Heavy-Flavor Theory at Hard+EM Probes '18

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Hard & Electromagnetic Probes of High-Energy Nuclear Collisions

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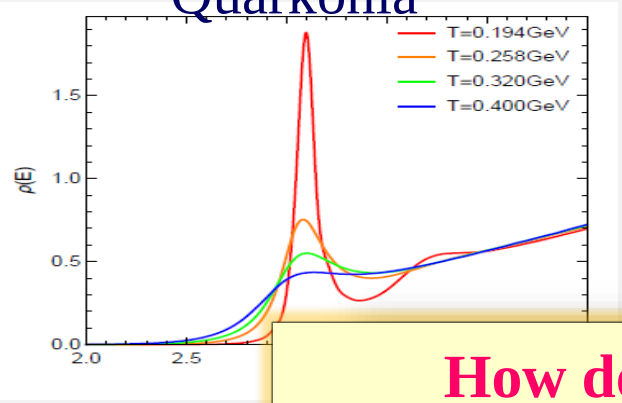
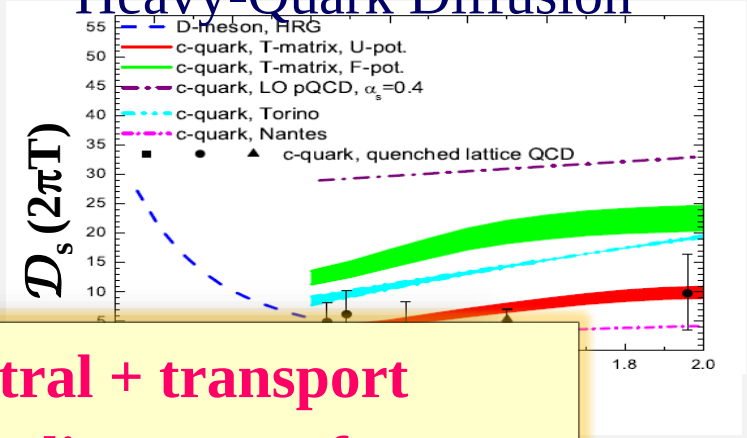
1.) Heavy Quarks and in-Medium QCD Force

Hard-produced probes with unique access to soft-medium properties

Quarkonia

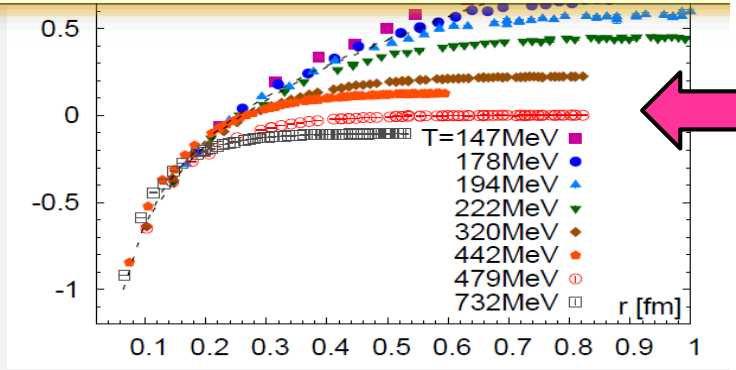


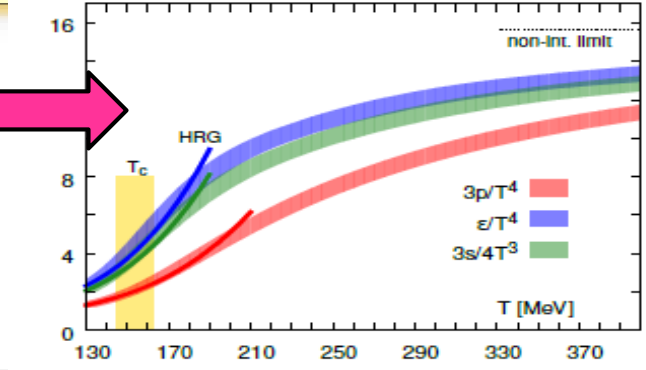
Heavy-Quark Diffusion



- $E_B(T)$, ve

How do heavy-flavor spectral + transport properties emerge from in-medium QCD force?





Outline

1.) Introduction

2.) Heavy-Quark Diffusion

3.) Hadronization

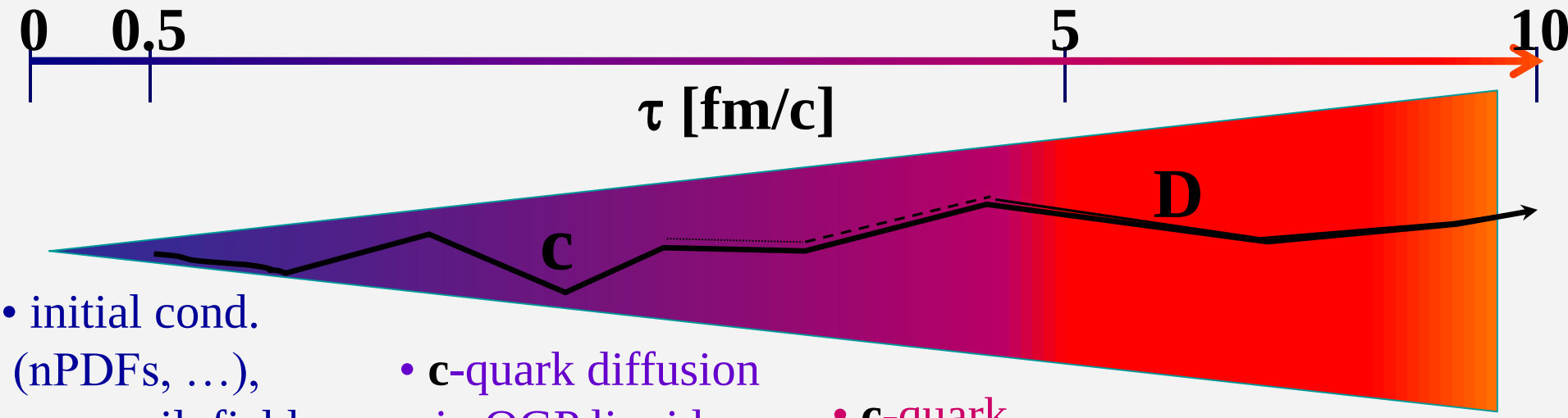
4.) Quarkonium Transport

5.) High-p_T Suppression

6.) Small Systems

7.) Conclusions

2.1 Heavy-Flavor Transport in URHICs



- initial cond. (nPDFs, …), pre-equil. fields
- **c**-quark diffusion in QGP liquid
- **c**-quark hadronization
- **D**-meson diffusion in hadron liquid

