Transport approach in pA and AA collisions

From history to the future

Quarkonia As Tools 2022

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CRC-TR 211
Strong-interaction matter under extreme conditions

Quarkonia and QGP formation

Quark-gluon plasma (QGP) formation

- Jpsi suppression in Heavy-ion collisions (HICs): Matsui & Satz 1986

Volume 178, number 4 PHYSICS LETTERS B 9 October 1986

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

T. MATSUI
Center for Theoretical Physics, Laboratory for Nuclear Science, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

and

H. SATZ
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Received 17 July 1986

If high energy heavy ion collisions lead to the formation of a hot quark–gluon plasma, then colour screening prevents $c\bar{c}$ binding in the deconfined interior of the interaction region. To study this effect, the temperature dependence of the screening radius, as obtained from lattice QCD, is compared with the J/ψ radius calculated in charmonium models. The feasibility to detect this effect clearly in the dilepton mass spectrum is examined. It is concluded that J/ψ suppression in nuclear collisions should provide an unambiguous signature of quark–gluon plasma formation.

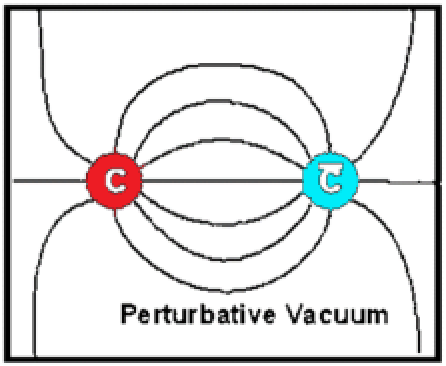
Matsui, Satz, PLB178(1986)486

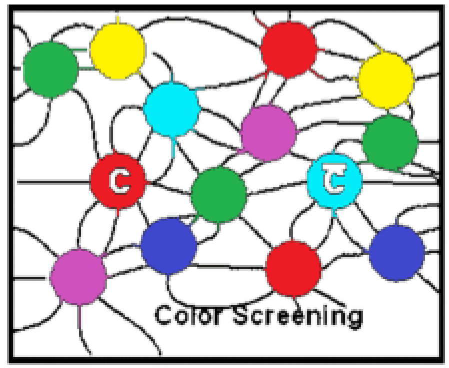
3000+ citations

Quarkonia in medium

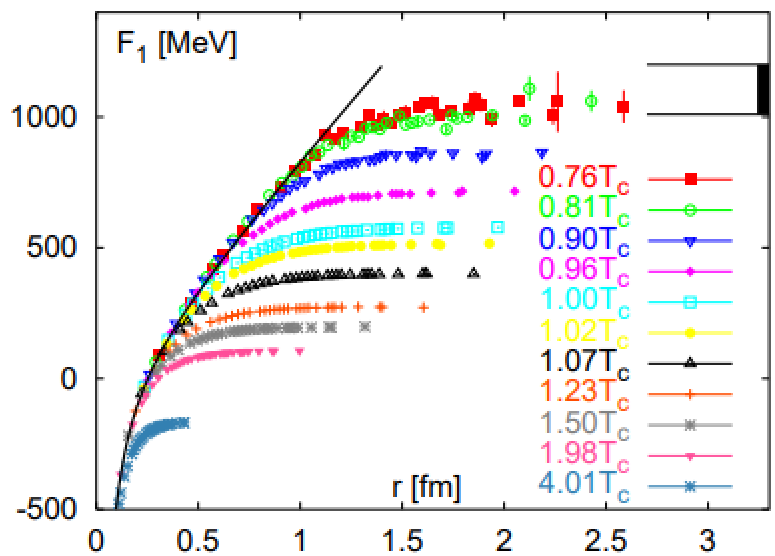
In medium color screening for heavy quark-antiquark pairs

- Color screening

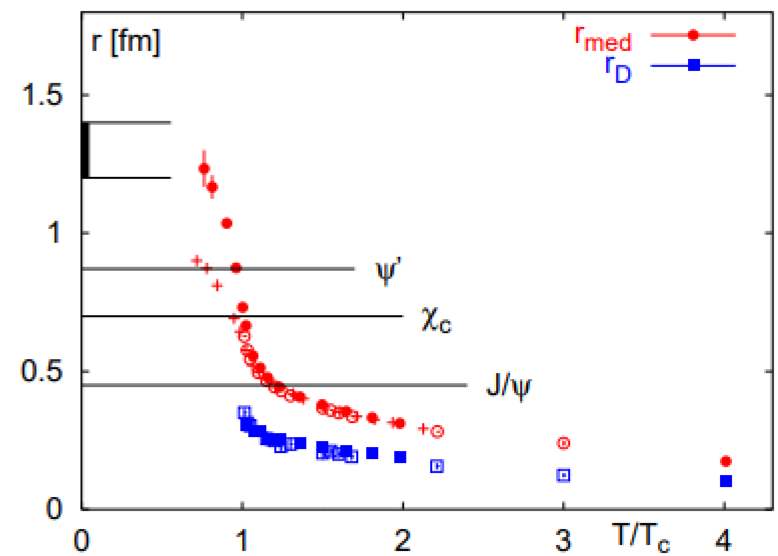




- In-medium heavy quark free energy:



