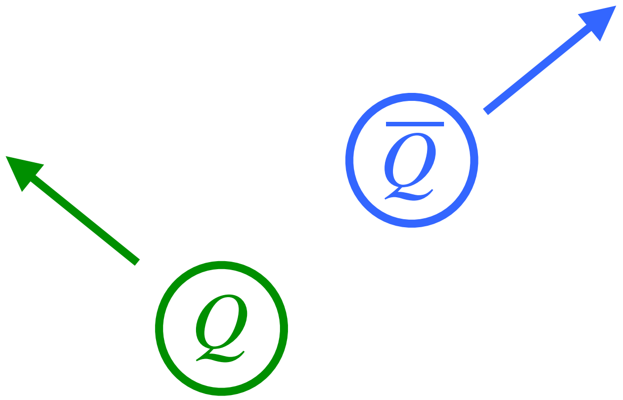
Analog of Langevin Equation for Quarkonia?

- **Quantum Brownian motion (high T)**



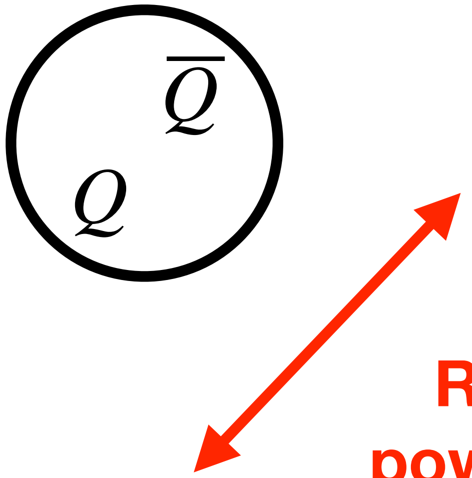
Resolving power of QGP

Diffusion of heavy Q pair



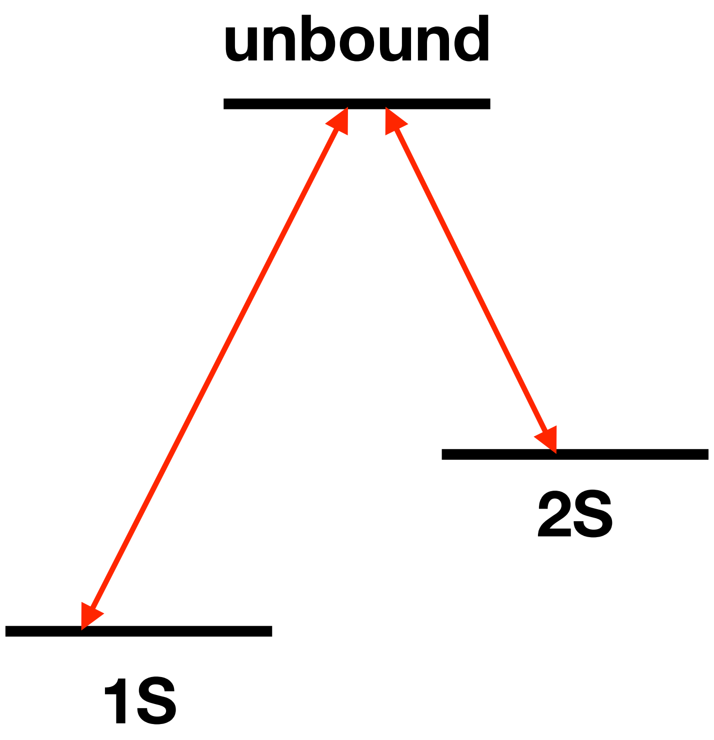
Wavefunction decoherence
—> dissociation

