T-Matrix Approach to Strongly Coupled QGP

Ralf Rapp

Cyclotron Institute +
Dept of Phys & Astro
Texas A&M University
College Station, TX, USA

CYCLOTRON INSTITUTE
TEXAS A&M UNIVERSITY

NATIONAL SCIENCE FOUNDATION
NSF

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Outline

1.) Introduction

- Nonperturbative QCD Matter + Heavy Quarks

2.) Thermodynamic T-Matrix

- Selfconsistent Quantum Many-Body Theory
- Input Potential + Constraints from Lattice QCD

3.) Hamiltonian Approach to sQGP Structure

- Thermodynamic Potential + EoS
- Spectral + Transport Properties, Susceptibilities
- Spin-Induced Interactions + Nature of Confining Force
- Wilson Line Correlators + QCD Potential

4.) Heavy-Flavor Transport in Heavy-Ion Collisions

- Hadronization
- Open HF Phenomenology

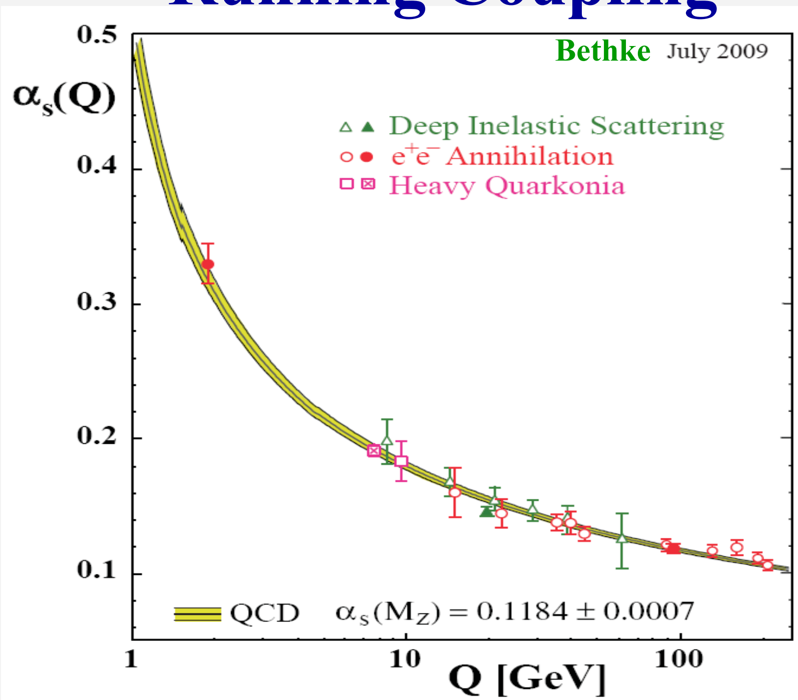
5.) Conclusions

1.1 Quantum Chromodynamics in Vacuum

$$\mathcal{L}_{QCD} = \bar{q}(i\gamma^\mu D_\mu - \mathcal{M}_q)q - \frac{1}{4}G^a_{\mu\nu}G^{\mu\nu}_a$$

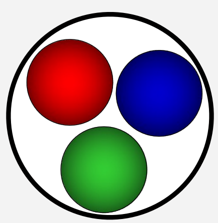
[Gross,Politzer +Wilczek '73]

Running Coupling

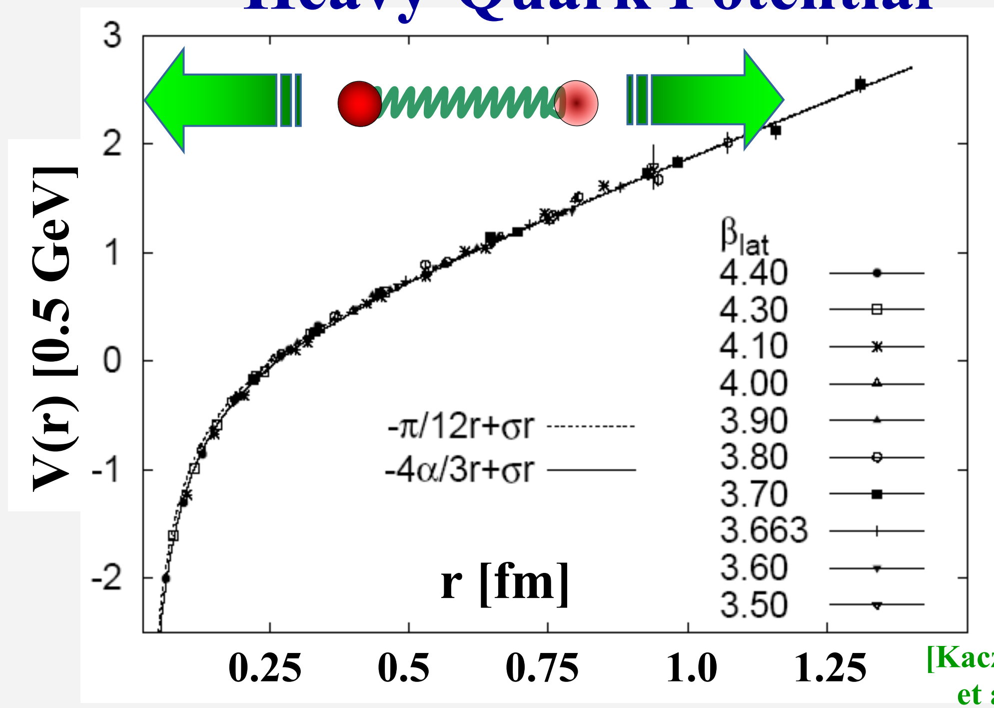


$Q^2 \leq$ 1 GeV^2 → **"strong QCD"**

- **Confinement**
- mass generation ($M_p \approx$ *1 GeV*)



Heavy-Quark Potential

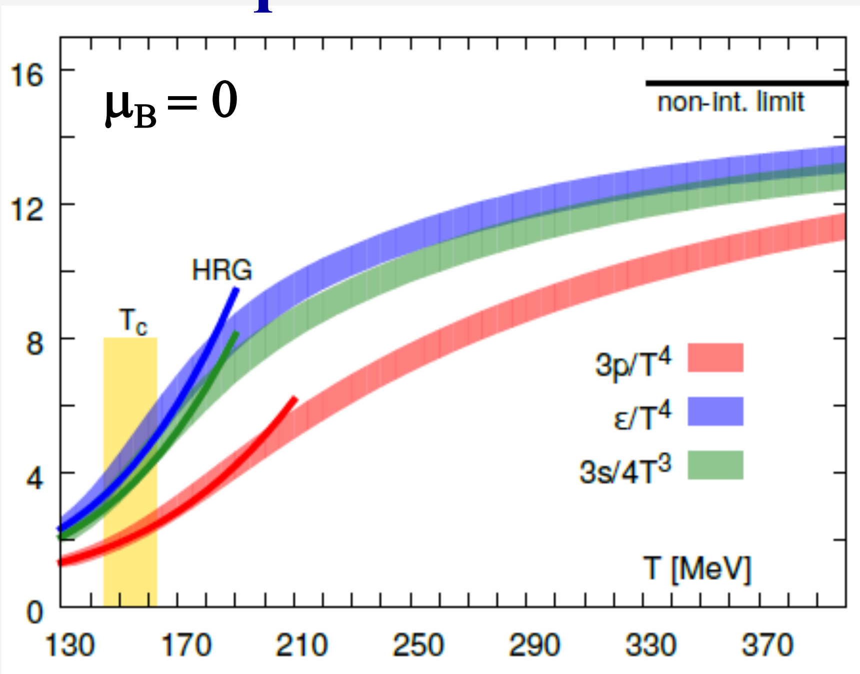


[Kaczmarek et al '05]

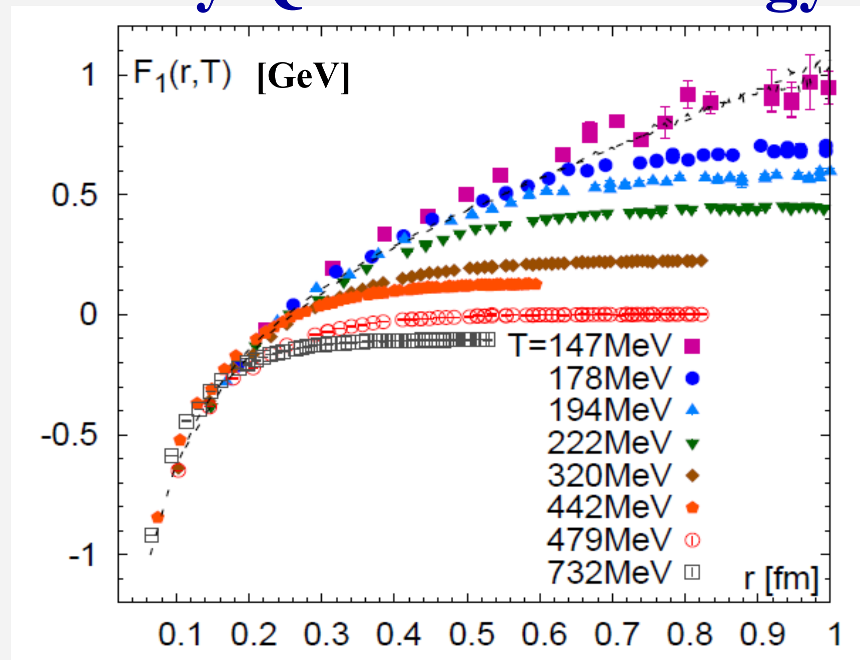
- Non-perturbative for *$r \geq 0.25$ fm*
- Operational definition of confinement
- Well-calibrated force describes charm-/bottom-onium spectroscopy

1.2 QCD Matter and In-Medium Force

Equation of State



Heavy-Quark Free Energy



[Bazavov et al ’13,’14]

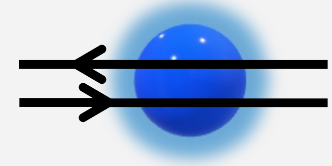
- “Change” in dofs above **T~160 MeV**

- $F_{Q\bar{Q}} = U_{Q\bar{Q}} - T\,S_{Q\bar{Q}}$
- Non-perturbative above T_c

- **How to probe the QCD force in medium?**
- **Consequences for heavy-quark transport + spectral functions?**
- **What is the structure of the strongly coupled QGP?**

1.3 Quarkonia in Medium: A Force Gauge

- potential **V(r,T)** → binding energy **E_B(p,T)**
- Dissociation rate → width **Γ(p,T,E_B)**

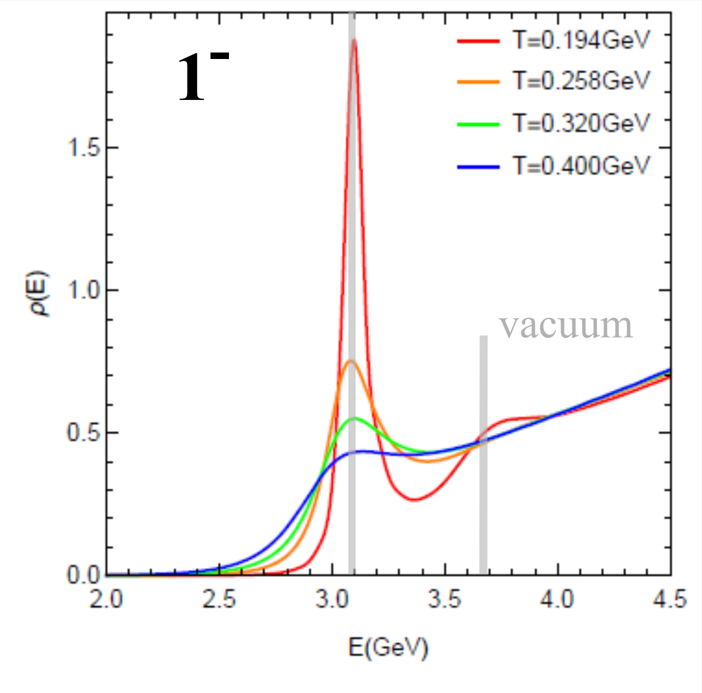


[Matsui +Satz '86]

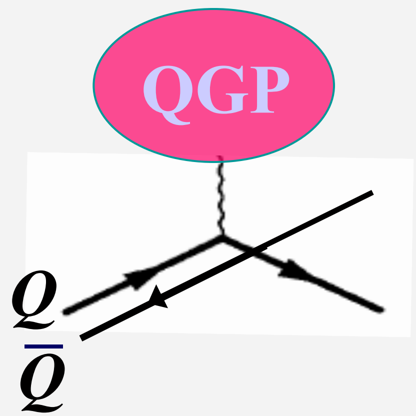
- **ϒ(1S): color-Coulomb force**
  J/ψ, ϒ(2S), …: confining force

→ **Quarkonium spectral functions**

Charmonium Spec. Fct.