- Sequential melting of charmonia



Kaczmarek, Zantow, Lattice 2005

Quarkonia in medium

In medium potential for heavy quark-antiquark pairs

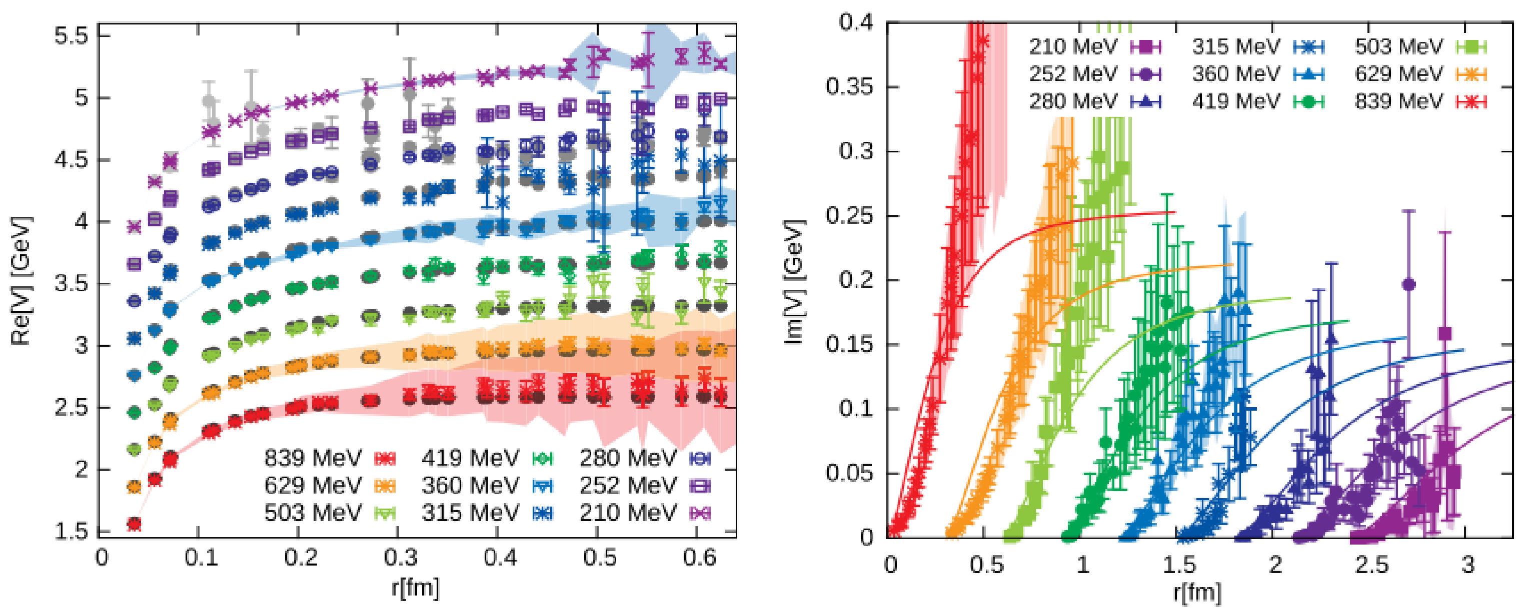
- Real (Color screening) & Imaginary (Landau damping):

$$V(r) = -\frac{g^2 C_F}{4\pi}\left[m_D + \frac{e^{-m_D r}}{r}\right] - \frac{i g^2 T C_F}{4\pi}\phi(m_D r)$$

$$\phi(x) = 2\int_0^\infty \frac{z dz}{(z^2+1)^2}\left[1 - \frac{\sin(zx)}{zx}\right]$$

Laine, Philipsen, Romatschke, Tassler, JHEP03(2007)054

- Real and Imaginary potential from lattice calculation



lQCD: Burnier, Kaczmarek, Rothkopf, PRL114(2015)082001

What do we need for a model?

What do Real and Imaginary potential tell us?

- Real part (Hermitian): Internal transition between states (different binding energy)
- Imaginary part (non-Hermitian): Breakup of states (suppression of total yield)

Why do we need transport model?

- Quarkonia binding energy E_B > $T_{typical\ HIC}$, survive in QGP in HICs
  (initial production & hadronization are not enough, consider the whole evolution)
- Heavy quark mass M_Q large, short wave-length, not following fluid dynamics
- Heavy quark mass M_Q not too large, not static in medium

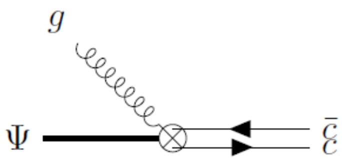
What do we need for a transport model?

- Transport equation with microscopic dynamics (from in-medium potential)
  (simplest case: semi-classical transport equation with coefficient from field theory)
- Encoding effects from both real and imaginary potential
  - ❖ Real part: reduced binding energy, internal quantum evolution
  - ❖ Imaginary part: quarkonium dissociation width in medium

Reaction rates for quarkonia in HICs

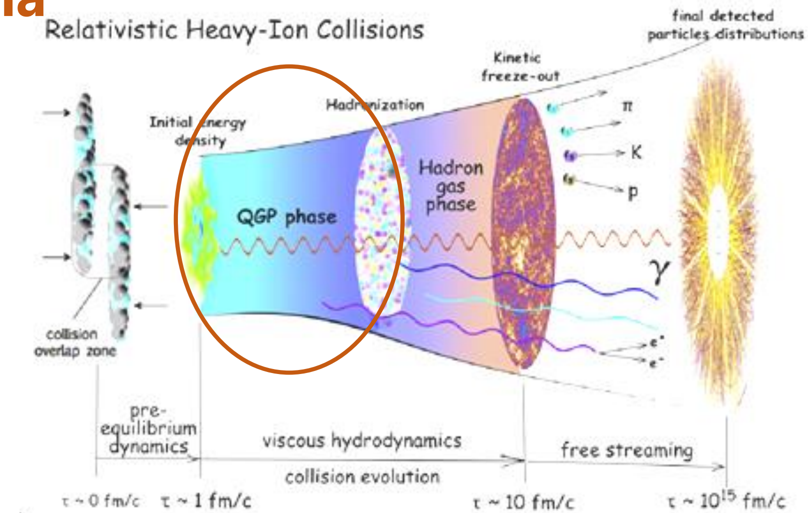
Reaction rates in quark-gluon plasma

- Gluon dissociation (singlet-octet transition)

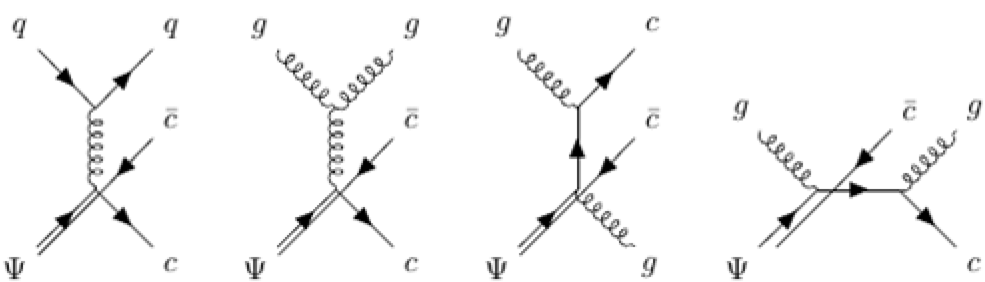


Dominates when
$E_B \sim M_Q v^2 > m_D \sim gT$

Large-Nc limit:
Peskin, NPB156(1979)365,
Bhanot, Peskin, NPB156(1979)391
pNRQCD:
Brambilla, Escobedo, Ghiglieri, Vairo, JHEP12(2011)116