- **Quantum optical limit (low T)**

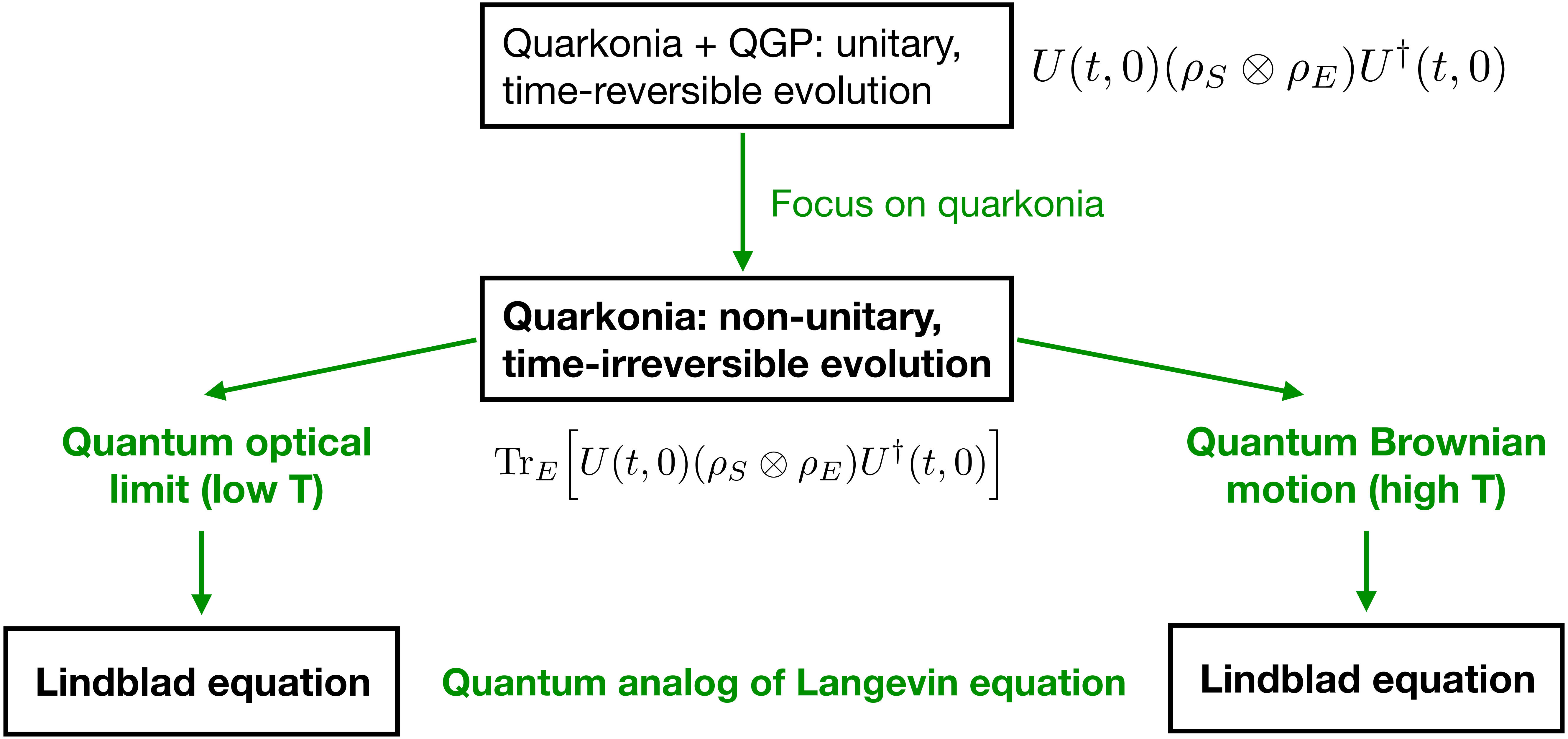


Resolving power of QGP

Transitions between levels



Lindblad Equation for Quarkonia



Quarkonia + QGP: unitary, time-reversible evolution

$U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)$

Focus on quarkonia

Quarkonia: non-unitary, time-irreversible evolution

$\mathrm{Tr}_E\Big[U(t,0)(\rho_S \otimes \rho_E)U^\dagger(t,0)\Big]$

Quantum optical limit (low T)

Quantum Brownian motion (high T)

Lindblad equation

Quantum analog of Langevin equation

Lindblad equation

$$\frac{d\rho_S(t)}{dt} = -i\big[H_{S,\mathrm{eff}}, \rho_S(t)\big] + \sum_n D_n\Big(L_n\rho_S(t)L_n^\dagger - \frac{1}{2}\{L_n^\dagger L_n, \rho_S(t)\}\Big)$$