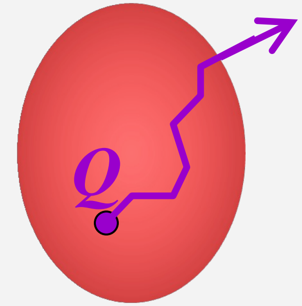
- **How do heavy quarks within quarkonia interact with the medium?**



→ **Simpler problem: one heavy quark!**

(m_c ~ 1.5 GeV, m_b ~ 4.5 GeV)

1.4 Heavy Quarks in QGP

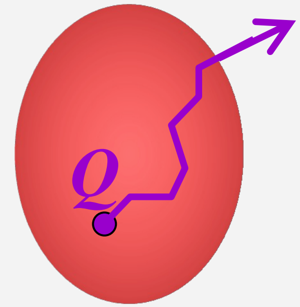


- **Brownian motion via elastic interactions** (radiation suppressed $q_0 \sim q^2/2m_Q << q \sim T << m_Q$)
- Thermalization **delayed** by m_Q/T → memory in heavy-ion collisions
- Direct access to **transport coefficient:** $\langle x^2 \rangle - \langle x \rangle^2 = 6\, \mathcal{D}_s\, t$
- **Scattering rates**
  → widths (**quantum effects**), quasiparticles?
  → estimate: $\mathcal{D}_s(2\pi T) = 3 \Rightarrow \Gamma_Q \sim 1$ GeV $> T$
  ⇒ **Implications for QGP structure**

- **Non-perturbative effects** (potential interactions)
- Probe of hadronization: **c → D, D_s, Λ_c, …** ($m_Q >> T_c$)

1.5 Strongly Coupled QGP

⇔ **Quantum liquid with transport coefficients near conjectured lower bounds**



- Microscopic calculation of transport coefficients should **obey** quantum-lower bounds

- Description of **bulk medium** through which heavy quarks propagate should encode strong-coupling properties
  → transport coefficients: $(4\pi)\eta/s$, $\mathcal{D}_s(2\pi T)$, σ_{el}/T

- **Large scattering rates** → large collisional widths
  → broad spectral functions → **off-shell (quantum) effects**

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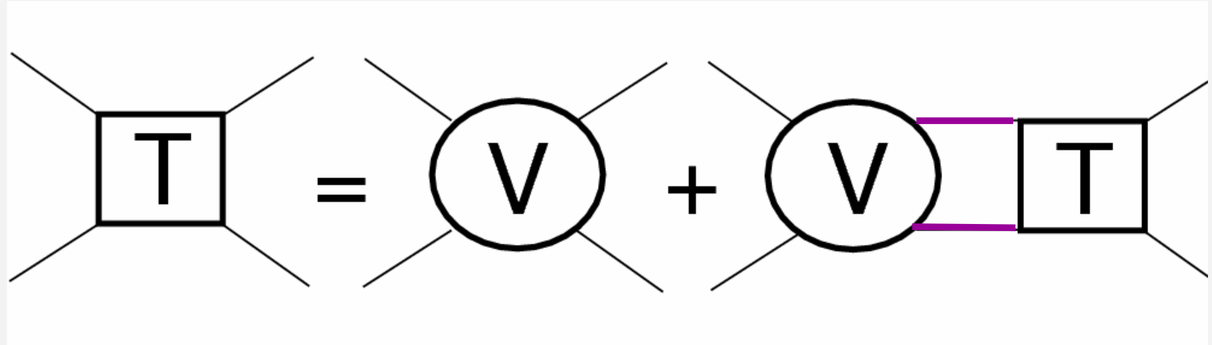
2.1 Thermodynamic T-Matrix in QGP

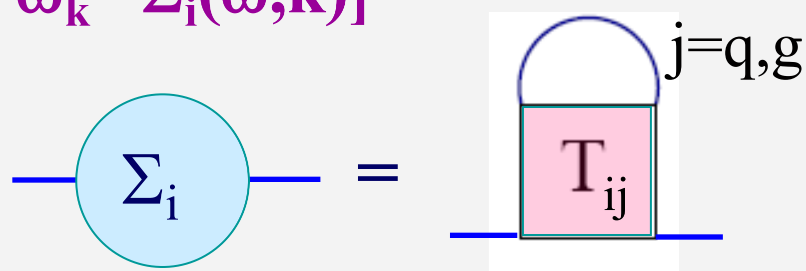
- **Scattering equation**

i=Q

j=Q,q,g



- Born approximation (**weak** coupling): $T_{ij} \approx V_{ij}$
- **Strong** coupling → resummation: $T_{ij} = V_{ij} + \int V_{ij}\, G_i\, G_j\, T_{ij}$
- Thermal parton propagators: $G_i = 1 / [\omega - \omega_k - \Sigma_i(\omega,k)]$
- Parton **self-energies** → **self-consistency**:



- $q \sim T << m_Q \;\Rightarrow\; q_{(4)}^2 = q_0^2 - q^2 \approx -q^2$

  ⇒ **3D** reduction of Bethe-Salpeter equation

- **In-medium potential V?**

[van Hees, Mannarelli, Cabrera, Riek, He, Liu, Tang + RR, ’04-date]

2.2 Potential Extraction from Lattice Data

- **Free energy ≠ potential:** $F_{QQ} = U_{QQ} - T\,S_{QQ}$
- Microscopic many-body approach:

$$F_{Q\bar{Q}}(r_1 - r_2) = -\frac{1}{\beta}\ln\left(\int_{-\infty}^{\infty} d\omega\,\sigma(\omega, r_1 - r_2)\,e^{-\beta\omega}\right)$$

- **$Q\bar{Q}$** spectral function

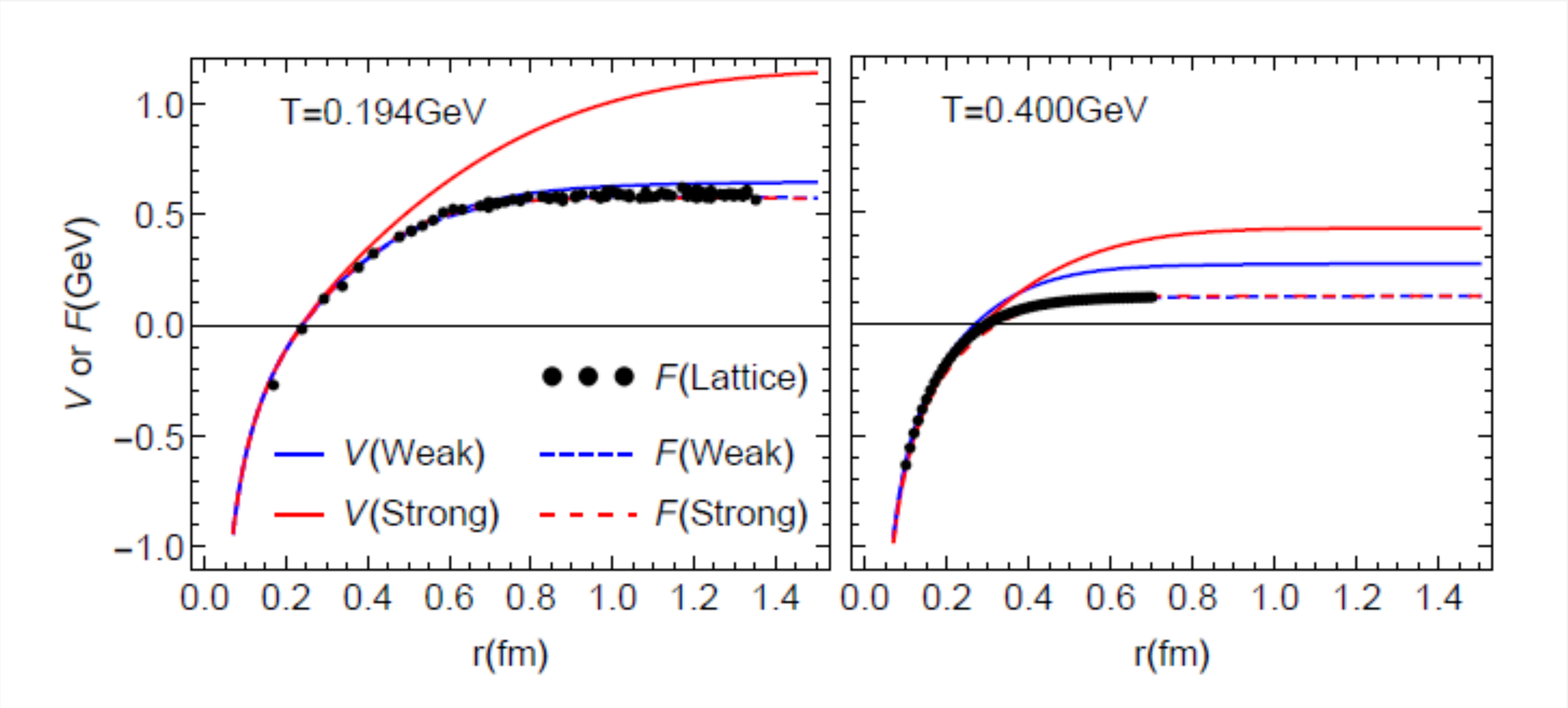
$$\sigma(\omega, r) = \frac{1}{\pi}\frac{(V+\Sigma)_I(\omega)}{(\omega - (V+\Sigma)_R)^2 + (V+\Sigma)_I^2(\omega)}$$

- Use trial potential $V_C + V_S = -\frac{4}{3}\alpha_s\frac{e^{-m_d r}}{r} - \frac{\sigma\,e^{-m_s r - (c_b m_s r)^2}}{m_s}$
- Self-consistently calculate self-energies to fit lattice-QCD data for F_{QQ}
- Weak coupling (small Σ_I): $F \rightarrow V$

2.2.2 In-Medium Potential from Lattice Data

- Two types of solutions:

  weakly coupled scenario (WCS) vs. strongly coupled scenario (SCS)

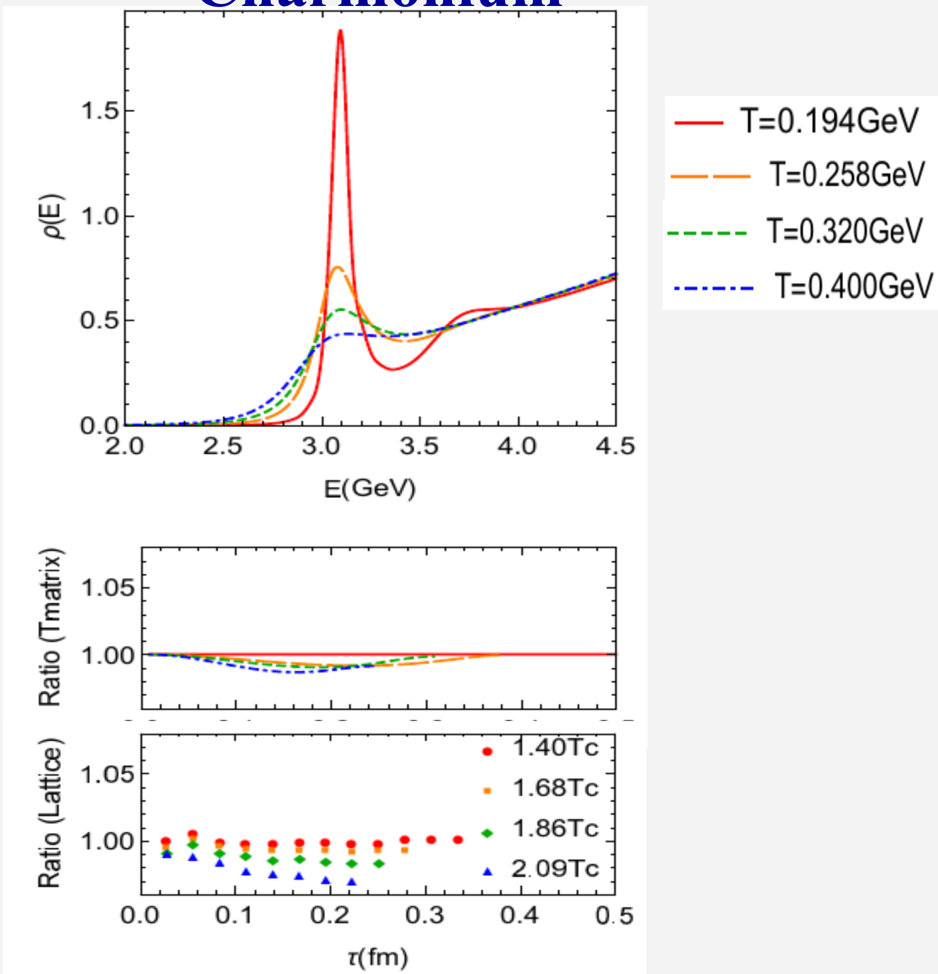


- **WCS: potential close to free energy F, $\Gamma_Q = 2\Sigma_I \sim 0.1$ GeV**
- **SCS: remnants of confining force well above T_c, $\Gamma_Q \sim 0.6$ GeV**