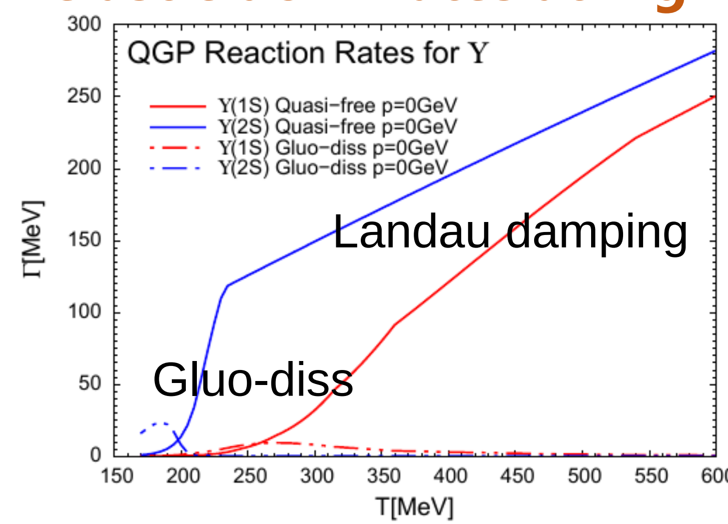
- Inelastic scattering (Landau damping)



Quasifree Approximation:
Grandchamp, Rapp, PLB523(2001)60
pNRQCD:
Brambilla, Escobedo, Ghiglieri, Vairo, JHEP05(2013)130

Dominates when
$E_B \sim M_Q v^2 < m_D \sim gT$

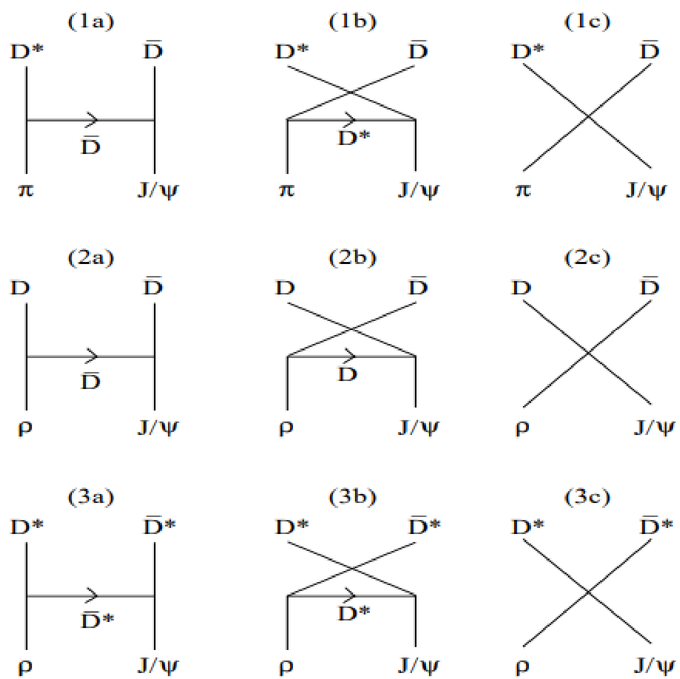
Inelastic dominates at high-T



Reaction rates for quarkonia in HICs

Reaction rates in hadronic matter

- Meson exchange model

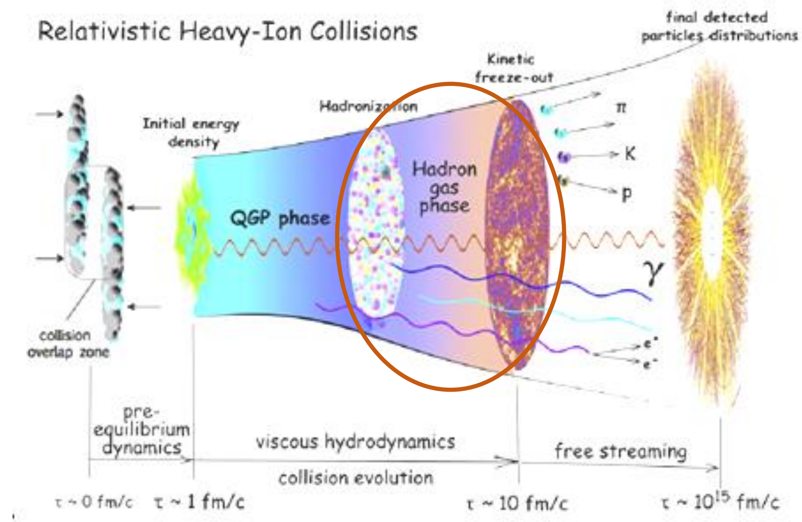


- π, ρ Induced interaction

  Lin, Ko, PRC62(2000)034903
  Oh, Song, Lee, PRC63(2001)034901
  Haglin, Gale, PRC63(2001)065201

- Including more hadron resonances

  Du, Rapp, NPA943(2015)147



Essence of hadronic interaction

- Not so important in AA collisions
- Important in pA collisions

  (short QGP lifetime)