Review: XY, 2102.01736

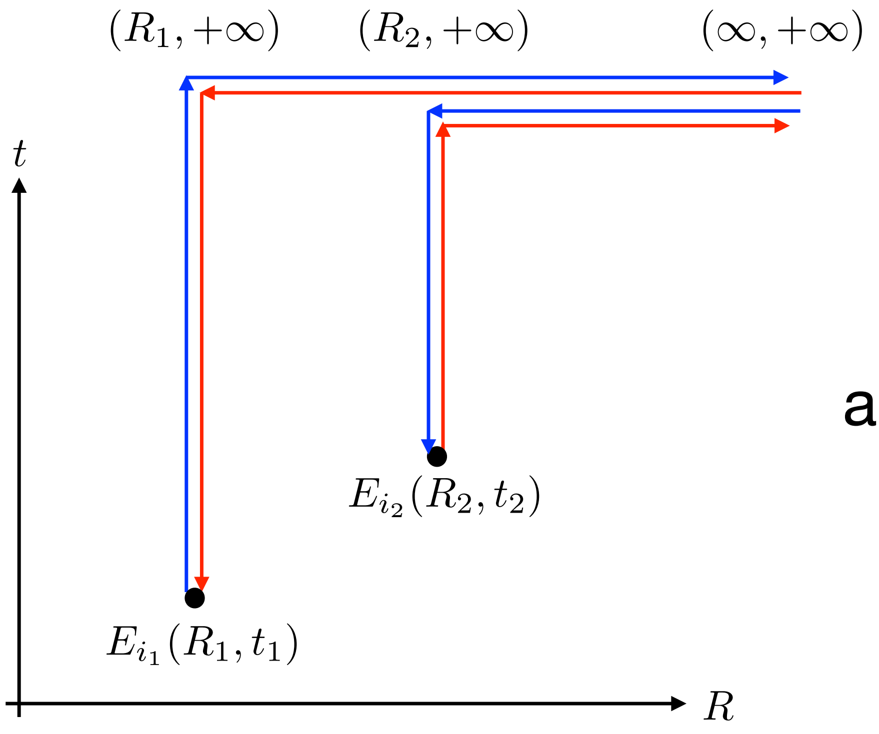
Transport Properties for Quarkonium

- **“D” term in Lindblad equation**

Gauge invariant

$$[g_E^{++}]^{>}_{ji}(y,x) \equiv \Big\langle \big[E_j(y)\mathcal{W}_{[(y^0,\boldsymbol{y}),(+\infty,\boldsymbol{y})]}\mathcal{W}_{[(+\infty,\boldsymbol{y}),(+\infty,\boldsymbol{\infty})]}\big]^a \times \big[\mathcal{W}_{[(+\infty,\boldsymbol{\infty}),(+\infty,\boldsymbol{x})]}\mathcal{W}_{[(+\infty,\boldsymbol{x}),(x^0,\boldsymbol{x})]}E_i(x)\big]^a \Big\rangle_T$$

$$[g_E^{--}]^{>}_{ji}(y,x) \equiv \Big\langle \big[\mathcal{W}_{[(-\infty,\boldsymbol{\infty}),(-\infty,\boldsymbol{y})]}\mathcal{W}_{[(-\infty,\boldsymbol{y}),(y^0,\boldsymbol{y})]}E_j(y)\big]^a \times \big[E_i(x)\mathcal{W}_{[(x^0,\boldsymbol{x}),(-\infty,\boldsymbol{x})]}\mathcal{W}_{[(-\infty,\boldsymbol{x}),(-\infty,\boldsymbol{\infty})]}\big]^a \Big\rangle_T$$