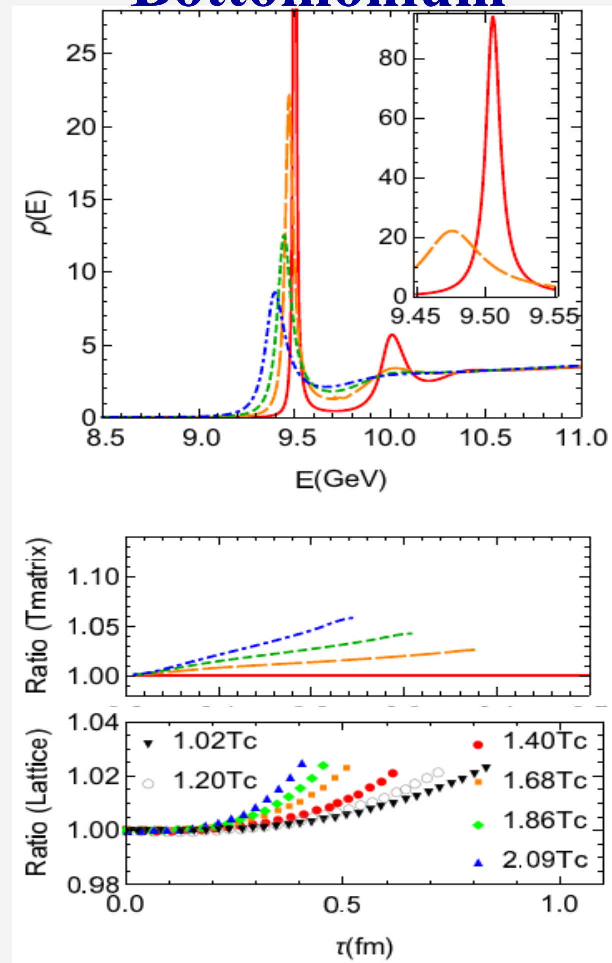
2.3 Lattice Constraints II: Euclidean Correlators

$$G_\alpha(\tau,T) = \int \frac{dE}{2\pi} \; \rho_\alpha(E,T) \; \frac{\cosh[E(\tau - 1/2T)]}{\sinh[E/2T]}$$

Charmonium



Bottomonium



[Liu et al '18]

[Aarts et al '18]

- J/ψ melts near T~ 320 MeV
- ϒ(1S) survives until T > 500 MeV

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3.) Hamiltonian Approach to QGP

- **In-Medium Hamiltonian** with ``bare" 2-body interactions

$$H = \sum \varepsilon_i(\mathbf{p})\psi_i^\dagger(\mathbf{p})\psi_i(\mathbf{p}) + \psi_i^\dagger(\frac{\mathbf{P}}{2} - \mathbf{p})\psi_j^\dagger(\frac{\mathbf{P}}{2} + \mathbf{p})V_{ij}^a\psi_j(\frac{\mathbf{P}}{2} + \mathbf{p}')\psi_i(\frac{\mathbf{P}}{2} - \mathbf{p}')$$

  - effective light-parton masses $\varepsilon_i(\mathbf{p}) = \sqrt{M_i^2 + \mathbf{p}^2}$

- Interaction: **Cornell potential** with relativistic corrections

$$V_{ij}^a(\mathbf{p}, \mathbf{p}') = \mathcal{R}_{ij}^{\mathcal{C}}\mathcal{F}_a^{\mathcal{C}}V_{\mathcal{C}}(\mathbf{p} - \mathbf{p}') + \mathcal{R}_{ij}^{\mathcal{S}}\mathcal{F}_a^{\mathcal{S}}V_{\mathcal{S}}(\mathbf{p} - \mathbf{p}')$$

  - **as used in heavy-quark sector**

- **Implement into Brueckner / Luttinger-Ward-Baym approach**

3.2 QGP Equation of State + Spectral Functions

Thermodynamic Potential (2-PI)

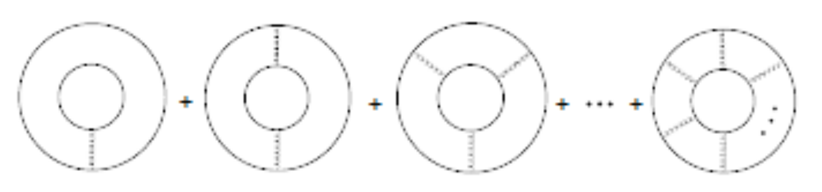
$$\Omega = \mp \frac{-1}{\beta} \sum_n \mathrm{Tr}\{\ln(-G^{-1}) + (G_0^{-1} - G^{-1})G\} \pm \Phi$$

Selfconsistent SFs

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

Lutttinger-Ward Functional

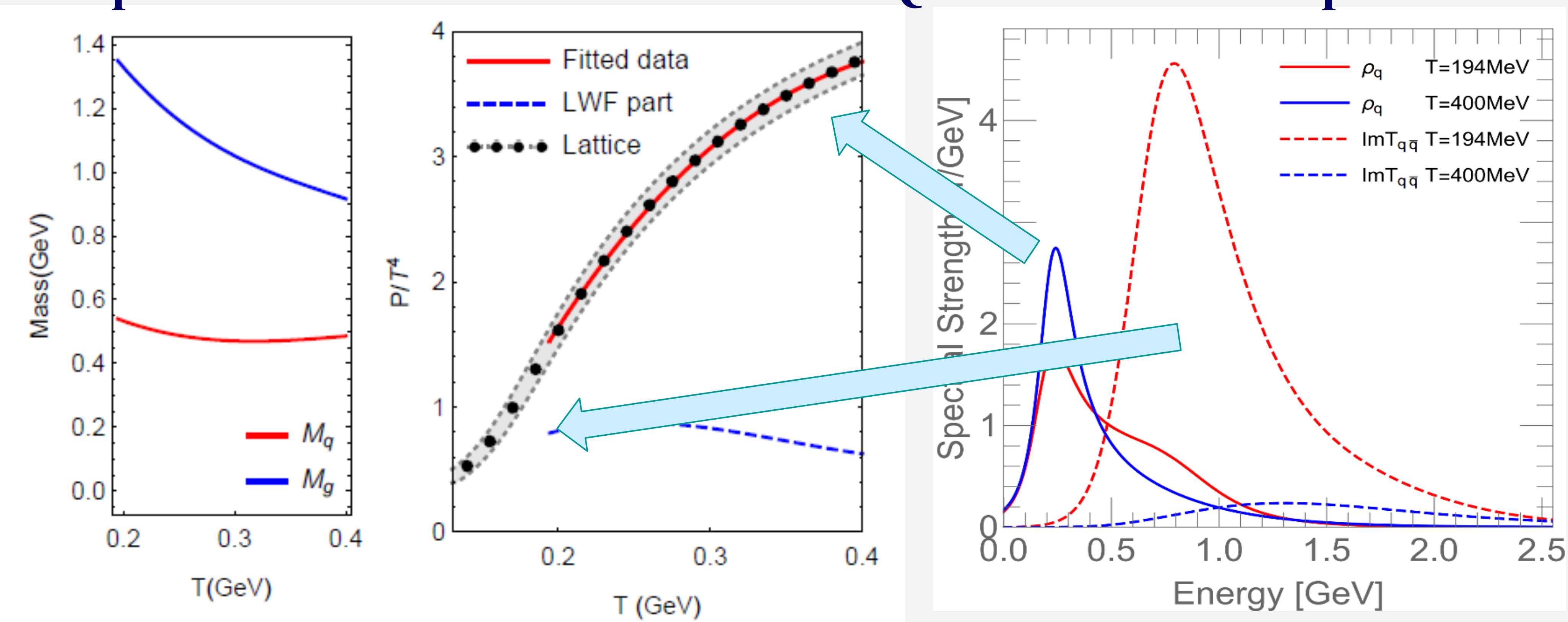
$$\Phi = \frac{-1}{\beta} \sum_{n,\nu} \mathrm{Tr}\{\frac{1}{2\nu}(\frac{-1}{\beta})^\nu [(-\beta)^\nu \Sigma_\nu(G)]G\}$$



- **Full off-shell resummed Luttinger-Ward functional (!)**
  → allows for dynamically emerging **hadronic resonances**
- Fit “bare” quark + gluon masses

3.3 QGP Equation of State + Degrees of Freedom

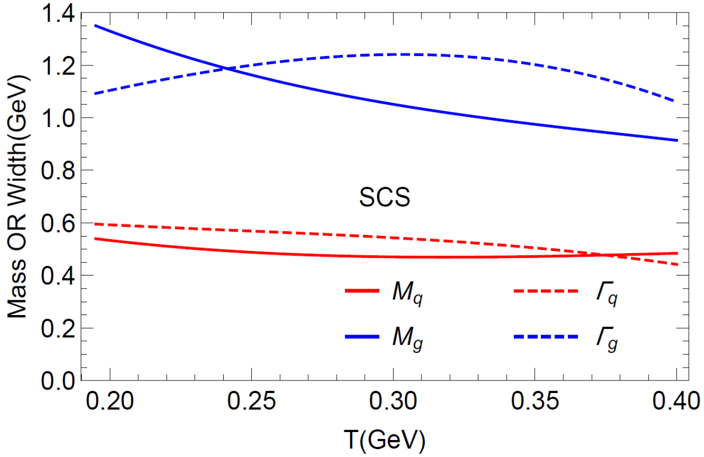
Input Masses **Pressure** **Quark + "Meson" Spectral Fcts**

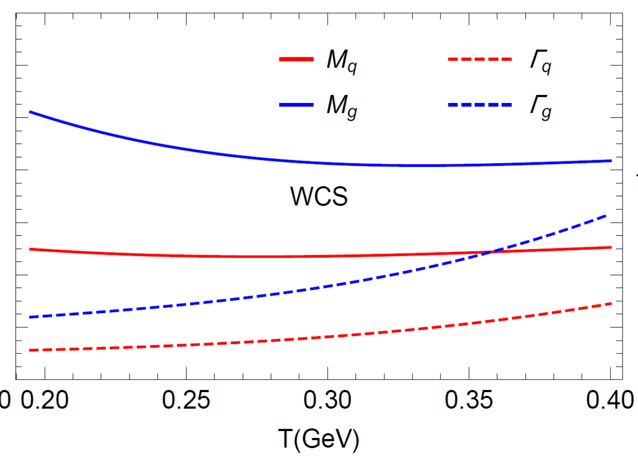


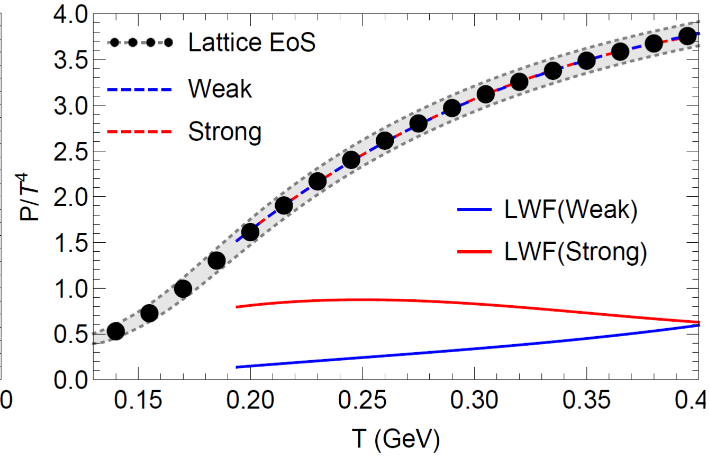
- Confining force near T_{pc} : - soft partons melt
  - broad hadronic resonances emerge