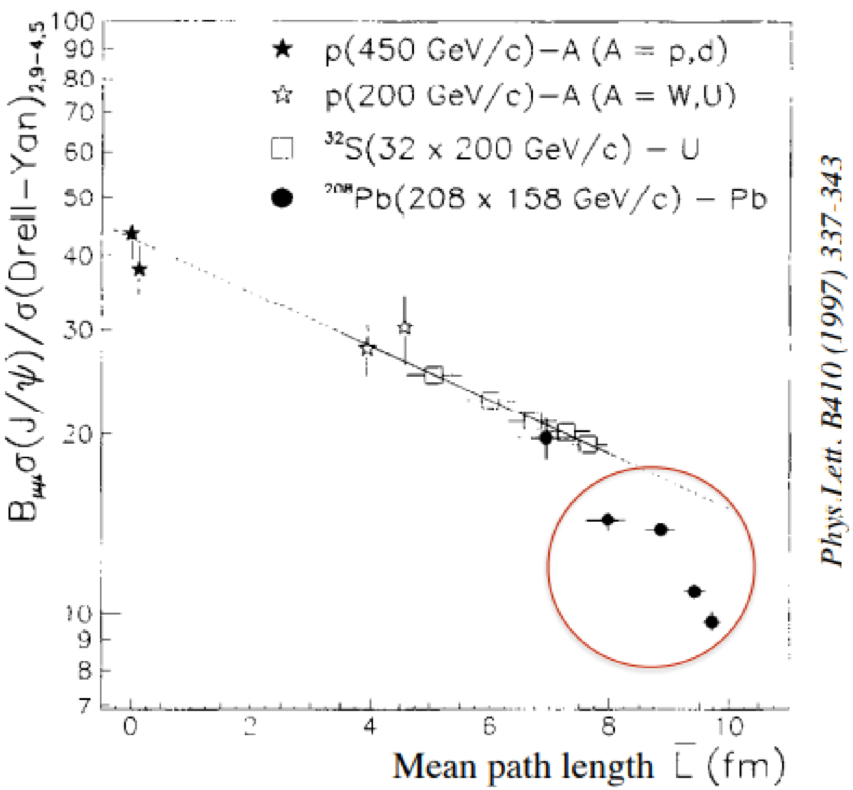
Quarkonium suppression in HICs

Nuclear modification factor

- Indicating the quarkonium suppression in nucleus-nucleus (AA) collision

$$R_{AA} = \frac{N_{AA}}{N_{coll} N_{pp}}$$

If nothing happens in AA, then R_{AA}=1



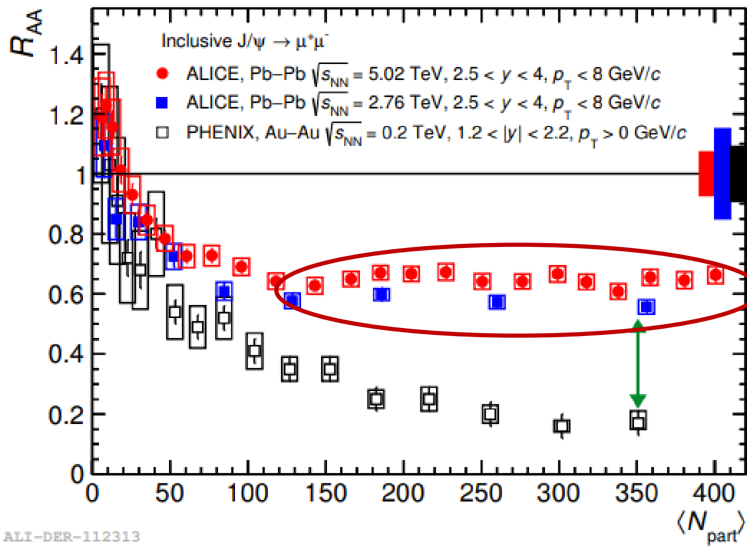
Anomalous suppression of J/ψ

- Abnormal suppression at higher multiplicity
- Hints of QGP formation at SPS energy

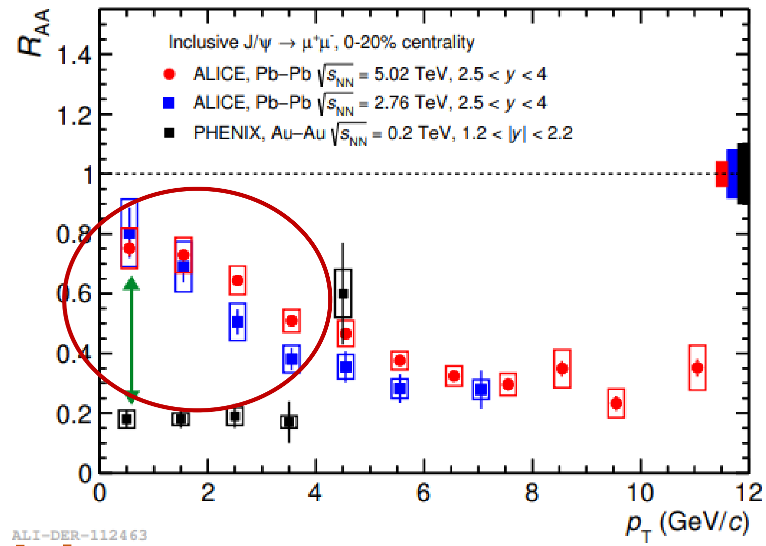
Quarkonium production at RHIC/LHC

Essence of regeneration process

- Flat R_{AA} at LHC



- Soft R_{AA} spectra at LHC



Two component transport model

- Suppression + recombination: Boltzmann equation

$$D_t f_\psi(x,p,t) = C[f_\psi](p,T(x,t))$$

Neglecting quantum statistical factor, more explicitly:

$$\partial_t f_\psi(x,p,t) + \vec{v}\cdot\nabla_x f_\psi(x,p,t) = -\boxed{\alpha(p,T(x,t))f_\psi(x,p,t)} + \boxed{\beta(p,T(x,t))}$$

Primordial suppression regeneration

Two component transport models

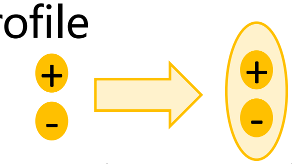
Suppression + Regeneration

$$\partial_t f_\psi(x,p,t) + \vec{v}\cdot\nabla_x f_\psi(x,p,t) = -\boxed{\alpha(p,T(x,t))f_\psi(x,p,t)} + \boxed{\beta(p,T(x,t))}$$

Primordial suppression regeneration

- What are the ingredients in the two-component model?