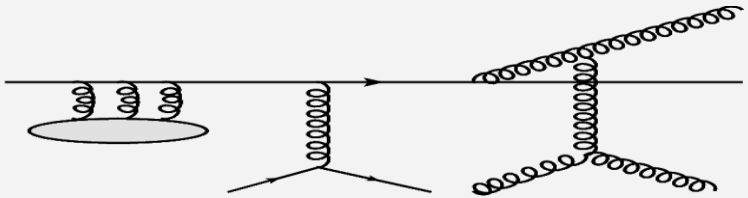
- **HQ** diffusion intrinsically non-perturbative **[S. Cao]**

  → strong coupling → remnants of confining force → resonances

⇒ **no principle difference between diffusion and hadronization int.'s**

2.2 Extraction of Diffusion Coefficient

- **Bayesian extraction using Langevin/Boltzmann** **[W. Ke]**

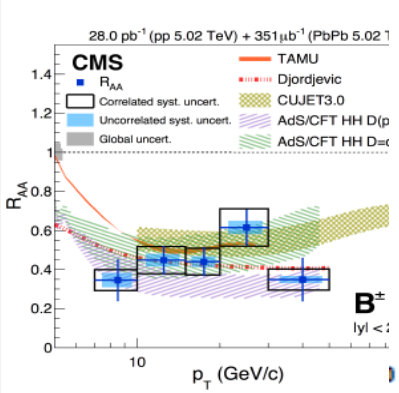


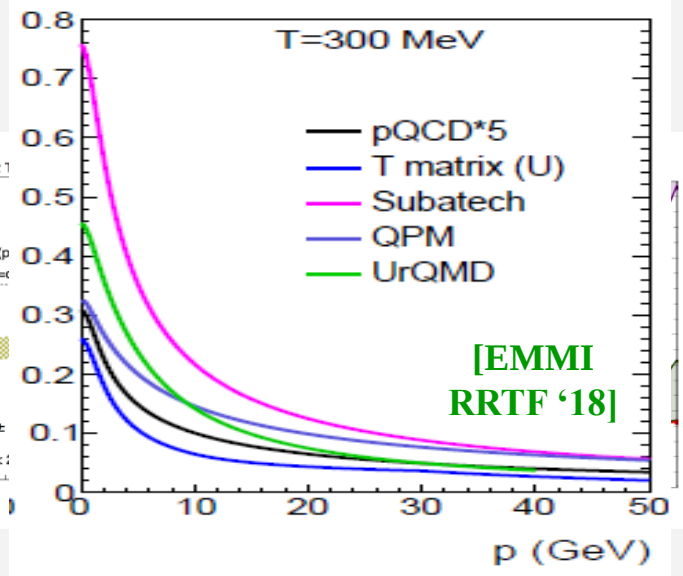
- Emphasized the importance of "realistic" model input to statistical analysis

- **AdS/CFT Approach** **[R. Hambrock]**

- $\mathcal{D}_s\,(2\pi T) = 4/\sqrt{\lambda} = 1.2\text{-}1.7$

- drag $\gamma = D/TE \sim 1/E$ favored (as in QCD-based models)

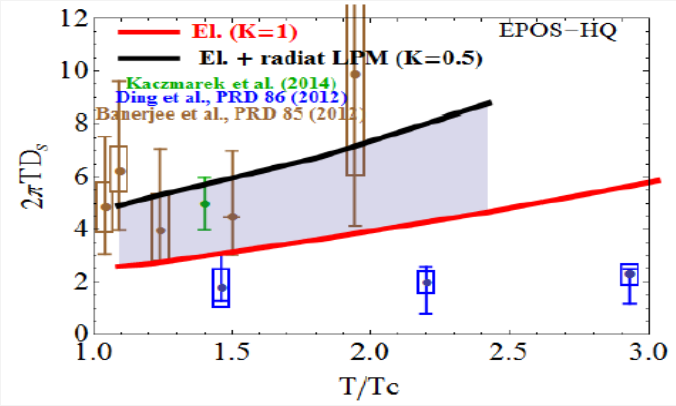




2.3 Diffusion and Bulk Evolution

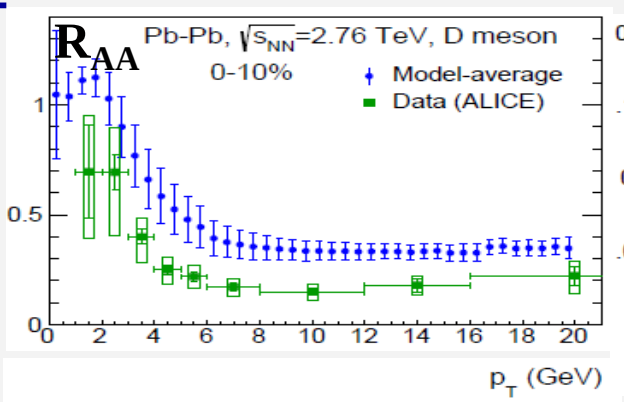
- **Update of Nantes Approach** **[P.B. Gossiaux]**
  - update of bulk evolution (EPOS2 → EPOS3)
  - requires moderate changes in HQ diffusion/ hadronization

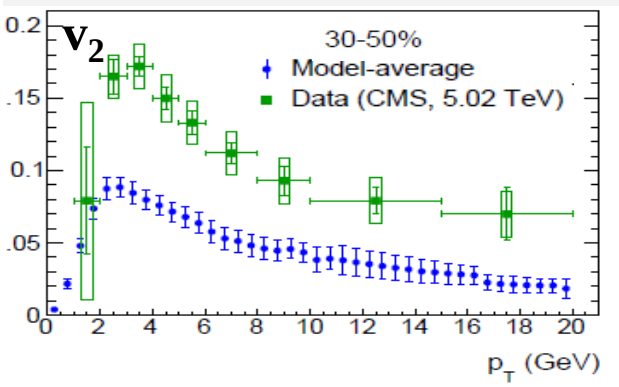
  ⇒ slightly larger $\mathcal{D}_s$ than before



- **Broader Theory Efforts** **[EMMI RRTF, HQ-jet]**

- Individual bulk+hadroniz. models + common HQ int. "pQCD**x5**", $\mathcal{D}_s(2\pi T) \cong 6$