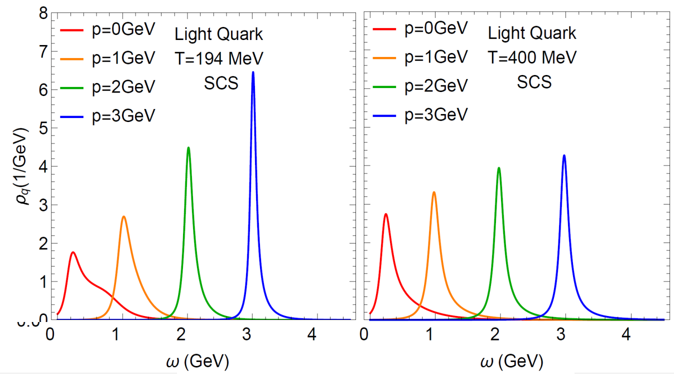
3.3.2 QGP Structure: Spectral Functions

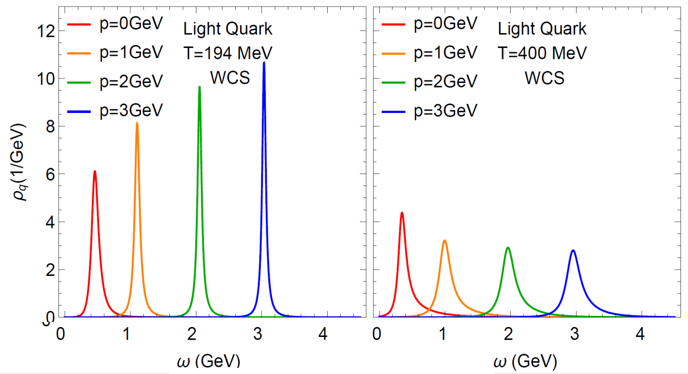
Strongly Coupled   Weakly Coupled

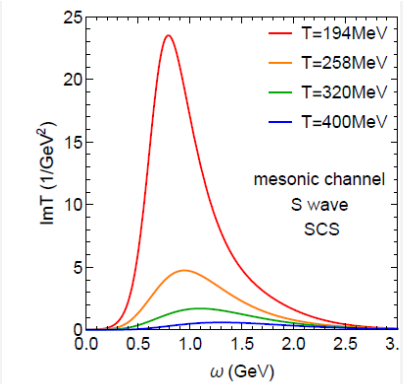


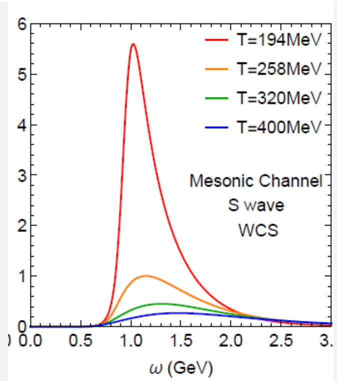










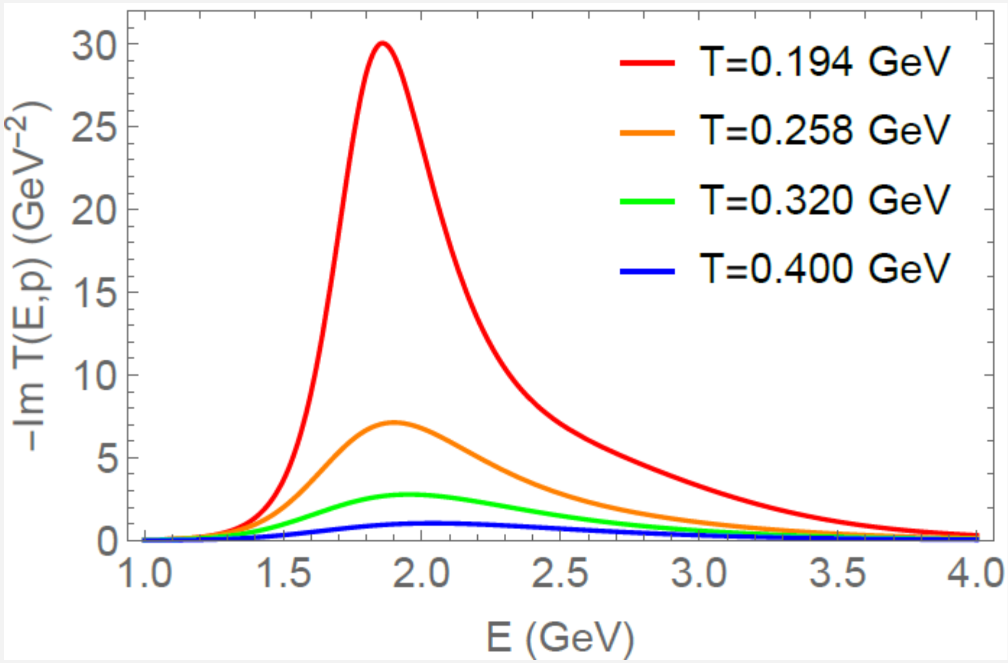


Strongly Coupled Scenario:

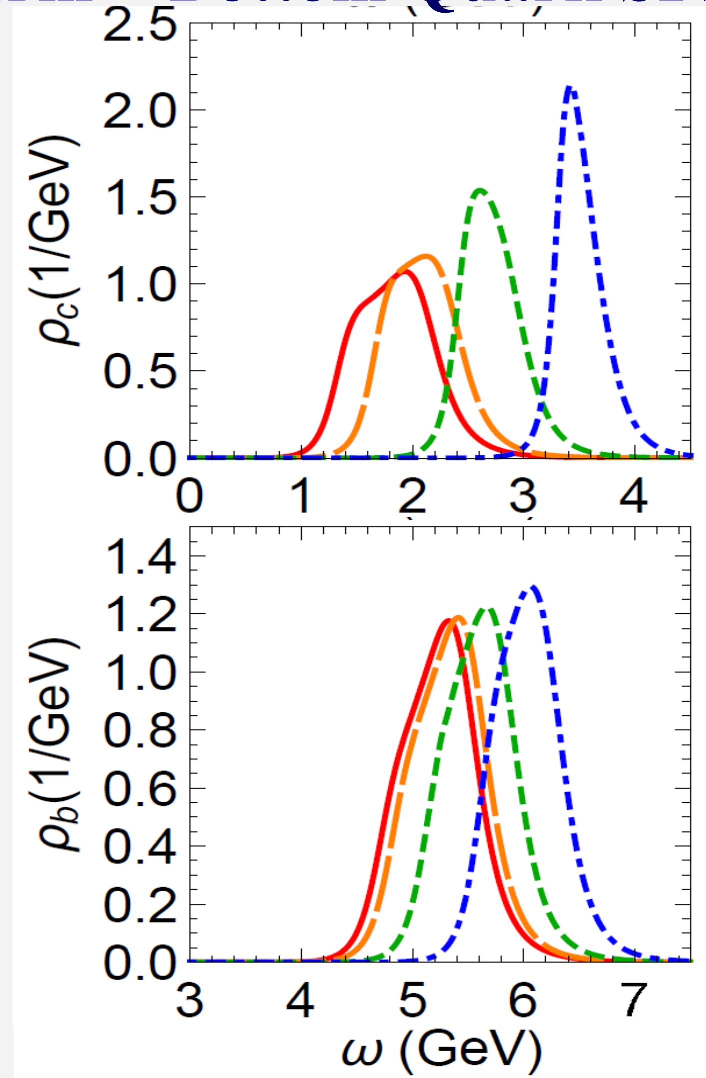
- Long-range confining force operative at low **T** + low **p**
- Quasiparticles at high **p**, **T**

3.3.3 Heavy-Flavor Spectral Functions

Charm-Light Quark T-Matrix



Charm + Bottom Quark SFs



- Broad **D**-meson resonances emerge near T_{pc}
- Despite large widths, $\Gamma_Q \sim 0.6\text{GeV} \ll \omega_Q$

⇒ **c** + **b** quarks remain reasonable **quasiparticles!**

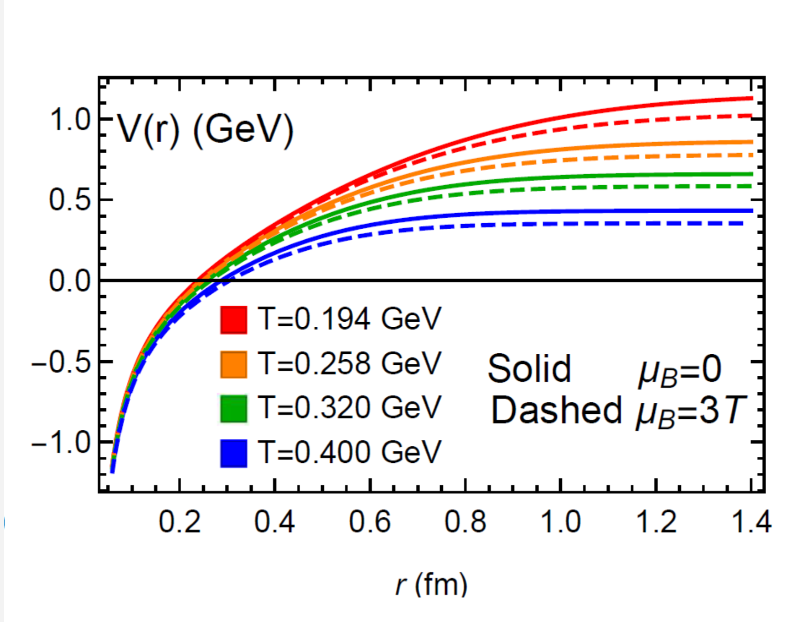
3.4 Susceptibilities

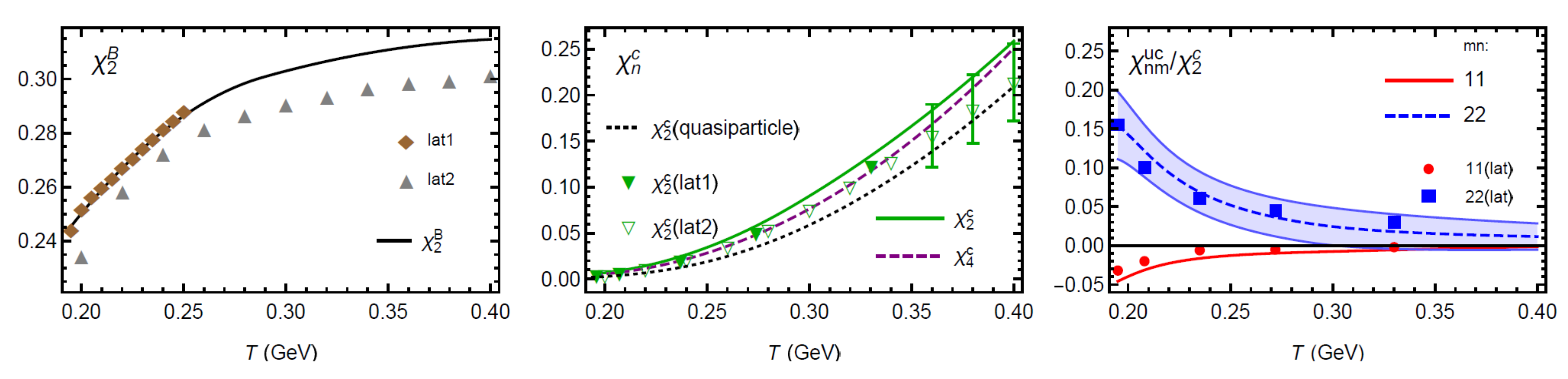
- μ_B dependence of bare masses + potential

$$M_i = M_i^0 \sqrt{1 + b_m \left(\frac{\mu_q}{T}\right)^2} + M_i^V \qquad m_d = m_d^0 \sqrt{1 + b_s \left(\frac{\mu_q}{T}\right)^2}$$