$f_\psi(x,p,t)$	Phase-space distribution
$\alpha(p,T(x,t))$	Reaction rates: gluo-diss, landau damping, …
$T(x,t)$	Space-time dependent temperature profile
$\beta(p,T(x,t))$	Regeneration rate



- Regeneration rate breakdown $\beta\big(p,T(x,t)\big)\sim\alpha(p,T(x,t))f_c\big(p,T(x,t)\big)f_{\bar{c}}\big(p,T(x,t)\big)$
- Thermal regeneration: Relaxation time approximation (RTA)

  Thermal charm $f_c f_{\bar{c}} \sim f_{eq}$ ⟹ Kinetic rate equation $\partial_t f_\psi = -\alpha(f_\psi - f_{eq})$

Various semiclassical models on the market

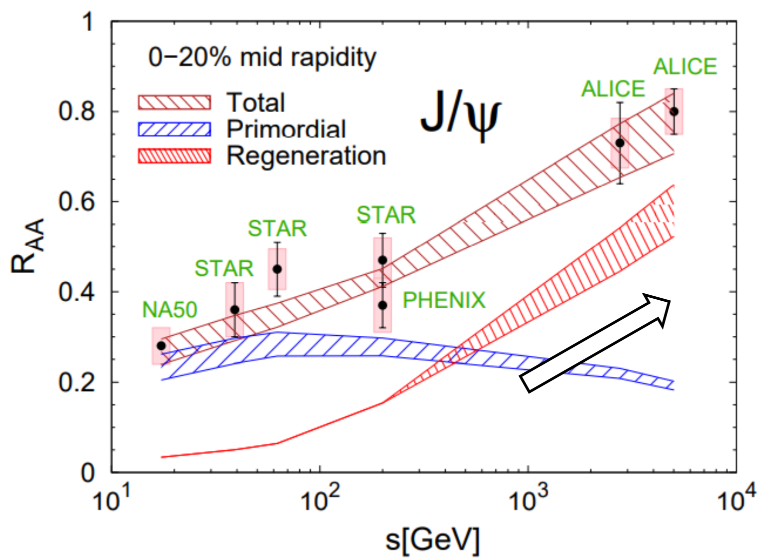
- Have differences in detail, but follow the basics of two-component feature

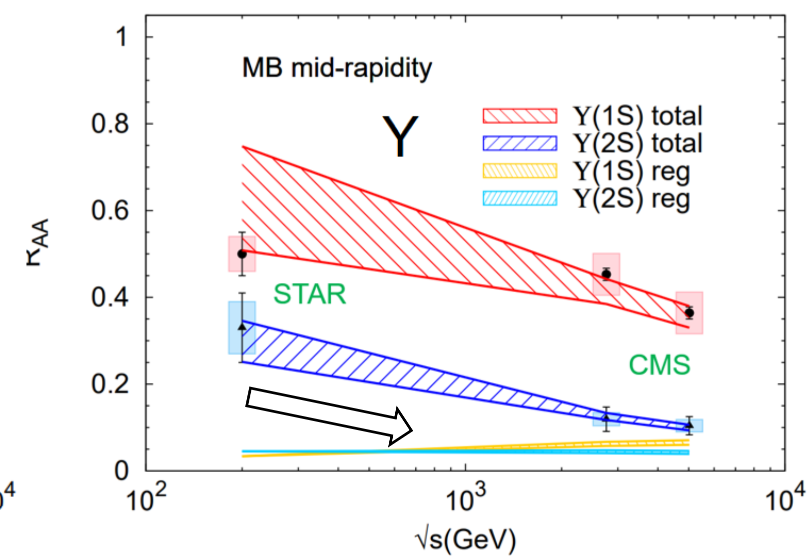
TAMU: R. Rapp, L. Grandchamp, X. Zhao, X. Du, B. Wu
Tsinghua: P. Zhuang, L. Yan, Y. Liu, K. Zhou, B. Chen, J. Zhao
Comover: E. Ferrerio, et al.
Yonsei-TAMU: SH. Lee, CM. Ko, T. Song, W. Park, Y. Liu, J. Hong
…

Charmonia and bottomonia

Energy excitation functions

- $N_{cc}>1$ large regeneration contribution, $N_{bb}\backsim 1$ small regeneration contribution
- J/ψ and Υ(2S) similar binding energies (similar width), different trend (regeneration)





Rapp, Du, NPA967(2017)216

- Two component model is essential for describing J/ψ

Non-thermal regeneration

Non-thermal heavy quark

Recall $\beta \sim \alpha f_c f_{\bar{c}}$ (Realistic quark spectra)

- Langevin/Fokker-Planck simulated heavy quark distribution (bottomonia)

$$dx = p/E\, dt$$

$$dp = -Apdt + \sqrt{2Ddt}\eta$$

drag diffusion

$$\Longrightarrow \quad \partial_t f_c = \nabla_p (Apf_c) + \nabla_p^2 (Df_c)$$

Du, He, Rapp, PRC96(2017)054901
Chen, Zhao, PLB772(2017)819

Hong, Lee, PLB801(2020)135147

- Coupled Boltzmann simulated heavy quark distribution (bottomonia)

Test particle method

$$\partial_t f_c = C_{diff} + C_{c\leftrightarrow\psi}$$

$$\partial_t f_\psi = C_{c\leftrightarrow\psi}$$

Onium spectra influence heavy quark spectra (Small effect since $\sigma_\Upsilon \sim 0.1\%\ \sigma_{bb}$)