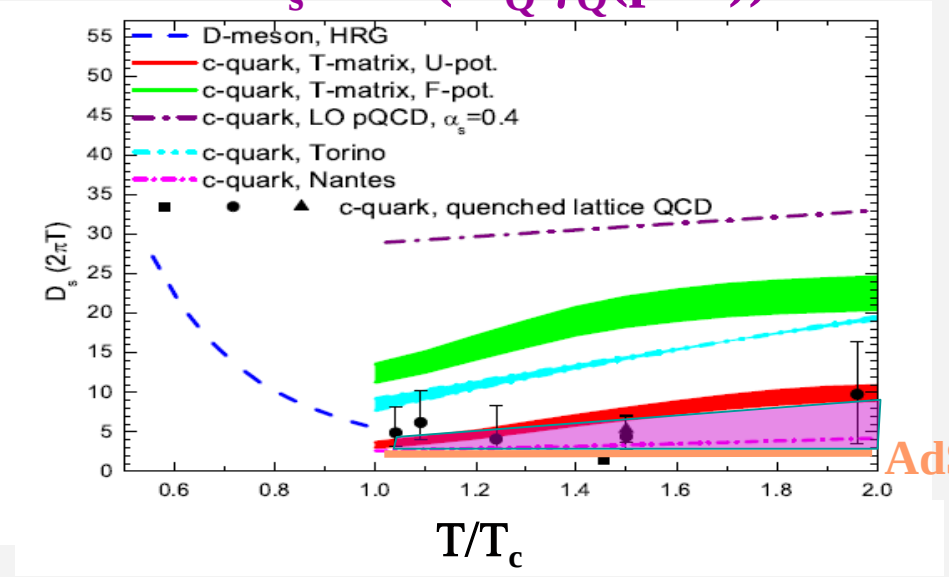




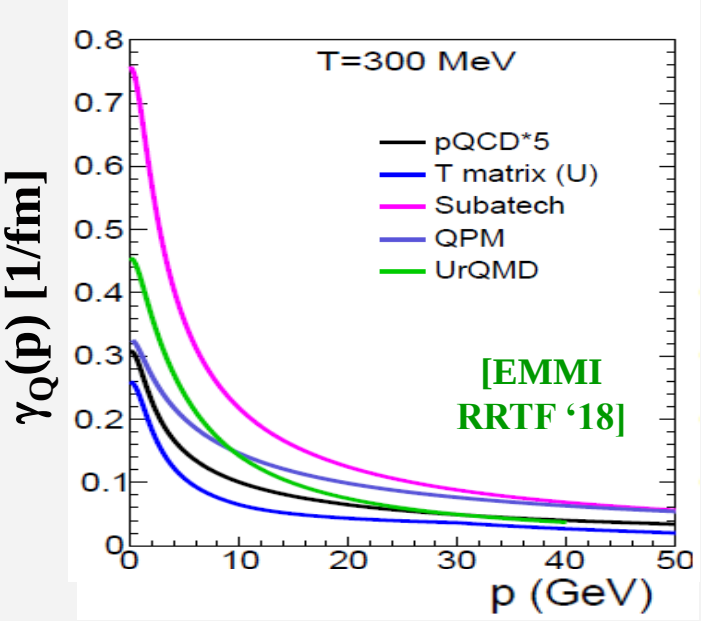
- **Pre-equilibrium phase** - Possibly significant **[S.Mrowczynski]**

2.4 Upshot of Charm Diffusion Coefficient

$\mathcal{D}_s = T / (m_Q \gamma_Q(p=0))$



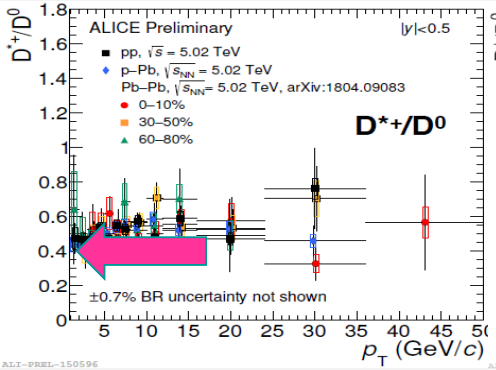
AdS/CFT

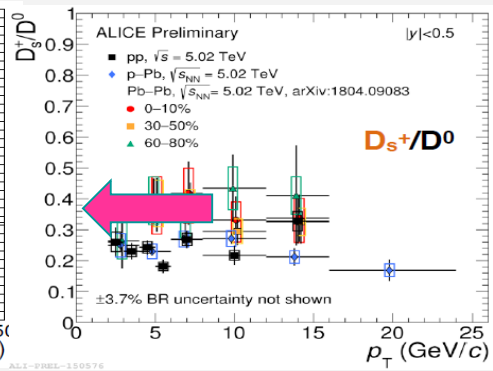


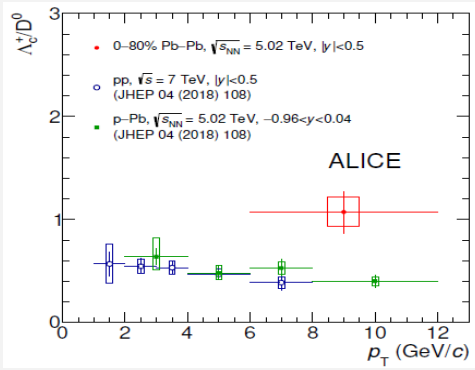
- suggests minimum of $\mathcal{D}_s(2\pi T) \sim 2\text{-}4$ near T_{pc}
- scatt. rate: $\Gamma_{coll} \sim 3/\mathcal{D}_s \sim 1$ GeV – **no light quasi-particles!**
- **T**- and **p**-dependence reflect core property of QCD

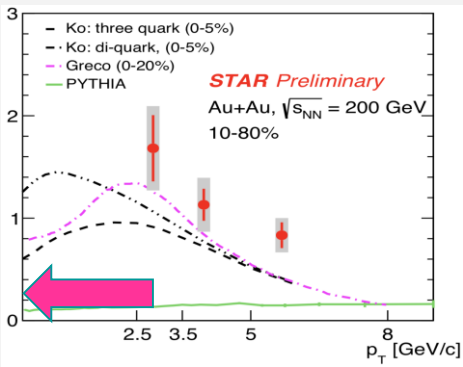
3.) Hadronization: Statistical vs. Coalescence

Charm Chemistry from pp to PbPb









- No surprises; **SHM**
- Strangeness enhanced!
- Flow push?!
- Coalescence … **> 5x SHM?**

- Control over wave-function effects, equilibrium limit?
- Chemical vs. kinetic equilibrium? (recall: recombination ↔ interaction)