PT transformation, assume state invariant

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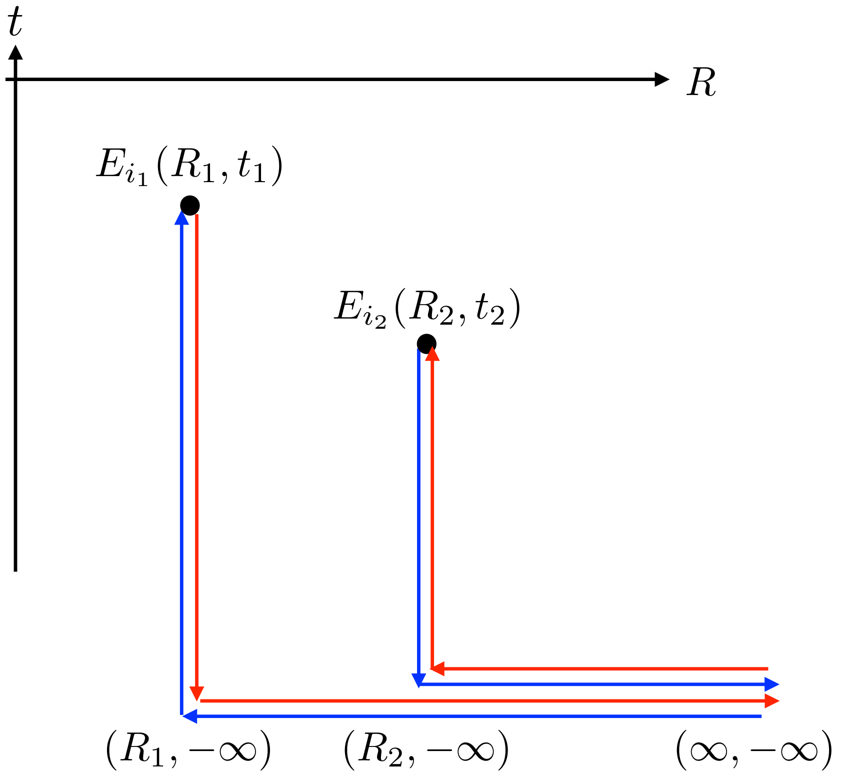
KMS relation



Dissociation: final-state interaction

Recombination: initial-state interaction

- **After Fourier transform**

Zero frequency in quantum Brownian motion limit (transport coefficient)

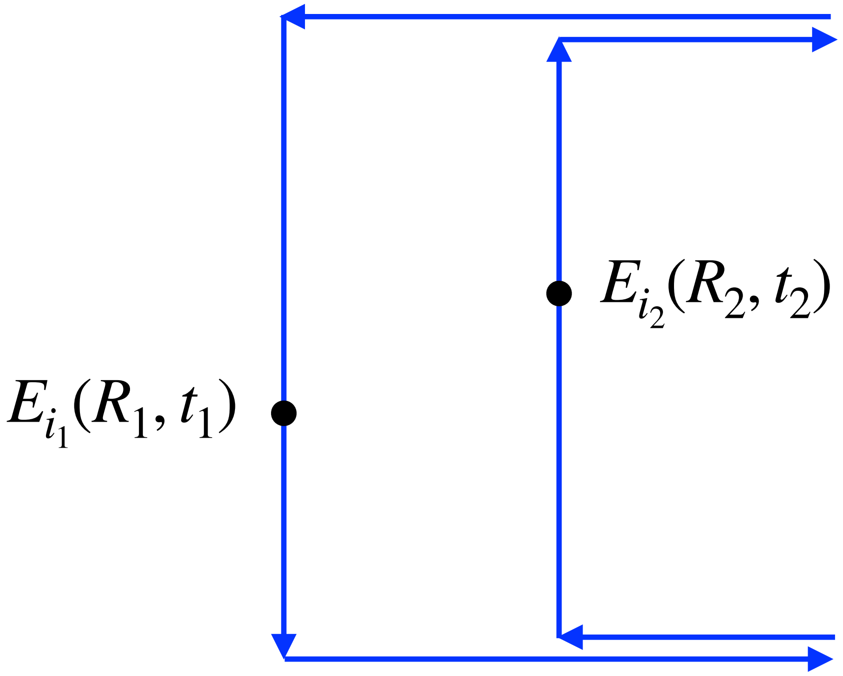
Finite frequency in quantum optical limit