- fit b_m=0.1, $b_s(T)$ to $\chi_2^B = \frac{\partial^2 \hat{P}}{\partial \hat{\mu}_B^2} = \frac{1}{9}\frac{\partial^2 \hat{P}}{\partial \hat{\mu}_q^2}$

- predict charm susceptibilities $\chi_{nm}^{qc} = \frac{\partial^{n+m} \hat{P}}{\partial \hat{\mu}_q^n \partial \hat{\mu}_c^m}$

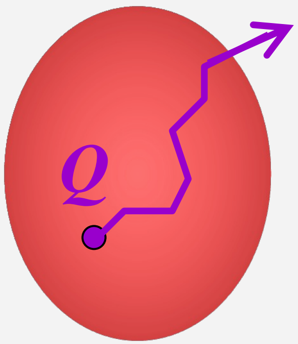




- Susceptibilities compatible with heavy-light resonances above T_{pc}
- Genuine prediction of negative χ^{uc}

[Liu+RR '22]

3.5 Heavy-Flavor Transport Equation



- $p^2 \sim m_Q T >> q^2 \sim T^2$ ⇒ **Brownian Motion**:

$$\frac{\partial}{\partial t} f_Q(t,p) = \gamma \frac{\partial}{\partial p_i}[p_i f_Q(t,p)] + D_p \Delta_{\vec{p}} f_Q(t,p)$$

Fokker-Planck

thermalization rate

$$\gamma p = \int d^3q \, w_Q(q,p) \, q$$
$$\sim \int |T_{Qj}|^2 (1-\cos\theta) f^j$$

diffusion coefficient

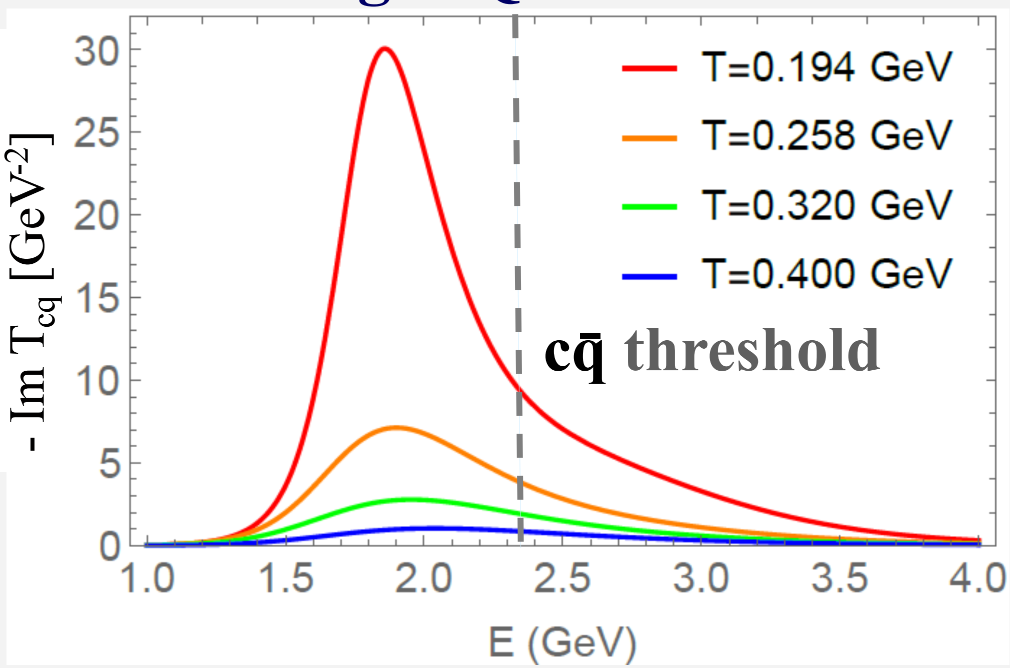
$$D_p = \int d^3q \, w_Q(q,p) \, q^2$$

- thermal relaxation time $\tau_Q = 1/\gamma$
- Einstein relation: $T = D_p / \gamma m_Q$
- Spatial diffusion constant: $\mathcal{D}_s = T/\gamma(0) m_Q$, $\langle x^2 \rangle - \langle x \rangle^2 = 6 \mathcal{D}_s t$
- Quantum effects encoded in γ, D_p via folding over spectral functions

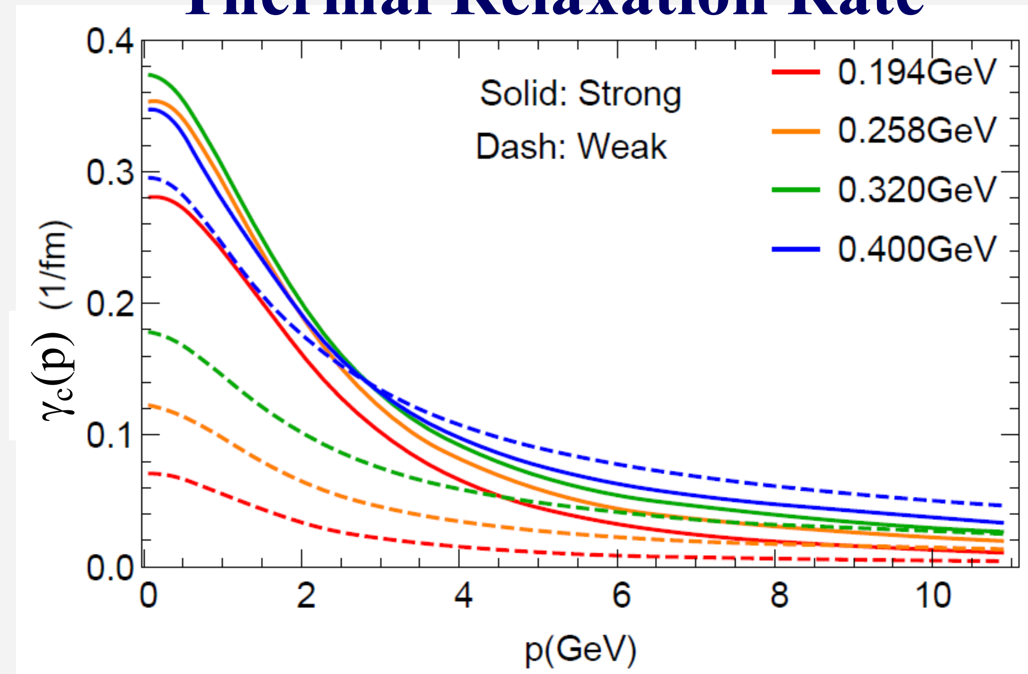
⇒ **Brownian particle in a liquid!**

3.5.2 Charm-Quark Transport Coefficient

Charm-Light Quark T-Matrix



Thermal Relaxation Rate

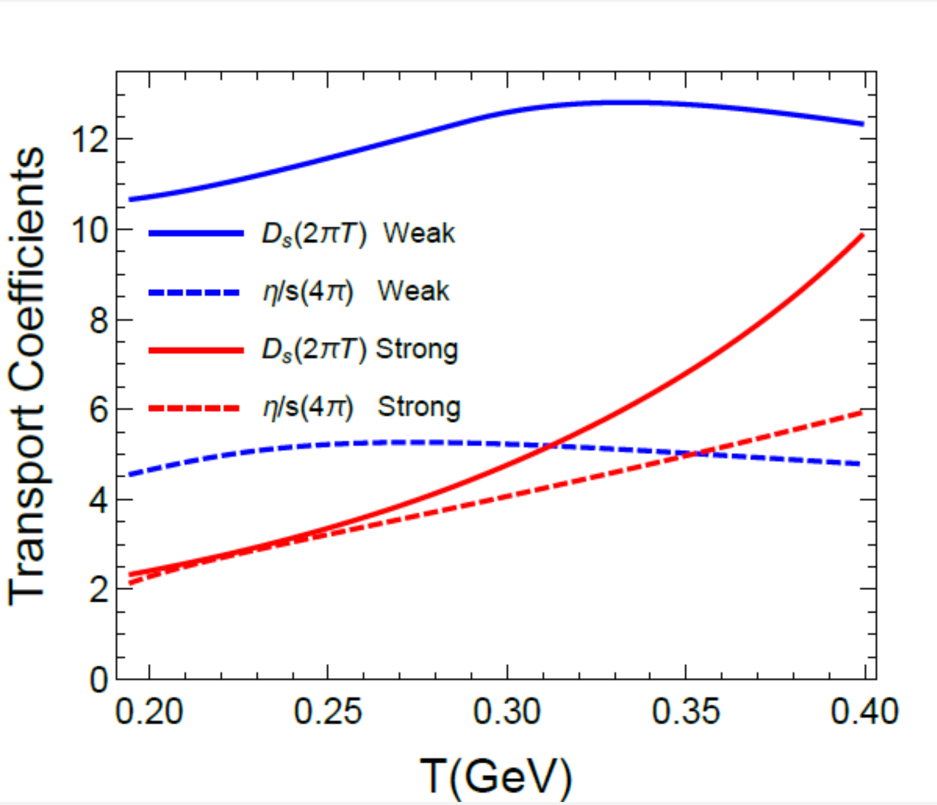


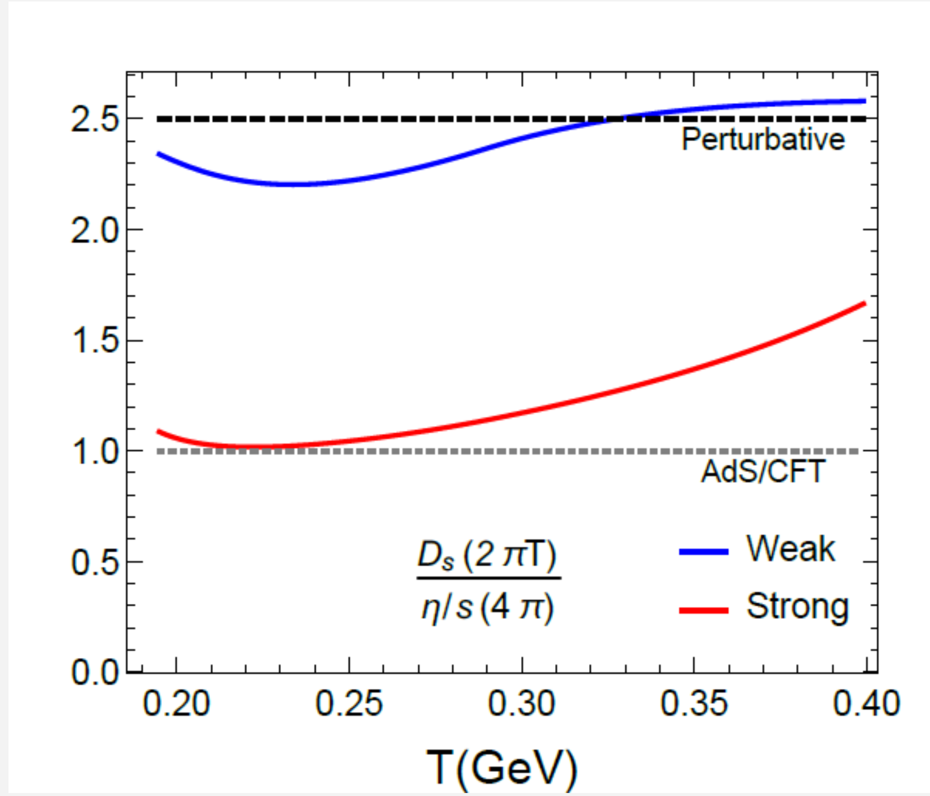
- Broad **D**-mesons near T_c
  - instrumental for non-pert. interaction strength (~10x pQCD)
  - **broad SFs to evaluate γ: quantum effects critical!**
  - **$\tau_c = 1/\gamma_c \approx 3$ fm/c , $\mathcal{D}_s (2\pi T) \approx 2$**
  - connects **diffusion** + **hadronization**

[Liu,He+RR '19]

3.6 Transport Coefficients + Strong-Coupling Limit

Shear Viscosity and Heavy-Quark Diffusion





- Strongly coupled: $(2\pi T)\,\mathcal{D}_s \sim (4\pi)\,\eta/s$
- Perturbative: $(2\pi T)\,\mathcal{D}_s \sim 5/2\,(4\pi)\,\eta/s$
- Transition as **T** increases