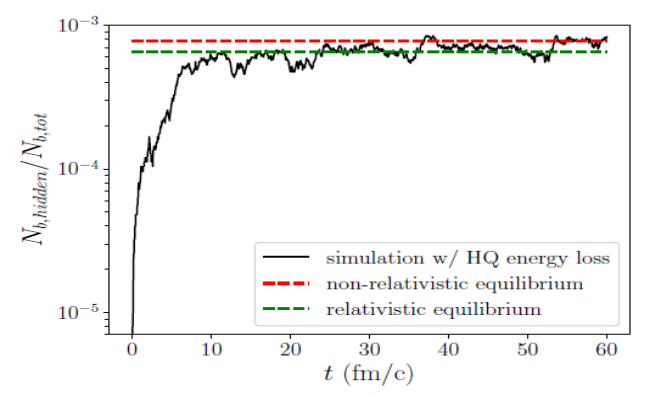
4.) Quarkonia Transport: Equilibrium Limits Matter

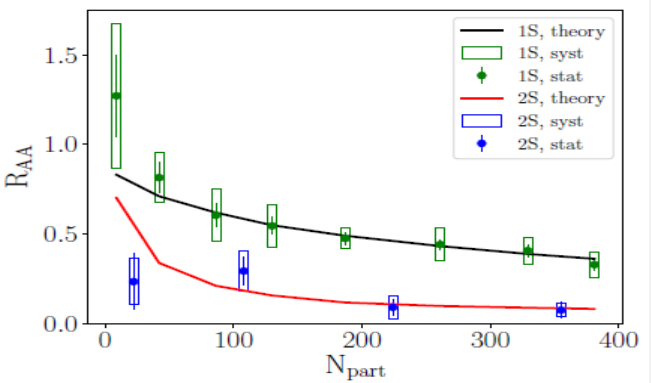
[M. Nardi]

$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left[N_\psi - N_\psi^{eq} \right]$$

- **Υ(1S,2S) Boltzmann transport with b-quark diffusion** [X. Yao]

- Υ yields relax to equilibrium:
  $\mathcal{R} \sim [1-\exp(-\tau/\tau_b)]$ with $\tau_b \sim 7$ fm/c
  -- consistent with [Du et al '17]
  -- implies $\mathcal{D}_s(2\pi T) \sim 4$
- QQ pot. $V_s(r)=-C_F\alpha_s/r$, $T_{diss}(2S)=210$MeV
- Significant regeneration (~20% for Υ(1S))



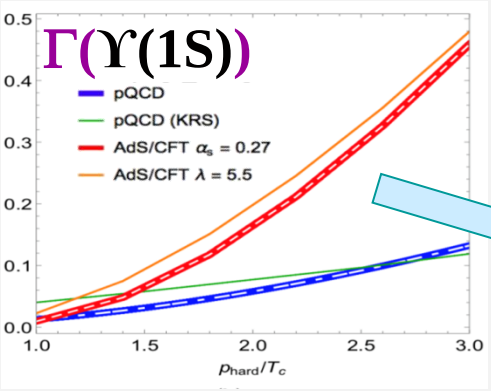


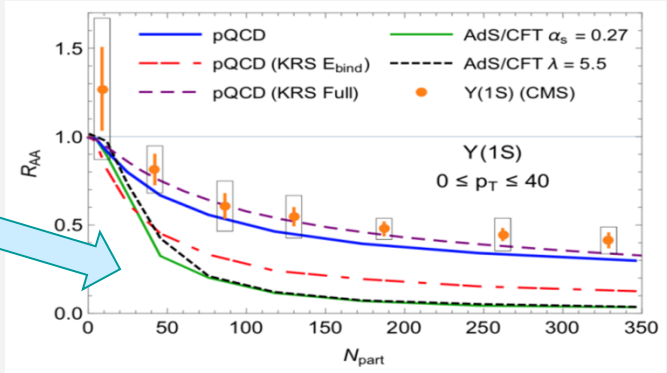
4.2 Quarkonia Transport II

- **AdS/CFT Approach**

- Coulomb potential
- Large dissoc. width

[W. Horowitz]



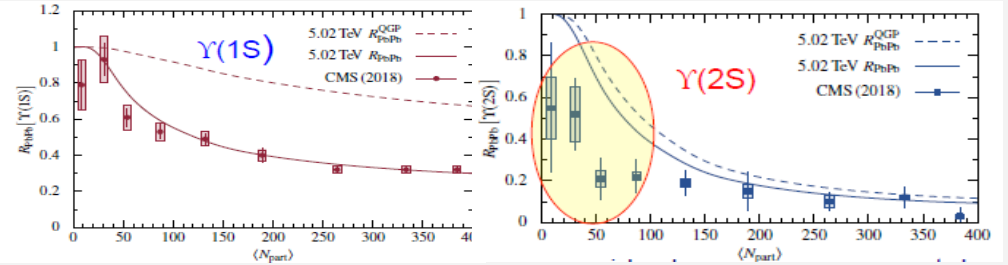


- over-predicts suppression

- **Rate Equation Approach**

- In-medium Cornell potential
- Relatively large widths
- Formation time effects

[G. Wolschin]



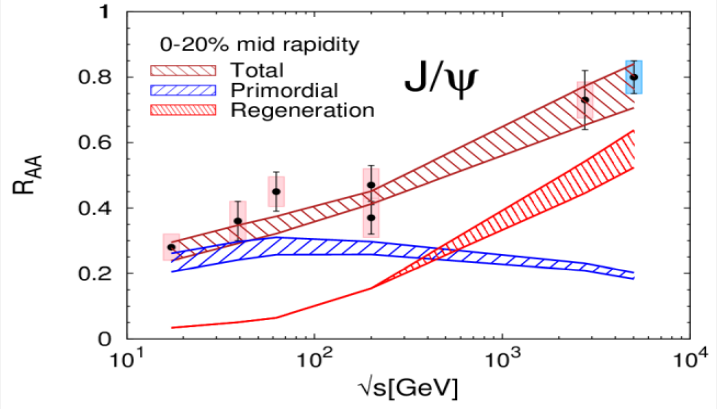
- **Quantum Evolution Approaches**

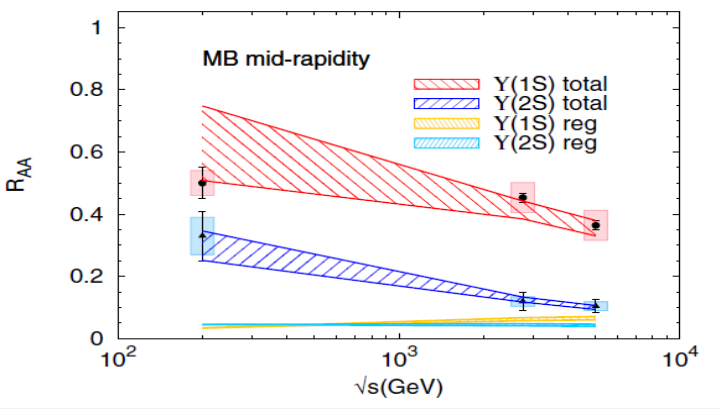
[M.A Escobedo]

$$\partial_t f_s = -i(H_{s,eff} f_s - f_s H^\dagger_{s,eff}) + \mathscr{F}(f_o)$$

- Significance of quantum effects?
- Can it be mapped into a rate equation?