XY, T.Mehen, 2009.02408

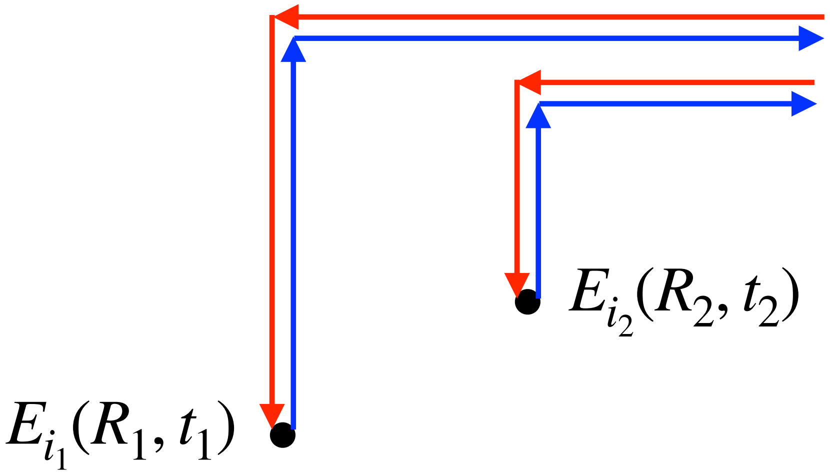
T.Binder, K.Mukaida, B.S.Hitschfeld, XY, 2107.03945

Chromoelectric Correlators for HQ and Quarkonia

Single heavy quark



Heavy quark antiquark pair



- At NLO: temperature-dependent parts agree but vacuum parts differ by a constant

Y.Burnier, M.Laine, J.Langelage, L.Mether, 1006.0867
T.Binder, K.Mukaida, B.S.Hitschfeld, XY, 2107.03945

- In temporal axial gauge, they are the same! Axial gauge cannot be applied in the presence of infinitely long Wilson lines

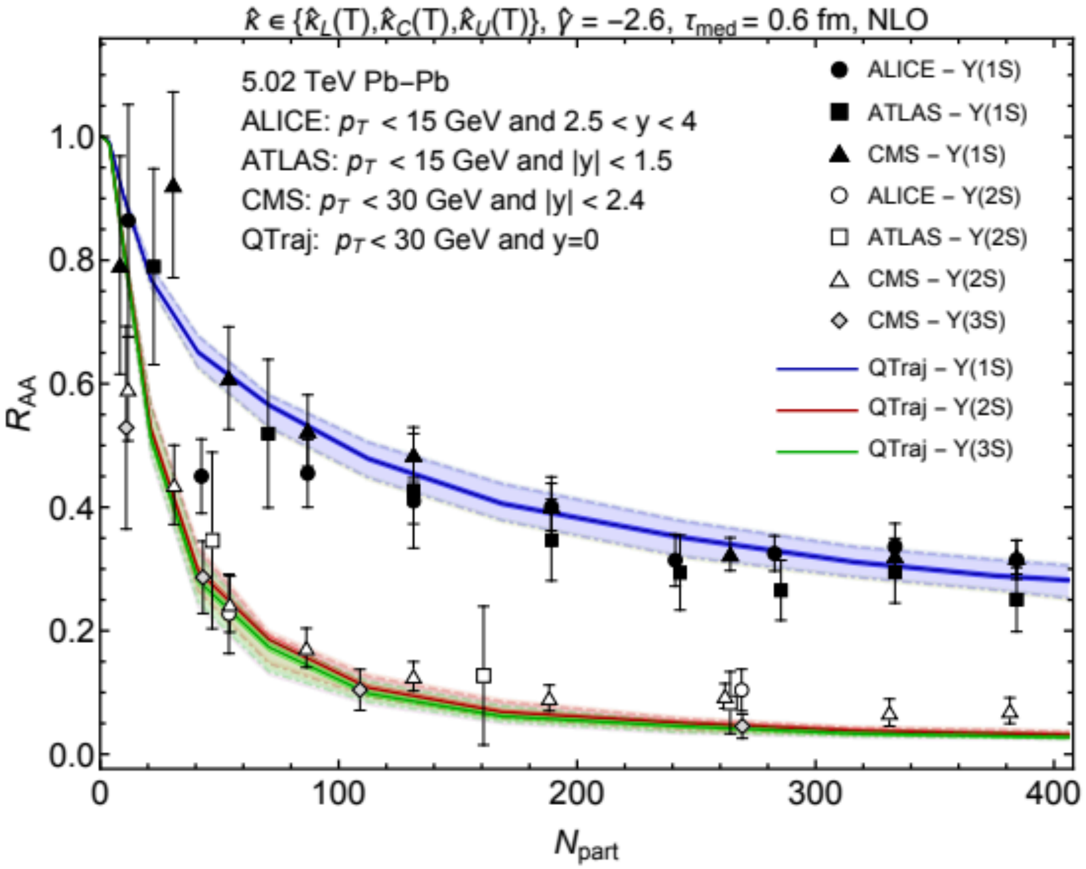
B.S.Hitschfeld, XY, 2205.04477

- Currently no NNLO calculations
- Currently no nonperturbative calculations for quarkonium correlator
- Some phenomenological studies exist by using quarkonium correlator