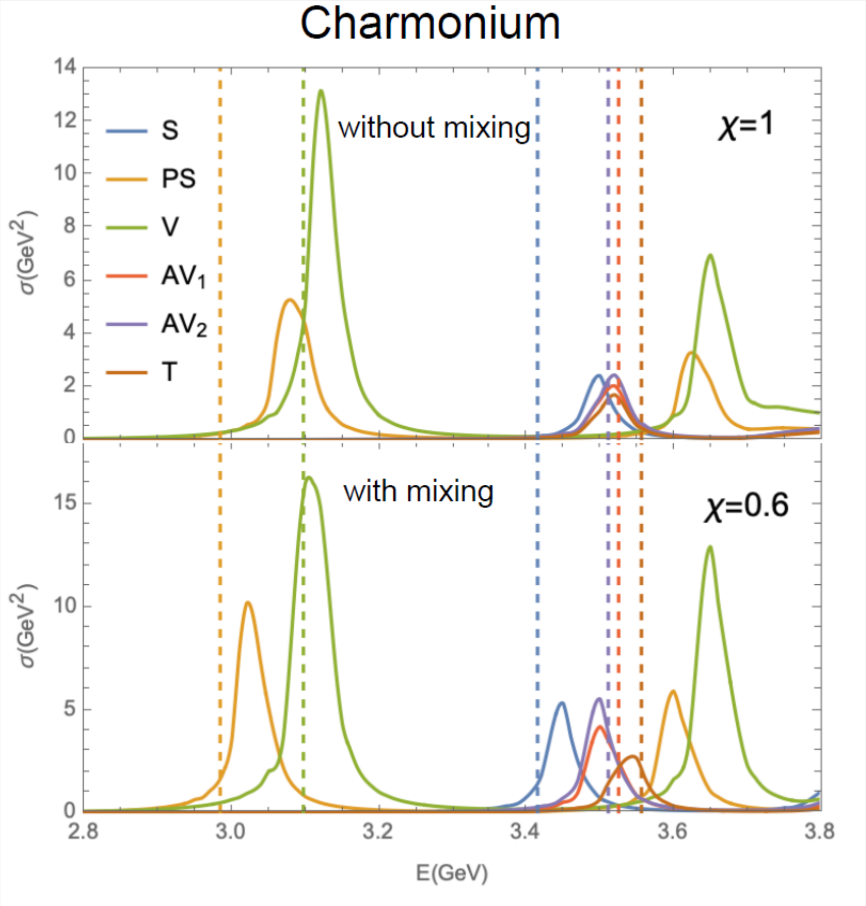
3.7 Recent Progress I: Spin-Induced Interactions

- Higher order in $1/m_Q$ expansion:

spin-orbit: $V^{LS} = \frac{1}{2M_Q^2 r}\langle \boldsymbol{L}\cdot\boldsymbol{S}\rangle\left(3\frac{d}{dr}V^{vec} - \frac{d}{dr}V^{sca}\right)$ spin-spin: $V^{SS} = \frac{3}{3M_Q^2}\langle \boldsymbol{S_1}\cdot\boldsymbol{S_2}\rangle \triangle V^{vec}$

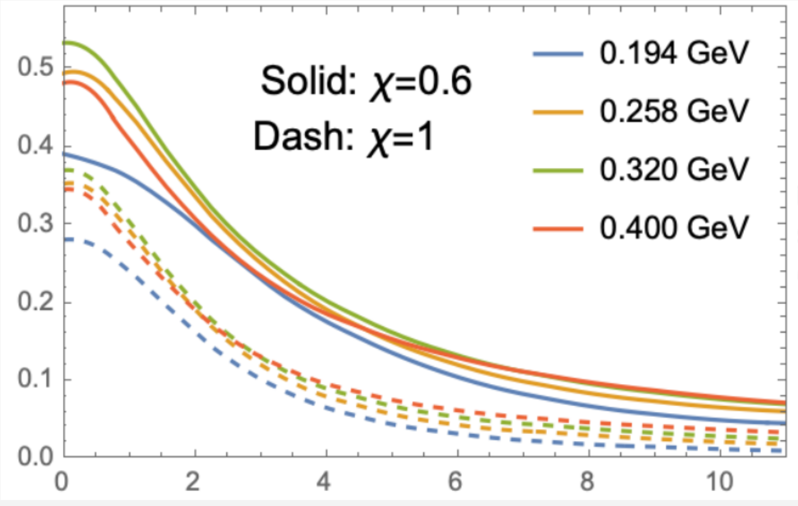
tensor: $V^T = \frac{1}{12M_Q^2}S_{12}\left(\frac{1}{r}\frac{d}{dr}V^{vec} - \frac{d^2}{dr^2}V^{vec}\right)$

- **Vector component** in confining potential $V^{vec} = V_{Coul} + (1-\chi)V_{conf}\ , V^{sca} = \chi V_{conf}$



⇒ Much improved hyper/fine splittings!

⇒ Significant impact on transport coefficient (harder 3-mom dependence)

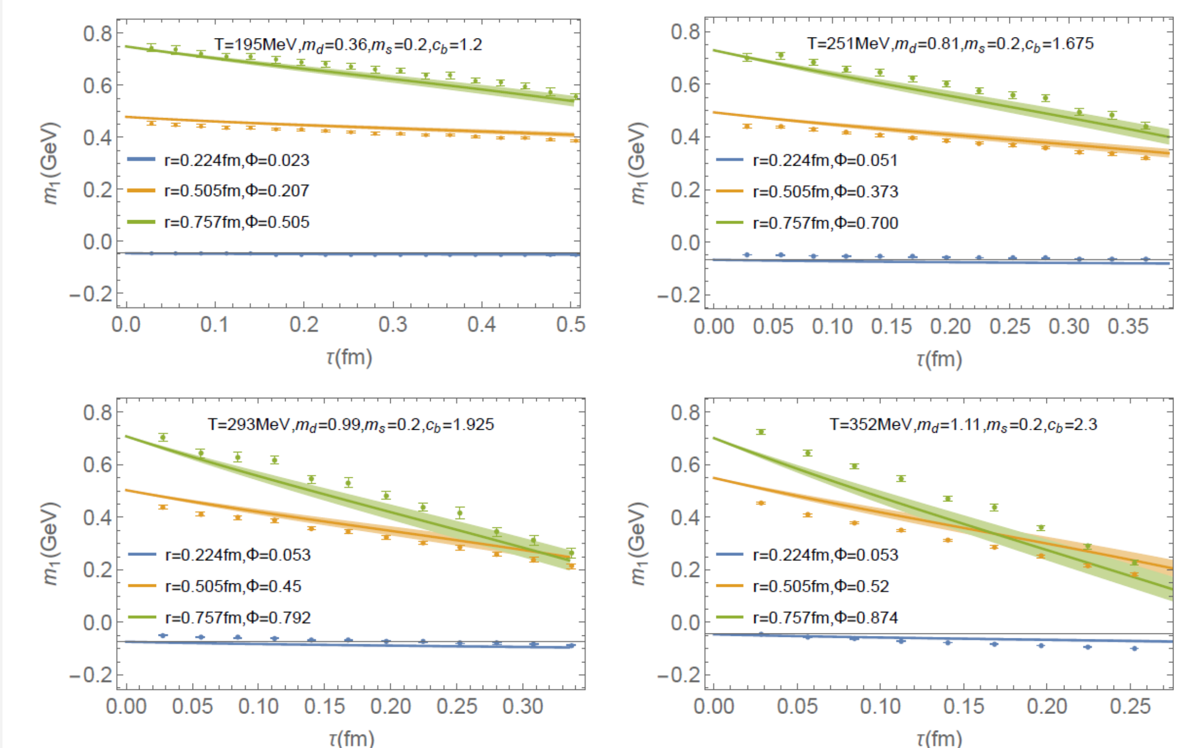


[Tang+RR '23]

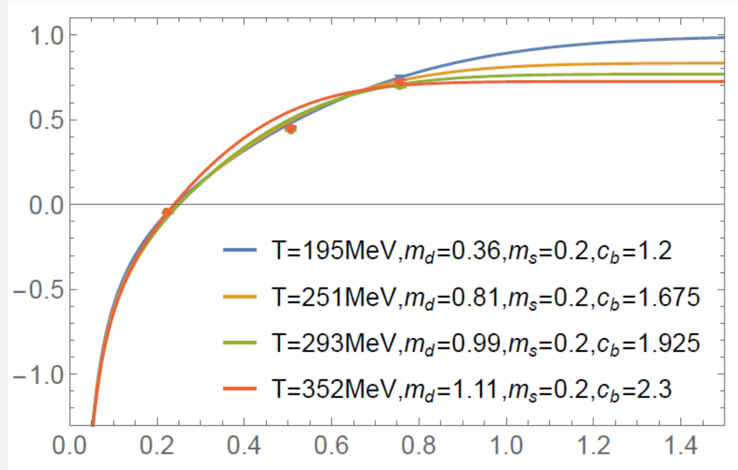
3.8 Recent Progress II: Wilson Line Correlators

[Tang,Mukherjee,Petreczky+RR, in prep]

- $$W(r,\tau,T) = \int_{-\infty}^{\infty} d\omega e^{-\omega\tau} \rho_{Q\bar{Q}}(\omega,r,T)$$
- Static quarkonium spectral fct: $$\rho_{Q\bar{Q}}(\omega,r,T) = \frac{-1}{\pi}\mathrm{Im}\left[\frac{1}{\omega - V(r,T) - \Phi(r,T)\Sigma_{Q\bar{Q}}(\omega,T)}\right]$$
- LQCD: first cumulant: $m_1(r,\tau,T) = -\partial_\tau \ln W(r,\tau,T)$ [Bala et al '22]



- Need smaller screening masses, even less potential screening
- First microscopic description



Outline

1.) Introduction
- Nonperturbative QCD Matter and Heavy Quarks

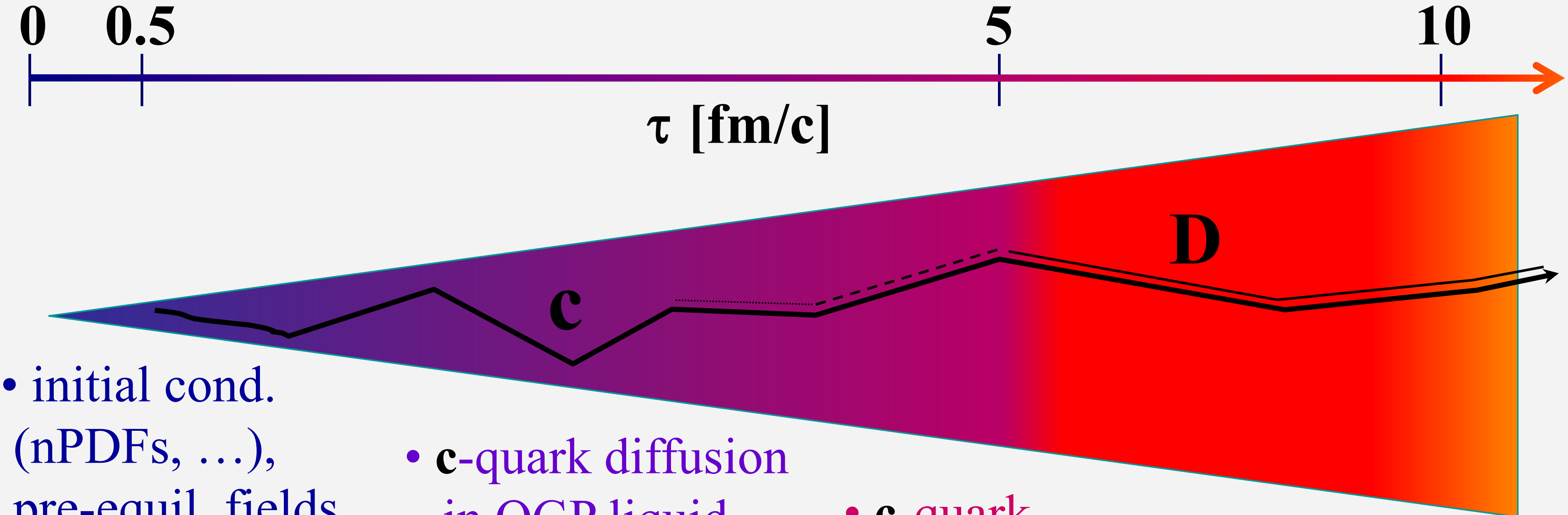
2.) Thermodynamic T-Matrix
- Selfconsistent Quantum Many-Body Theory
- Input Potential + Constraints from Lattice QCD