4.3 Quarkonium Upshot





[RR QM'17]

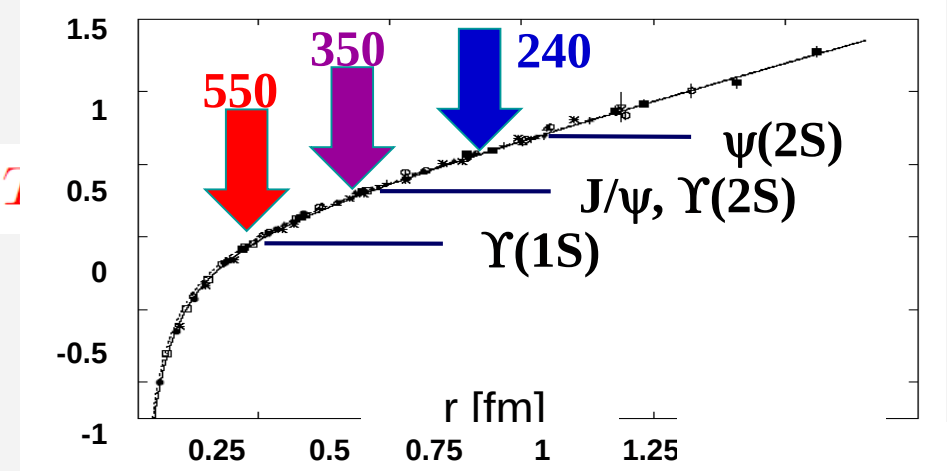
$T_d(\psi') < T_0^{SPS}$ (~240) $< T_d(J/\psi, \Upsilon') \leq T_0^{RHIC}$ (~350) $< T_d(\Upsilon) \leq T_0^{LHC}$ (~550)

- Summary of lattice-QCD results

$$T_d(\chi_c) \simeq 185 \text{ MeV} < T_d(J/\psi) \simeq$$

$$T_d(\Upsilon) > 407 \text{ MeV}$$

[P.Petreczky, MIAPP '18]



5.) High-p_T Heavy Quarks

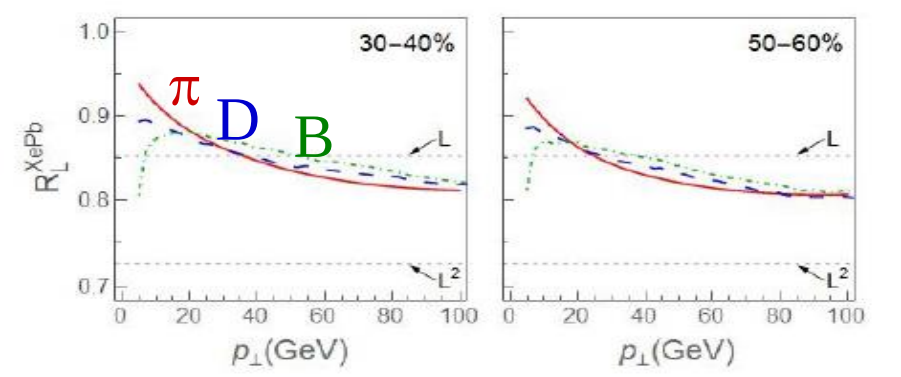
- **Path length dependence:**

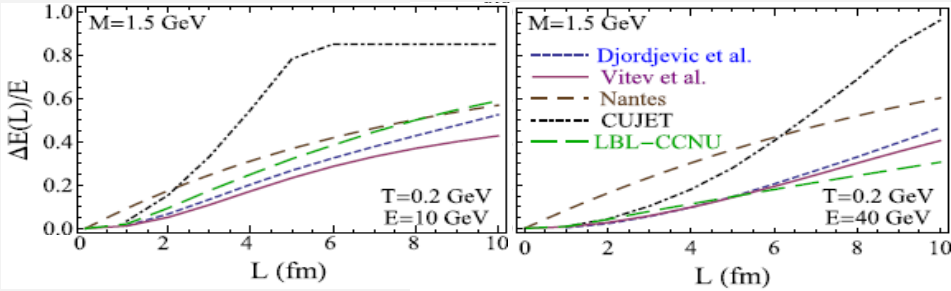
$$\Delta E/E \sim T^a L^b$$

[M. Djordjevic]

$$R_L^{XePb} \equiv \frac{1 - R_{XeXe}}{1 - R_{PbPb}} \approx \left(\frac{A_{Xe}}{A_{Pb}}\right)^{b/3}$$

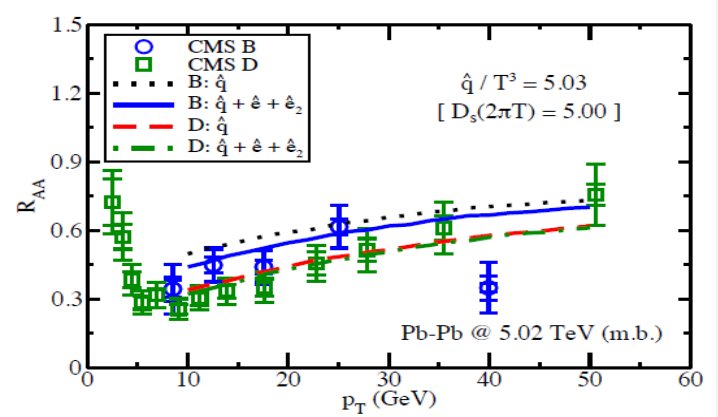
- Close-to-linear behavior predicted





- **Formation time effects** [A. Majumder]

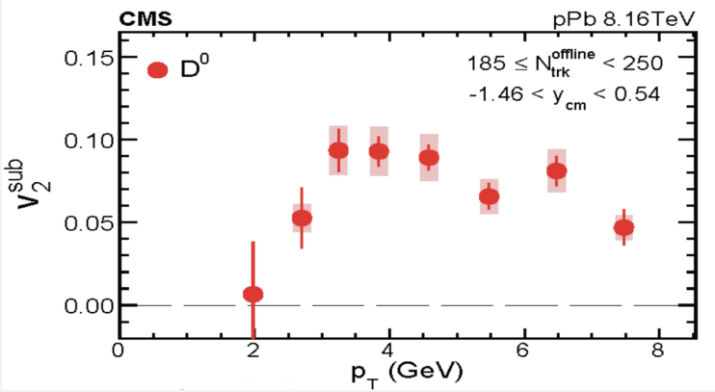
- **b**-quarks on shell faster than **c**-quarks
  $\Rightarrow$ earlier quenching