Phenomenology Using Quarkonium Correlators

Quantum Brownian motion

N.Brambilla, et al, 2205.10289

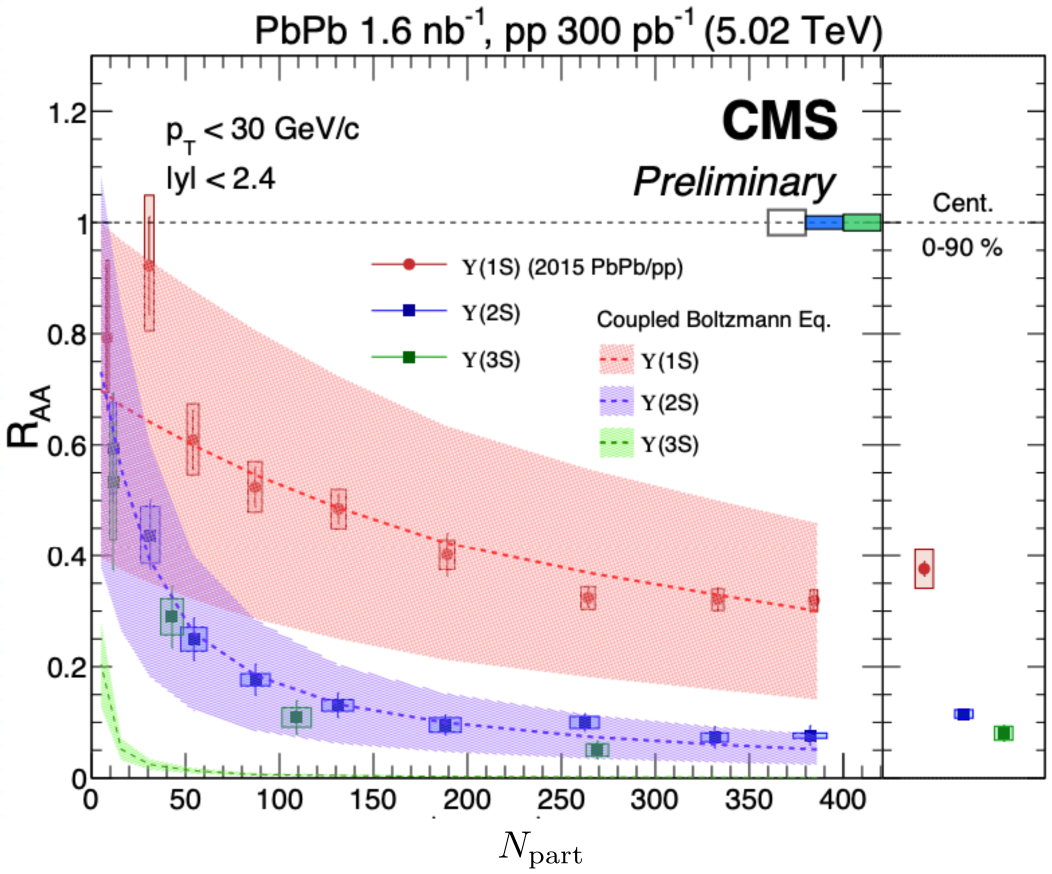


No nPDF effect

Use heavy quark correlator (nonperturbative)