3.) Hamiltonian Approach to sQGP Structure
- Thermodynamic Potential + EoS
- Spectral + Transport Properties, Susceptibilities
- Spin-Induced Interactions + Nature of Confining Force
- Wilson Line Correlators + QCD Potential

4.) Heavy-Flavor Transport in Heavy-Ion Collisions
- Hadronization
- Open HF Phenomenology

5.) Conclusions

4.1 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

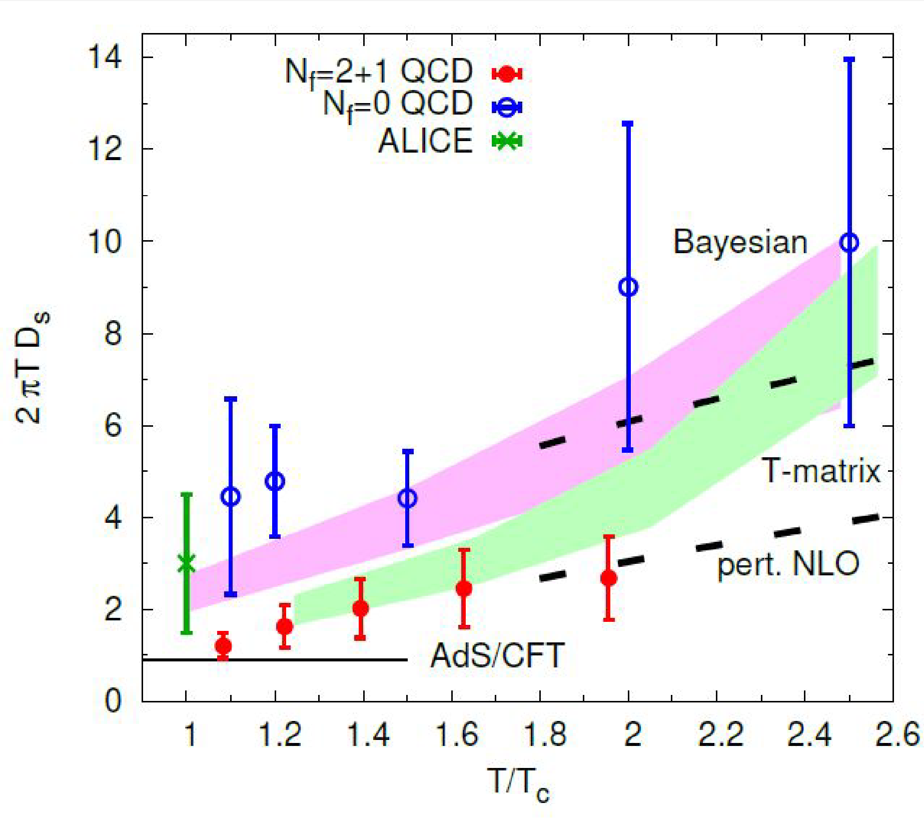
- no "discontinuities" in interaction

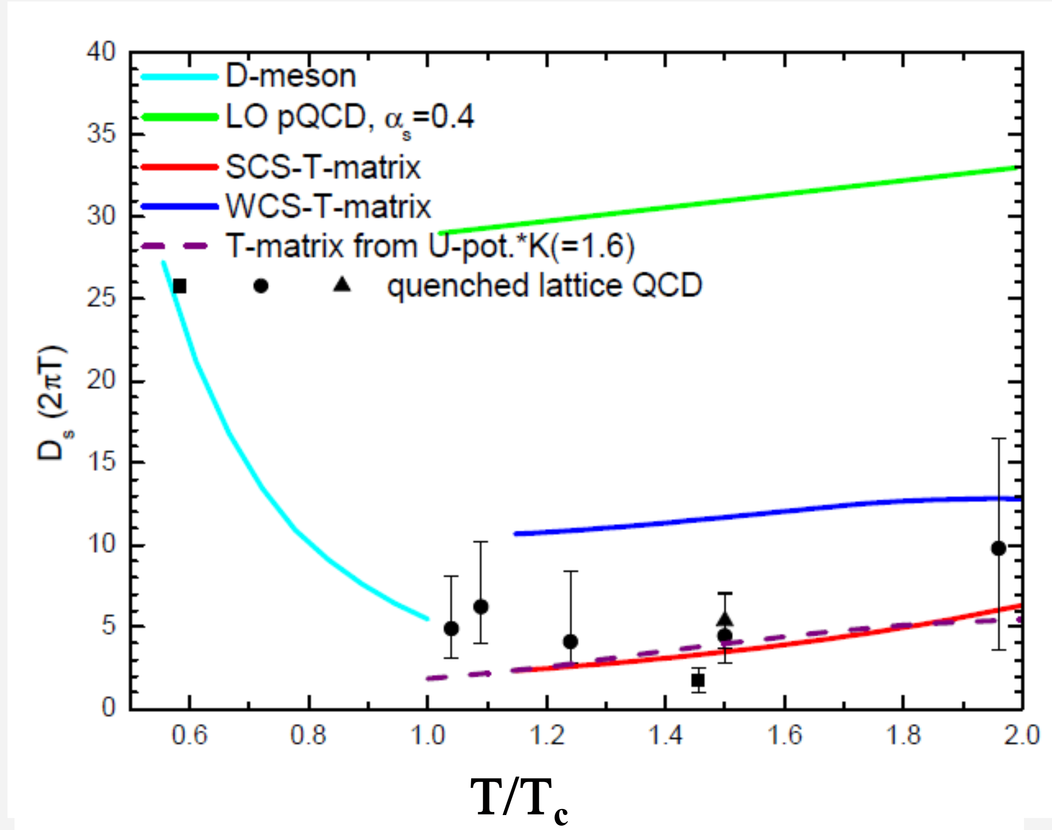
⇒ **diffusion toward** T_{pc} and **hadronization** same interaction (**confining!**)

[Svetitsky '87, Mustafa et al '04, Moore+Teaney '05, van Hees et al '05, Gossiaux et al '08, Vitev et al '08, Das et al '09, Uphoff et al '10, M.He et al '11, Beraudo et al '11, Cao et al '13, Greco et al '14, Bratkovskaya et al '14, …]

4.2 Spatial Charm-Quark Diffusion Coefficient

$\mathcal{D}_s = T / [m_Q\, \gamma(p=0)]$

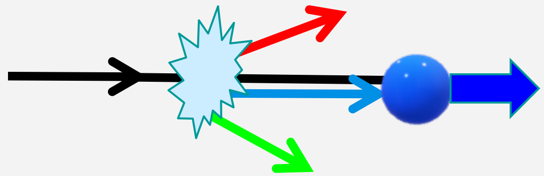




- suggests minimum of $\mathcal{D}_s(2\pi T) \sim 2$ near T_{pc}
- width: $\Gamma_{coll} \sim 3/\mathcal{D}_s \sim 1$ GeV – **no light quasi-particles!**

4.3 Hadronization of Heavy Quarks

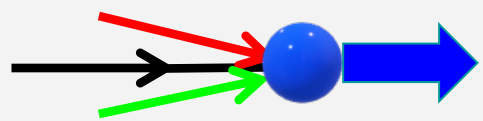
- **Fragmentation**



c → D, D*, D_s, Λ_c, …

- **empirical fragmentation functions $D_{c\to H_c}(z)$**
- universal in "vacuum": **e^+e^-, pp** collisions, large **p_T**

- **Coalescence/Recombination**



[Hwa et al '03, Fries et al '03, Greco et al '03]

c + q (s) → D (D_s), D*,… ; c + q + q (s) → Λ_c (Ξ_c), …

- depends on **environment** (surrounding anti-/quarks)
- test hadronization through "hadro-chemistry"
- **Resonance Recombination Model** [Ravagli+RR '07]

$$f_M(\vec{x},\vec{p}) = \frac{\gamma_M(p)}{\Gamma_M}\int \frac{d^3\vec{p}_1 d^3\vec{p}_2}{(2\pi)^3} f_q(\vec{x},\vec{p}_1) f_{\bar{q}}(\vec{x},\vec{p}_2)\, \sigma_M(s) v_{\rm rel}(\vec{p}_1,\vec{p}_2)\delta^3(\vec{p}-\vec{p}_1-\vec{p}_2)$$

$\sigma_M(s)\, v_{rel} \sim |T_{Qi}|^2$: resonant heavy-light amplitude

4.4 Two Main Observables in Heavy-Ion Collisions

• Modification of transverse-momentum (**p_T**) spectra in **AA** collisions relative to **pp** collisions:

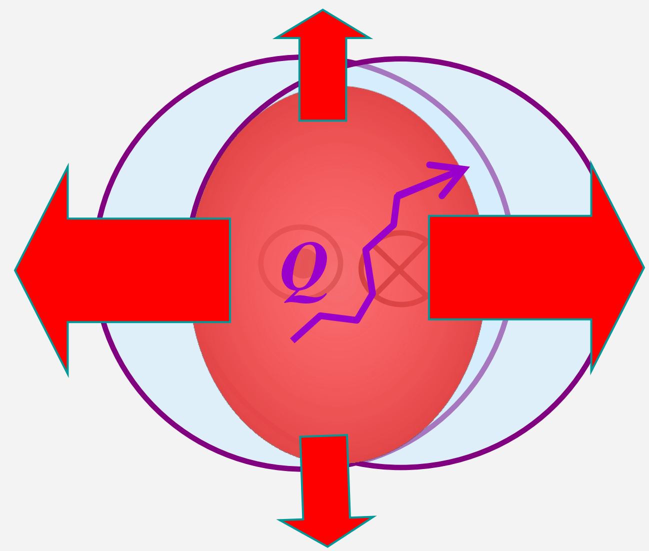
$$R_{AA}(p_T) \equiv (dN/dp_T)_{AA} \;/\; (N_{coll}\; dN/dp_T)_{pp}$$

• Angular distribution of the particle spectra

$$\frac{dN}{d^2p_T} = \frac{dN}{\pi\, dp_T^2}[1 + 2v_2(p_T)\cos(2\phi) + \ldots]$$