Yao, Ke, Xu, Bass, Muller, JHEP01(2021)046

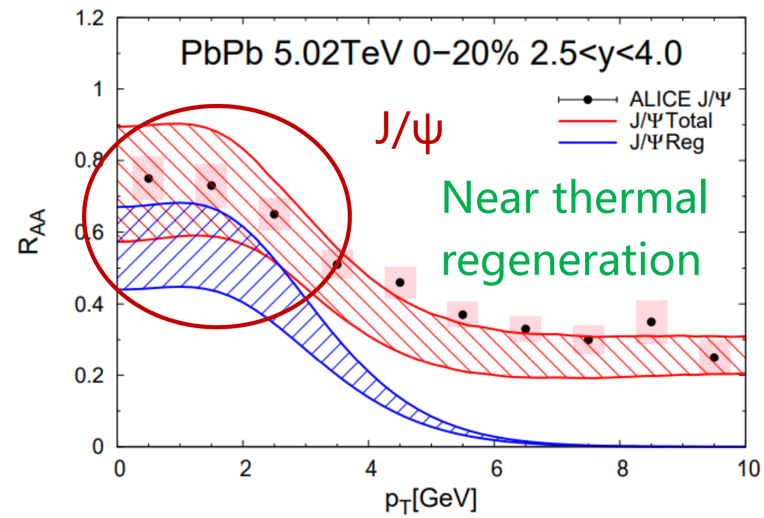
Charmonia and bottomonia

Momentum spectra

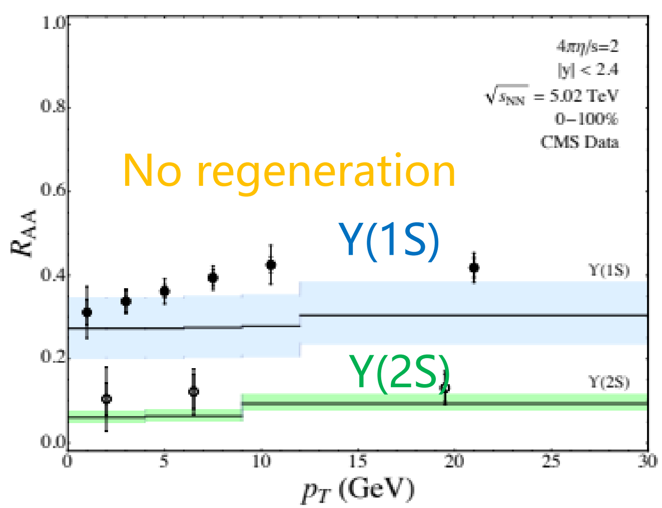
■ Near-thermal regeneration of charmonium from near-thermal charm quarks

■ Off-thermal regeneration of bottomonium from off-thermal bottom quarks

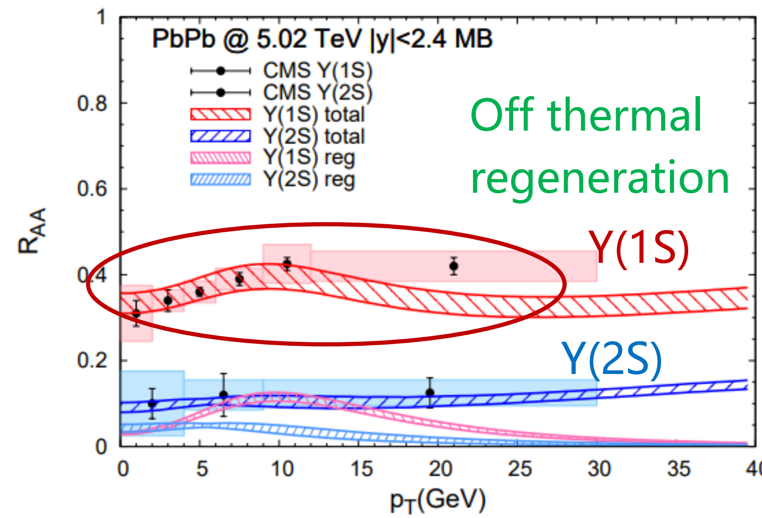
(Bottom $M_b > M_c$, more difficult to thermalize)



■ Bottomonium model without regeneration works as well (small regeneration contribution)

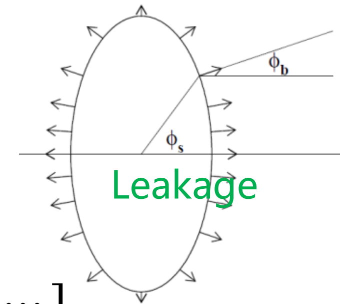


Krouppa, Rothkopf, Strickland, PRD97(2018)016017



Du, Rapp, NPA943(2015)147
Du, He, Rapp, PRC96(2017)054901

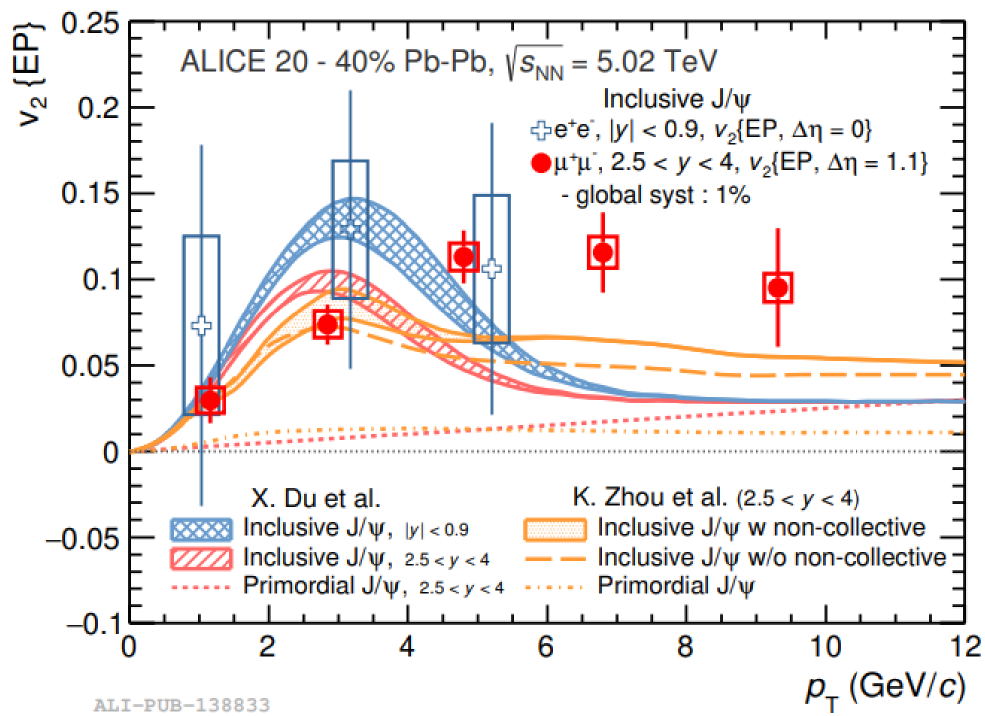
J/ψ elliptic flow at high-p_T



Elliptic flow

- Anisotropic production
- Two contributions:
  - Primordial: leakage
  - Regeneration: Anisotropic charm recombine

$$\frac{d^2N}{d^2p_T} = \frac{1}{2\pi}\frac{d^2N}{d^2p_T}[1 + 2v_2(p_T)\cos(2\phi) + \cdots]$$