Quantum optical limit —> semiclassical Botlzmann equation

XY, W.Ke, Y,Xu, S.A.Bass,B.Mueller, 2004.06746

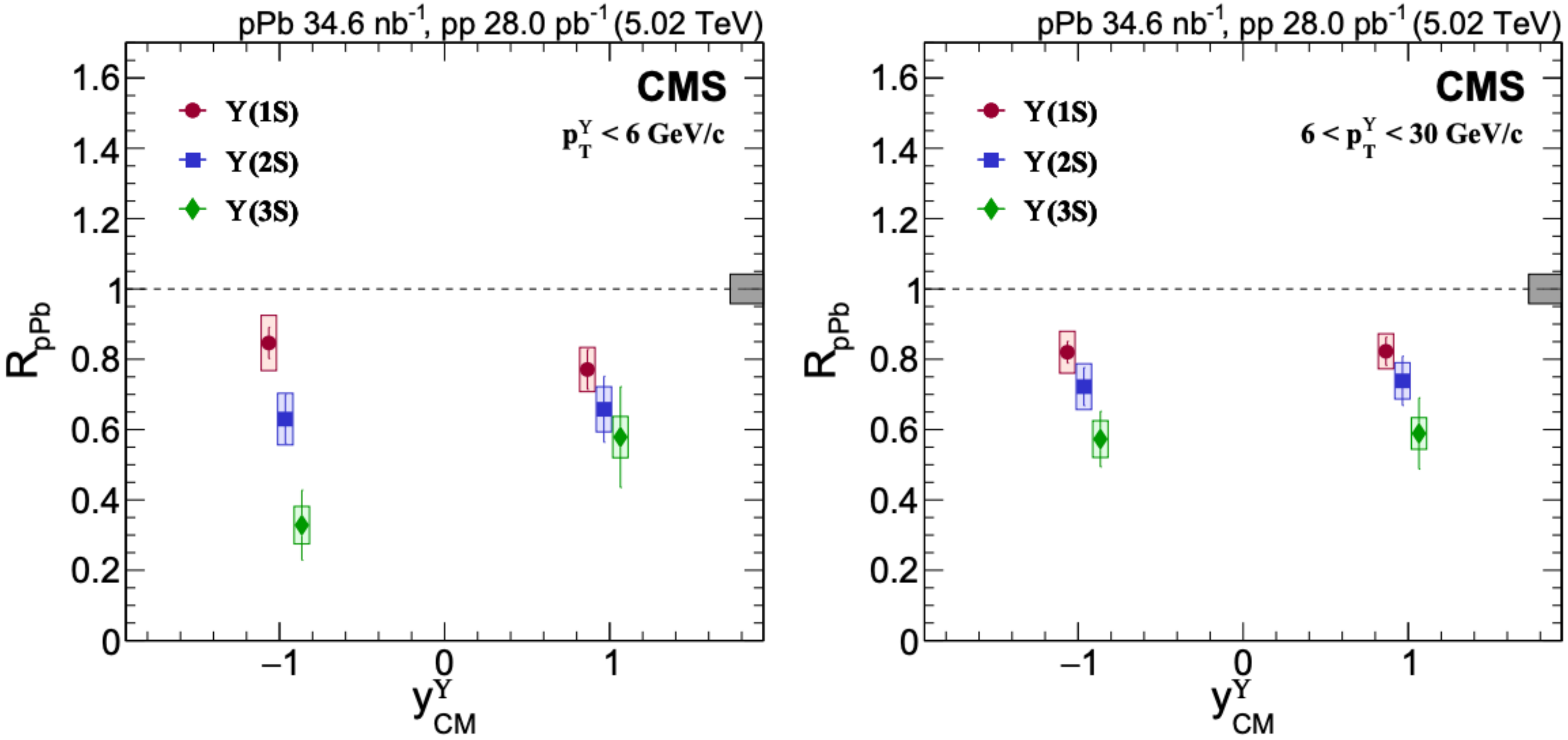


The nPDF uncertainty dominates
—> use ratios of RAA

Use quarkonium correlator (perturbative)

Transport in pA and eA collisions

- **Experimental evidence of final-state effects in pA collisions**



Lead-going direction (negative rapidity) exhibits sequential pattern

Extract transport properties (chromoelectric correlators) of cold nuclear matter?

- **Further information from eA collisions?**

Summary

- Transport properties of heavy quarks and quarkonia governed by gauge invariant chromoelectric field correlators, they are different in terms of Wilson lines

- Need nonperturbative calculation of the chromoelectric field correlator for quarkonium (zero frequency)