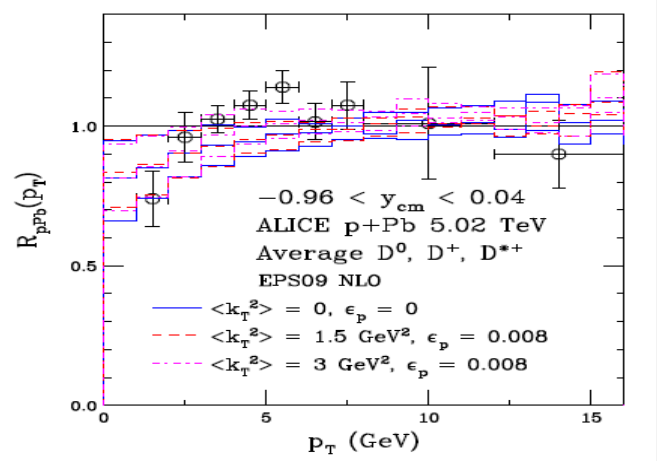


6.) Charm in pA Collisions:

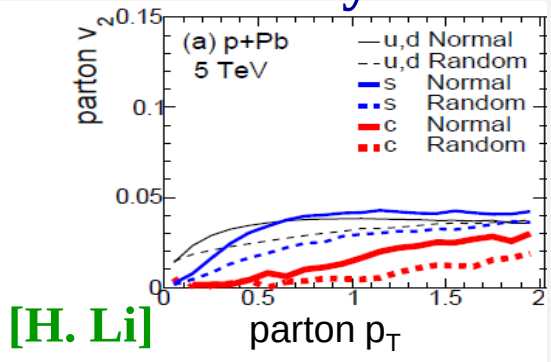
- R_{pA} data consistent with shadowing **[R. Vogt]**

  - But: large v_2

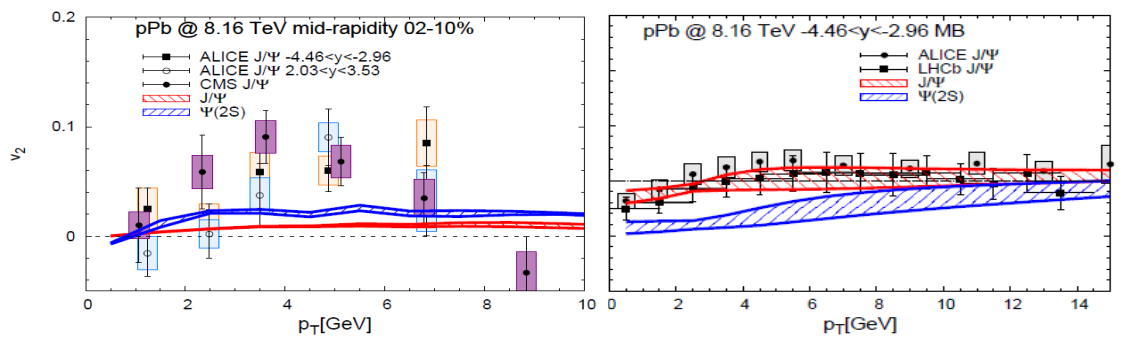




- **Collectivity?**



[H. Li]



- small **c**-quark v_2

- very similar for charmonia **[Du+RR'18]**

7.) Summary

- Continued progress on extracting diffusion coefficient (+ **p**-dependence): - -

  $(2\pi T)\,\mathcal{D}_s = 3\pm2$; implies melting of soft QGP quasi-particles

- Problem of charm chemistry for Λ_c

- Strengthened connections between: hidden $\leftrightarrow$ open heavy HF;

  lattice QCD $\leftrightarrow$ quarkonium transport (melting + regeneration)

  $\rightarrow$ Quantify transport parameters (in-med. potential?); quantum transport

- New views on high-p_T heavy quarks

- "Collectivity problem" of heavy quark/onium in small systems

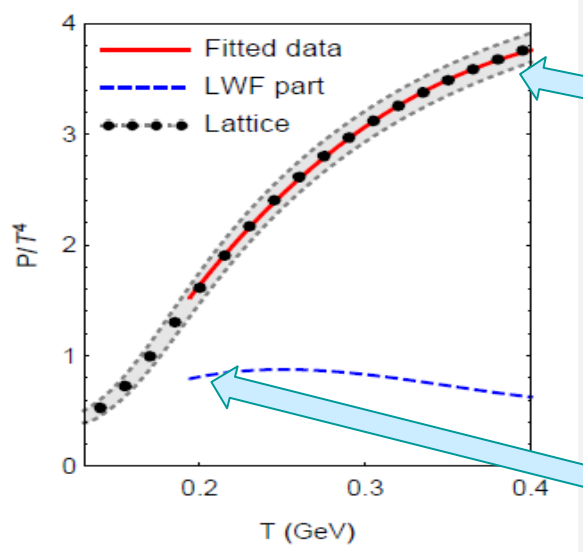
3.6 QGP Equation of State + Spectral Functions

Thermodynamic Potential

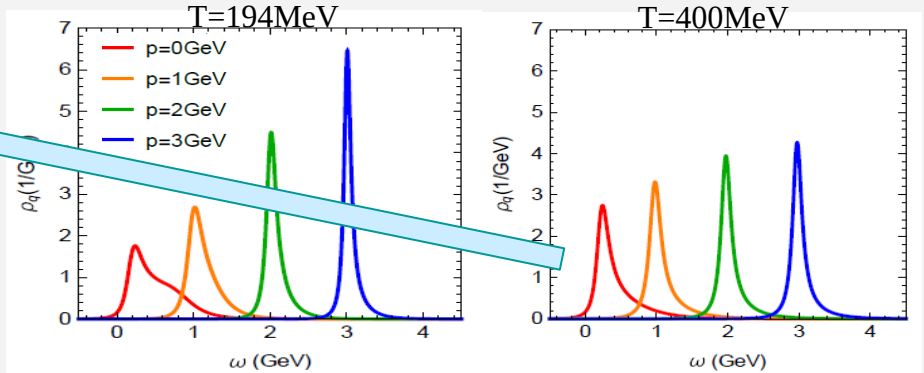
$$\Omega = \mp \frac{-1}{\beta} \sum_n \mathrm{Tr}\{\ln(-G^{-1}) + (G_0^{-1} - G^{-1})G\} \pm \Phi$$