Two-component models fail

- Two-component models v_2 :
  - Small primordial v_2
  - regeneration only at low momentum
- Two-component models underestimate v_2 at high momentum

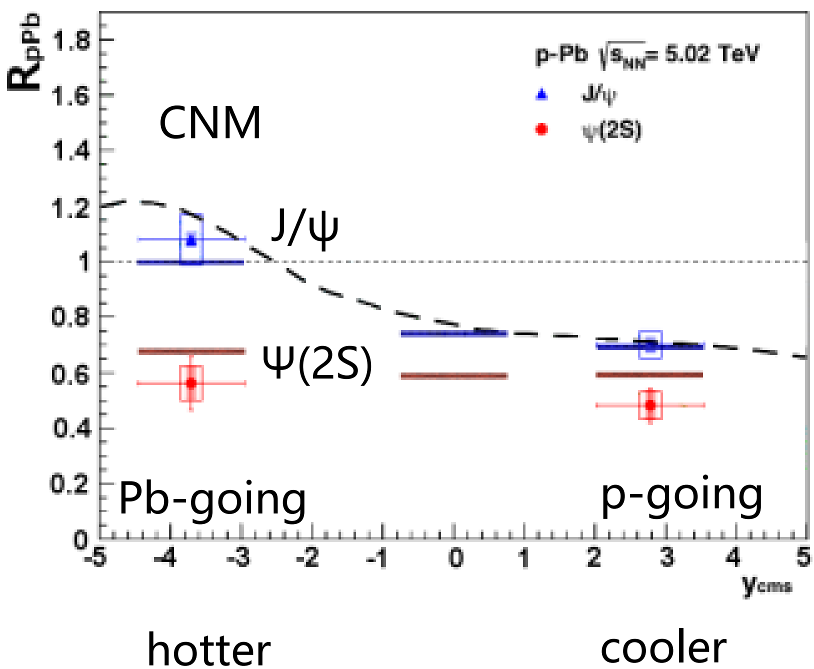
Missing J/ψ production mech?

- Recombination at higher-pT?
- Jet fragmentation to J/ψ?

Transport in small systems

Facts about charmonia in pA

- Ground state J/ψ / excited state Ψ(2S) similar cold nuclear matter (CNM) effect
- J/ψ binding > Ψ(2S) binding, more difficult to break up
- Backward rapidity (y<0, Pb-going direction), longer path length



Ferreiro, PLB749(2015)98

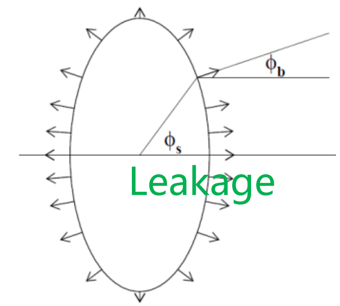
Medium formation in pA

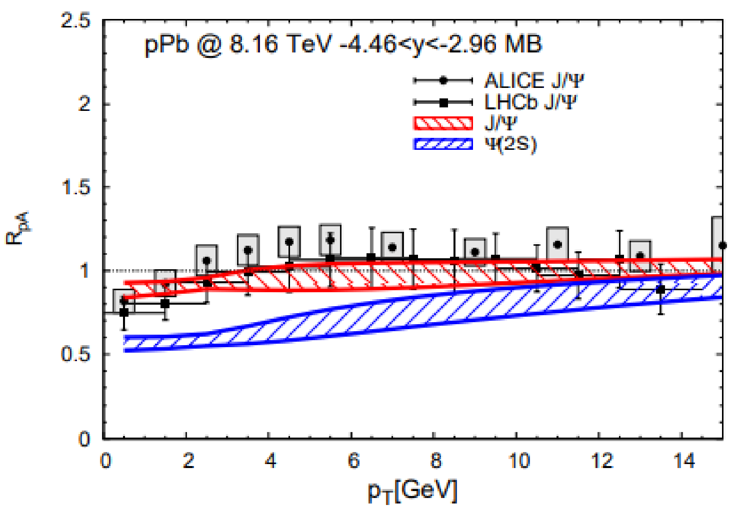
- J/ψ has moderate suppression, Ψ(2S) has large suppression at Pb-going direction
- J/ψ & Ψ(2S) both have moderate suppression at p-going direction
- Indication of medium formation in pA

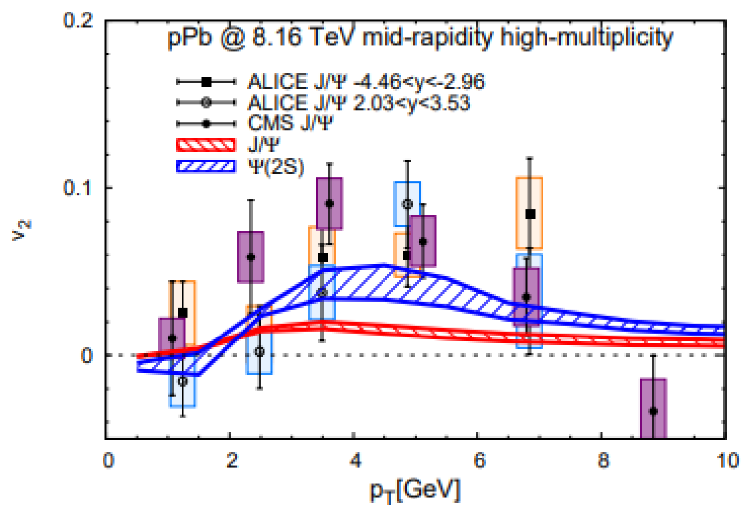
Transport in small systems

Elliptic flow in small system

- From transport model:
  - Small J/ψ suppression (small leakage effect) → small elliptic flow v_2
  - Small J/ψ regeneration in pA → negligible elliptic flow v_2
- From experimental date:
  - large v_2 observed
- Transport model with final state interaction only underestimate v_2







Du, Rapp, JHEP03(2019)015

- Large v_2 generated from initial state?