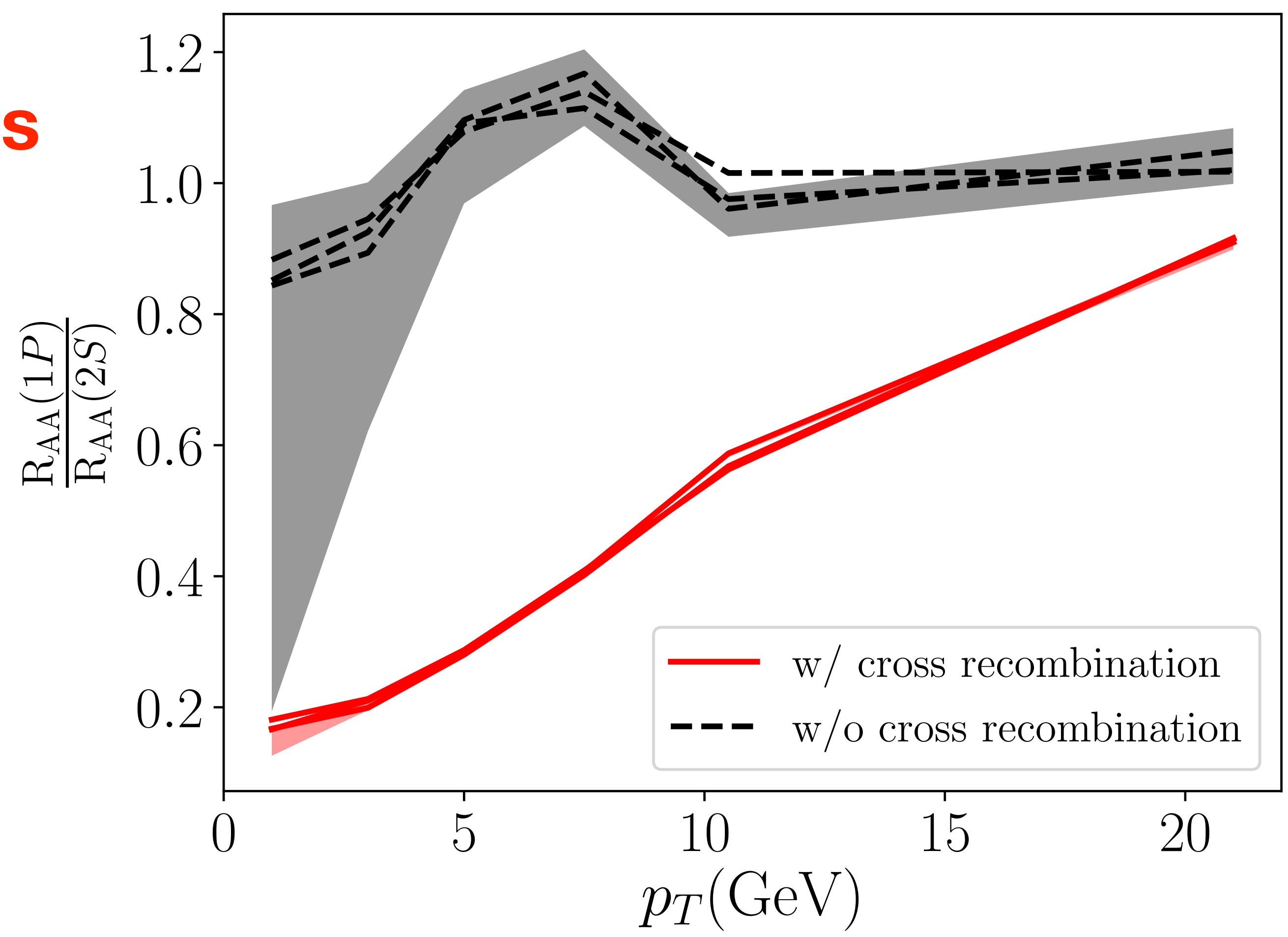
- Perform extraction from experimental data, unique opportunity at RHIC collision energy —> learn finite frequency of the correlator

- Transport properties in cold nuclear matter

Backup: Experimental Test of Correlated Recombination

XY, W.Ke, Y,Xu, S.A.Bass,B.Mueller, 2004.06746

Correlated recombination predicts 1P more suppressed than 2S



Traditional sequential suppression argument based on hierarchy of binding energy or size —> R_{AA}(2S) ~ R_{AA}(1P), since their binding energies are close

Correlated recombination rates (2S—>1P) ~ (1P—>2S) because of similar binding energy, but primordial production cross section

$$\frac{\sigma_{1P}}{\sigma_{2S}} \sim 4.5$$