Selfconsistent SFs

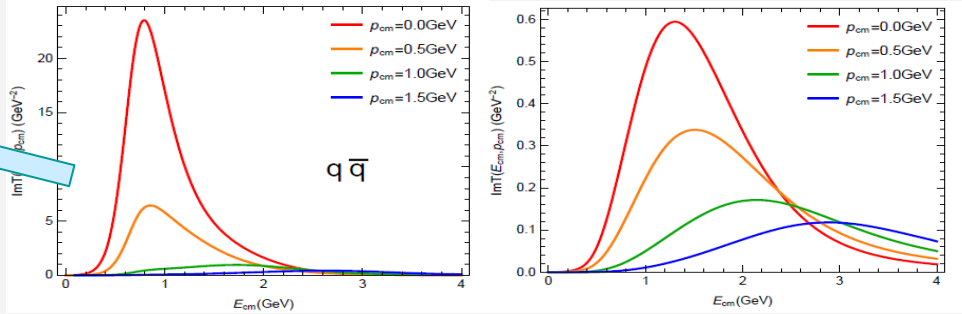
$G = G_0 + G_0 \Sigma G$ $\quad \Sigma = GT$ $\quad T = V + VGGT$



[S.Liu+RR '16]



Quark spectral functions

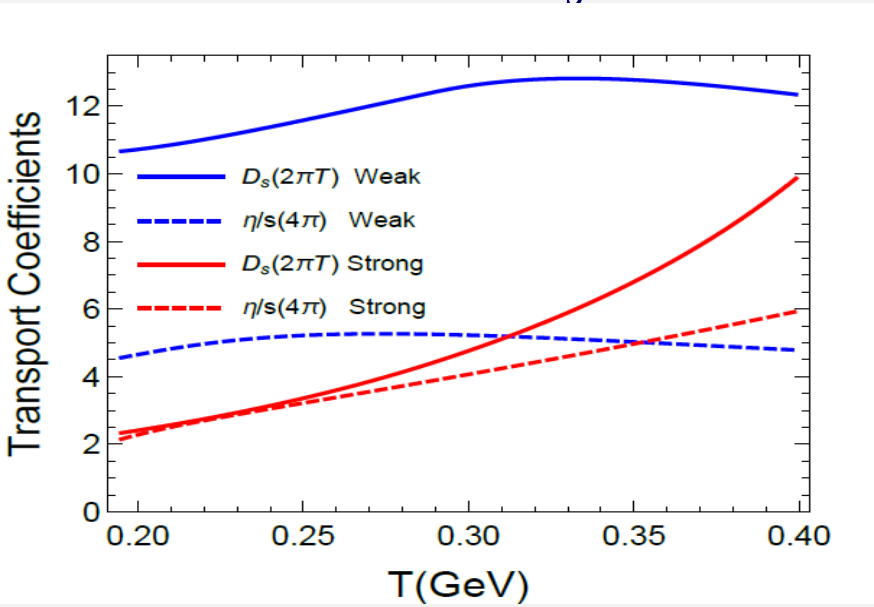


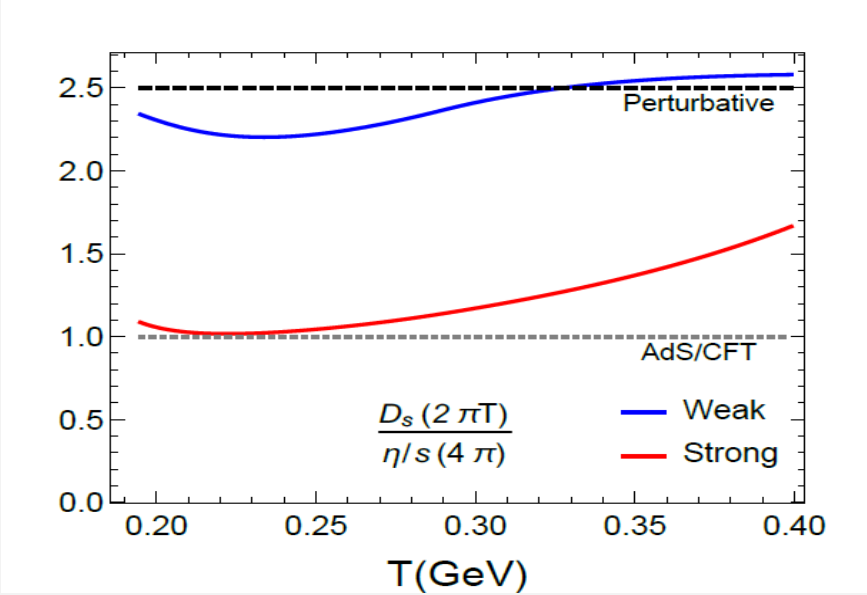
"Meson" T-matrix

- **Near T_c light partons melt + broad hadronic resonances emerge**

4.4 Transport Coefficients

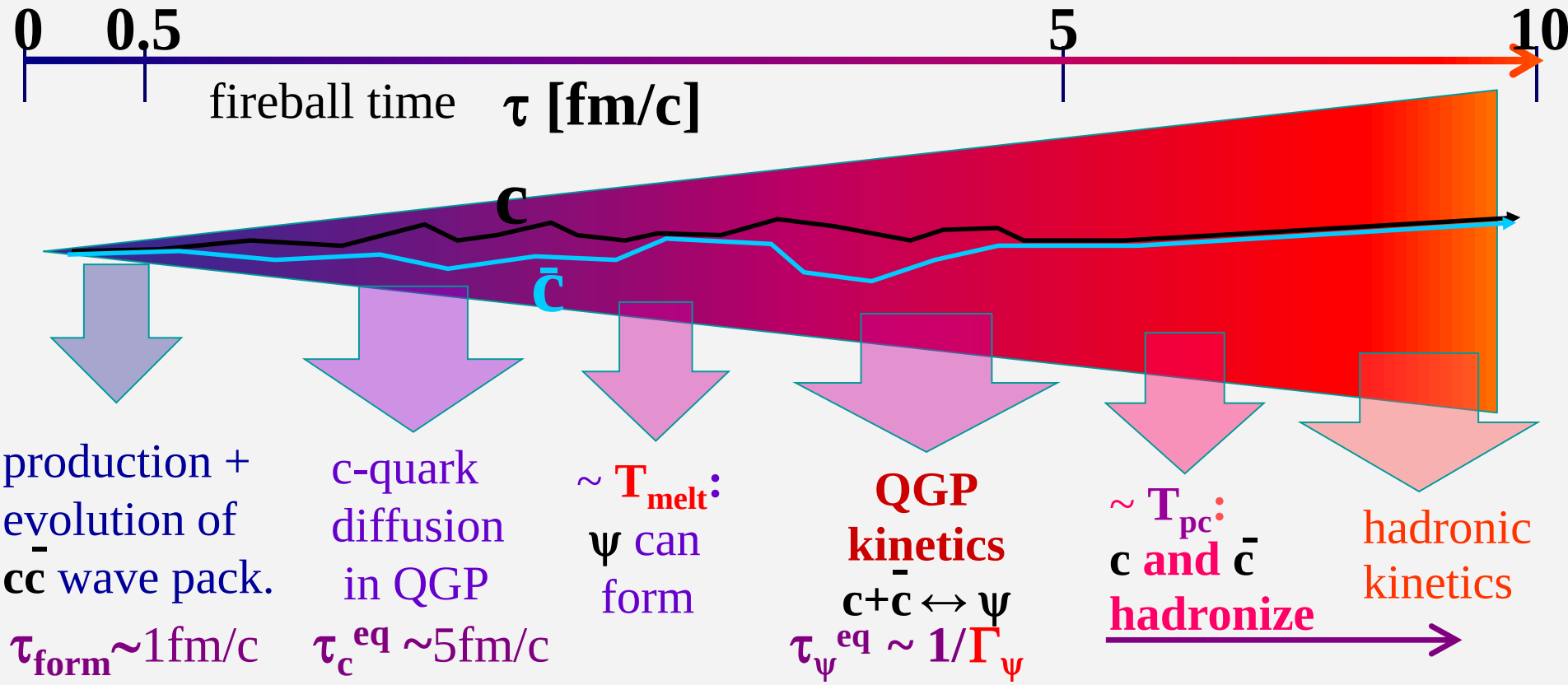
Viscosity and Heavy-Quark Diffusion





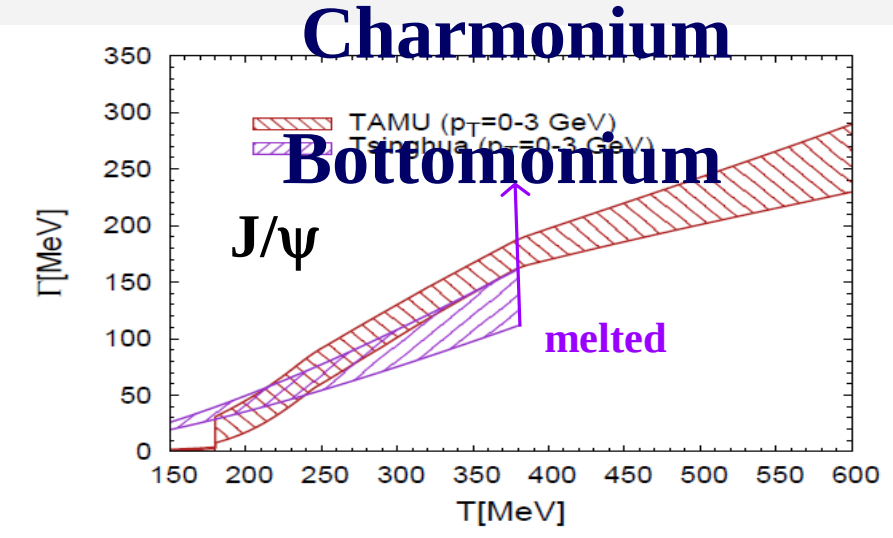
- Strongly coupled: **$(2\pi T)\ D_s \sim (4\pi)\ \eta/s$**