CGC: Zhang, Marquet, Qin, Wei, Xiao, PRL122(2019)172302

Beyond semiclassical approximation

What is missing in semiclassical approach?

- QQbar unitary evolution by real potential, explicit implementation of screening
  - Not just encode the real part into binding energy
  - Enable to track not only bound singlet, but also unbound QQbar pairs as well

➔ Evolution of wave-function (Schrodinger)/density matrix (von Neumann) with complex potential

$$i\partial_t|\psi\rangle = H|\psi\rangle \qquad i\partial_t\rho = [H,\rho]$$

➔ Tracking QQbar, imaginary part means disappearing of QQbar correlation

From complex to stochastic potential

- Another way of implementing decoherence is through stochastic potential

$$i\partial_t|\psi\rangle = (H + \Theta - i\Gamma)|\psi\rangle$$

Fluctuation ($+\Theta$) Dissipation/dissociation ($-i\Gamma$)

Akamatsu, Rothkopf, PRD85(2012)105011
Rothkopf, JHEP04(2014)085

More on model with potential

➔ Not easy to distinguish dissociation/regeneration

➔ Consider more explicit interaction with medium (other than potential)?

Quantum master equation

Open quantum system

- Factorize the Hamiltonian & density matrix into QQbar pair + environment:

$$H = H_{QQ} + H_{med} + V_{QQ} \otimes V_{med} \qquad \rho_{QQ} = Tr_{med}(\rho)$$

- QQbar Evolution follows von Neumann equation with trace on medium

Markovian limit

- Differential equation (master equation) to describe decoherence of open quantum system, only possible when the quantum system is Markovian (local in time)

$$\rho(t + dt) = \mathcal{E}_{dt}[\rho(t)]$$

$\mathcal{E}_{dt}$ (Quantum channel)

- Limit: the subsystem (QQbar) damping time larger than medium correlation time

$$\Delta t_{damp} \gg \Delta t_{env}$$

See recent reviews:
Akamatsu, PPNP, 2009.10559
Yao, IJMPA36(2021)20

Quantum master equation

Lindblad master equation

- Assuming the factorization of QQbar subsystem and medium preserve

$$\rho_{QQ}(t+dt) = \mathcal{E}_{dt}[\rho_{QQ}(t)]$$

Expand quantum channel $\mathcal{E}_{dt} = 1 + dt\mathcal{L} \quad \rightarrow \quad \mathcal{L} = \partial_t \rho_{QQ}$ (Lindbladian)

General solution $\rho_{QQ}(t) = \lim_{n\to\infty}\left(1+\frac{\mathcal{L}t}{n}\right)^n \rho_{QQ}(0) = e^{\mathcal{L}t}\rho_{QQ}(0)$

Operator sum rep $\mathcal{E}_{dt}[\rho_{QQ}(t)] = \sum_a M_a \rho_{QQ}(t) M_a^\dagger$

(Kraus-operator) $M_a = \sqrt{dt}\, L_a \qquad M_0 = I + \left(-iH - \frac{1}{2}\sum_{a>0} L_a^\dagger L_a\right) dt$

- Lindblad master equation

$$\partial_t \rho_{QQ} = -i[H_{eff}, \rho_{QQ}] + \sum_{a>0}\left(L_a \rho_{QQ} L_a^\dagger - \frac{1}{2} L_a^\dagger L_a \rho_{QQ} - \frac{1}{2}\rho_{QQ} L_a^\dagger L_a\right)$$

Screening — Regeneration — Primordial dissociation

H is Hermitian

Quantum evolution

Current quantum evolution calculations on the market

- Either (complex/stochastic) potential or density matrix

❖ Complex potential

Kent state: M. Strickland, J. Boyd, T. Cook, A. Islam

❖ Stochastic potential

Osaka-Stavanger: Y. Akamatsu, A. Rothkopf, S. Kajimoto, M. Asakawa
Nantes: R. Katz, P-B. Gossiaux

❖ Density matrix/state — See Griend's & Delorme's talks today

Munich: N. Brambilla, M Escobedo, J. Soto, A. Vairo.
Munich-Kent state: N. Brambilla, M. Strickland, M Escobedo, A Vairo, P. Griend, et al.
Nantes: R. Katz, S. Delorme, P-B. Gossiaux

Questions of current quantum evolution calculations

- How to match lattice potential to quantum operators in quantum master equation?
- How to consider correlation between different QQbar pairs?
- How to consider relativistic effect?

Might be OK for bottomonia (number N_{bb} small, mass m_b large)

- How to properly implement dynamical medium in open quantum system?
- What observables to test quantum effects?
- Efficient algorithms for numerical calculations for quantum evolution

Quantum computing for quarkonia

Quantum computing concepts

- With n qubits, one has $N=2^n$ total quantum states (could be exponentially faster)
- Quantum computer requites designing quantum circuits for quantum algorithm
- Quantum circuit is a set of quantum gates to perform the quantum algorithm
- Every quantum gate is a unitary transform of quantum state

Universality

- One can approach arbitrary unitary transform with quantum circuits

Open quantum system on quantum computer

- Reversible time evolution of systems can be expressed in a unitary transform
- For non-unitary transform (open quantum system with dissipation)
  - Using auxiliary qubits to make overall unitary transform
  - Trace out the auxiliary qubits to leave the system we are interested in

For open quantum system, see
De Jong, Metcalf, Mulligan, Ploskon, Ringer, Yao, PRD104(2021)051501

Conclusions

Semiclassical transport model construction

- Real & Imaginary potential → Physics meaning & roles in model
- Essence of regeneration in charmonium production → Two-component model

Quantum transport model construction

- Beyond semiclassical approximation → Quantum master equation
- Challenges in quantum models from open quantum system

Transport model in quantum era

- Future opportunity → Quantum circuit simulation of quantum evolution

Thank you!