- Perturbative: **$(2\pi T)\ D_s \sim 5/2\ (4\pi)\ \eta/s$**
- Transition as **T** increases

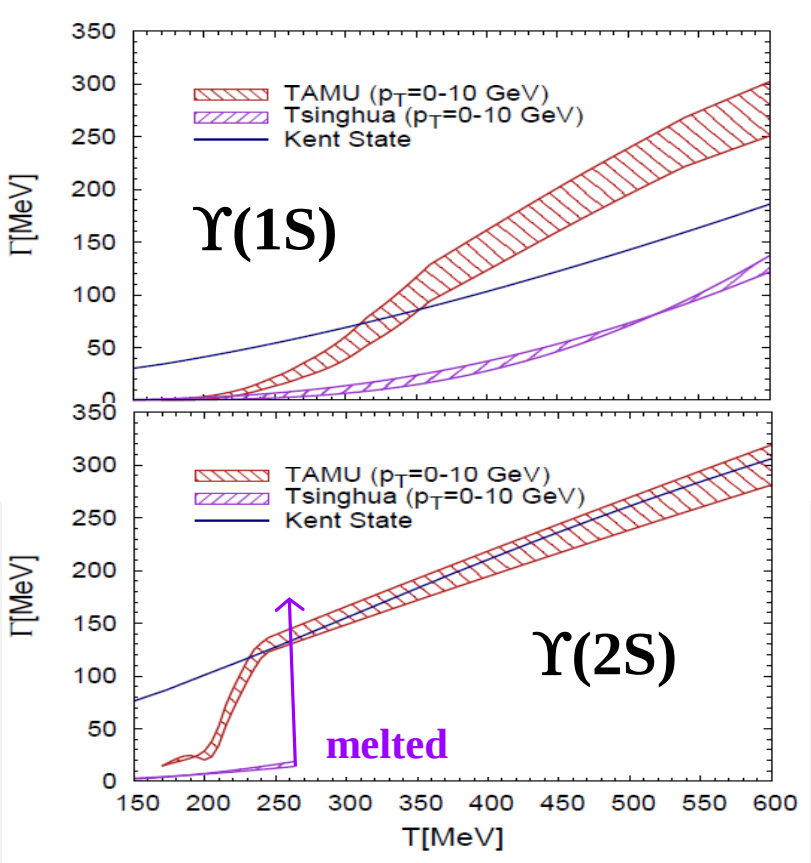
2.1 Quarkonium Transport in URHICs



[Satz et al, Capella et al, Spieles et al, PBM et al, Thews et al, Grandchamp et al, Ko et al, Zhuang et al, Zhao et al, Chaudhuri, Gossiaux et al, Young et al, Ferreiro et al, Strickland et al, Brambilla et al, …]

2.3 Quarkonium Width Comparisons





- Fair agreement for **J/ψ**
- Larger spread for ϒ states
- Binding energies differ