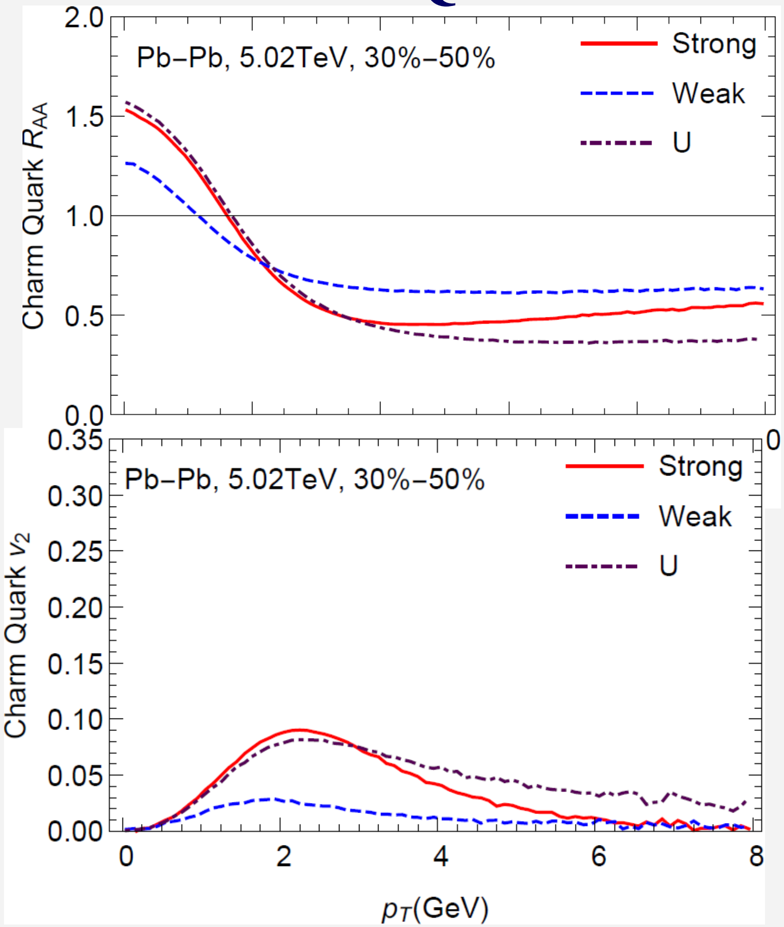
v_2: "elliptic flow" coefficient

→ reflects coupling strength of heavy quark to medium expansion

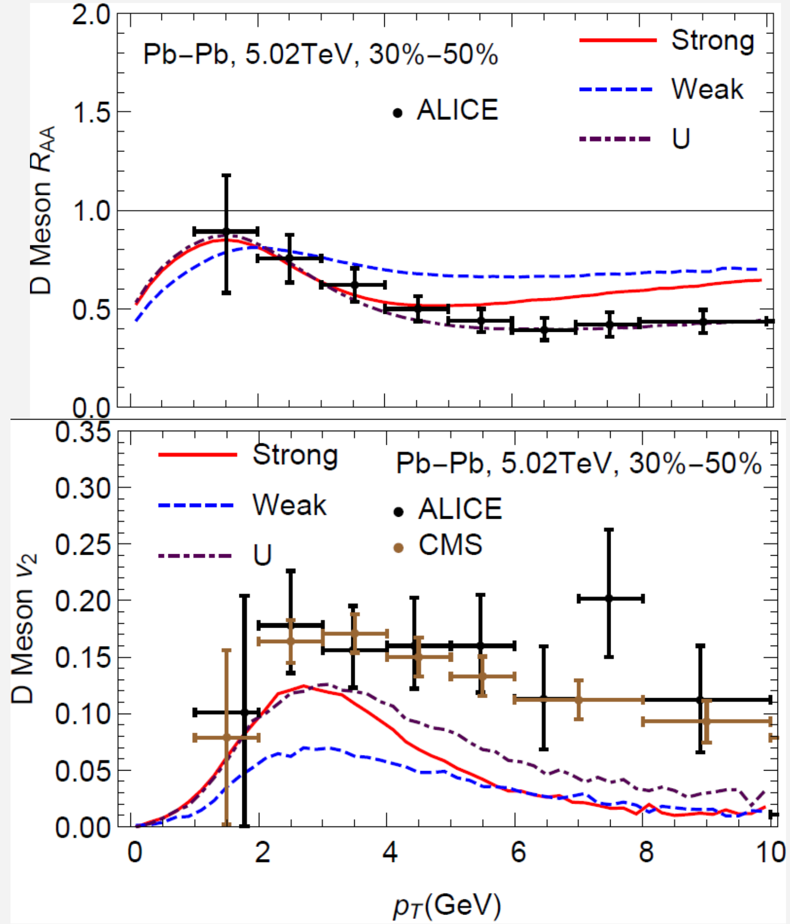


4.5 Sensitivity to Heavy-Quark Potential

Charm Quark



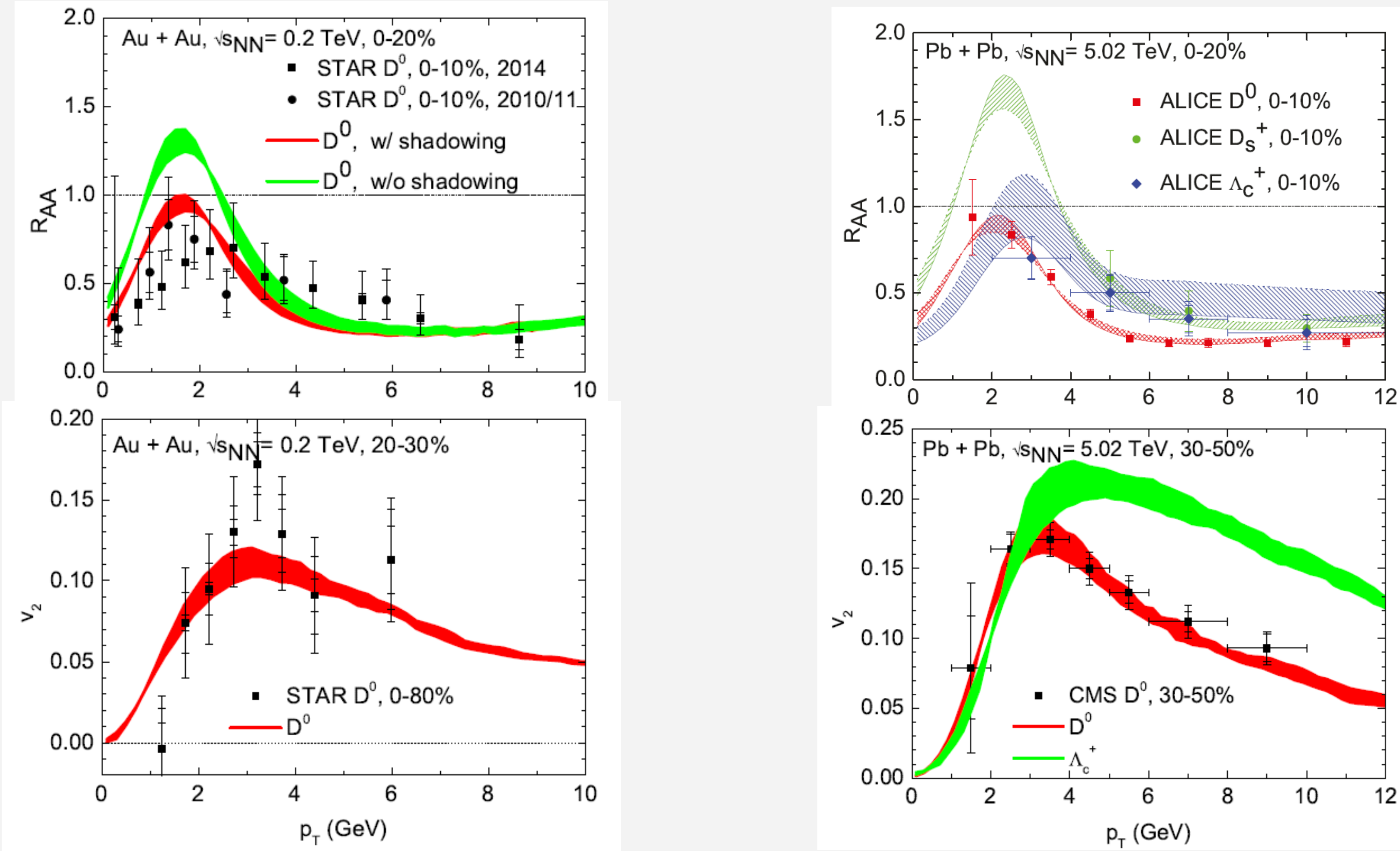
D Meson



- Strongly-coupled potential gives max. low-p_T c-quark v_2
- Weakly-coupled potential (~ free energy) insufficient

[Liu,He+RR '19]

4.6 Charm-Hadron Spectra at RHIC + LHC

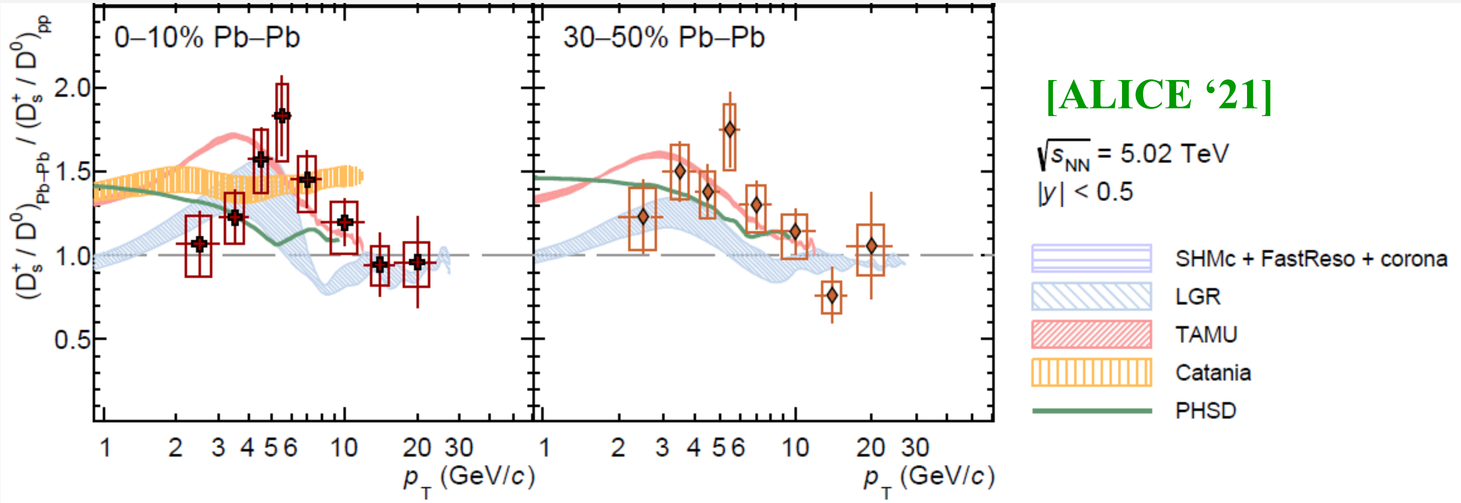


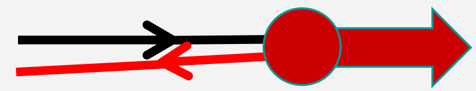
- Flow bump in $\mathbf{R_{AA}}$ + large $\mathbf{v_2}$ ↔ strong coupling near $\mathbf{T_{pc}}$
- Diffusion coefficient $\mathcal{D}_s(2\pi T) \sim 2$ near $\mathbf{T_{pc}}$
- Distinct hadronization patterns for **D** vs. $\mathbf{D_s}$ vs. $\mathbf{\Lambda_c}$

[M.He+RR ‘19]

4.7 Charm Hadro-Chemistry

D meson with strange quark: $D_s = (c\bar{s})$

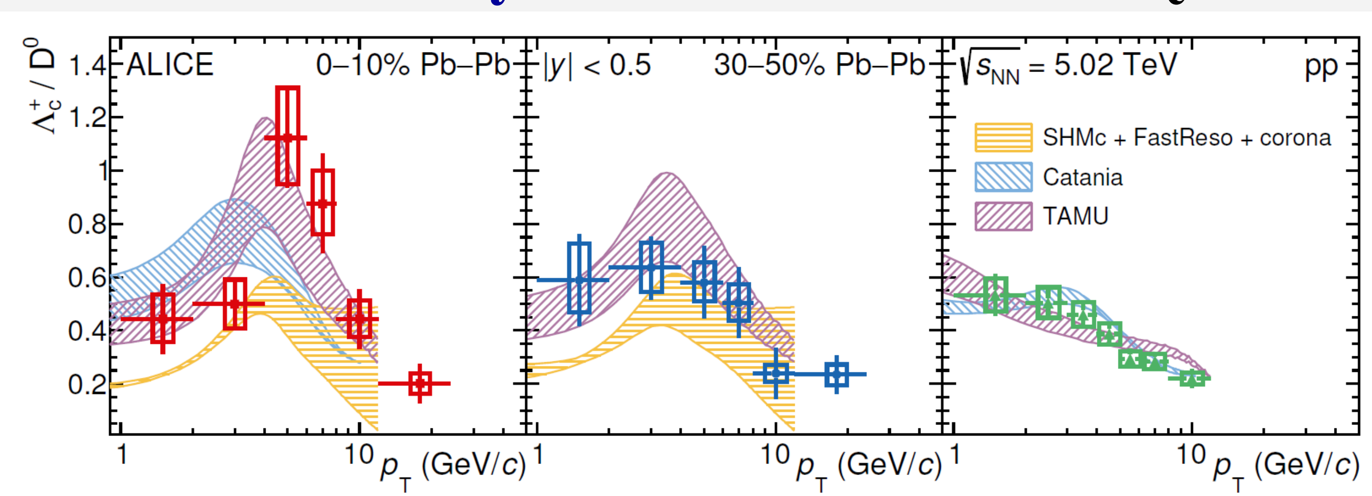


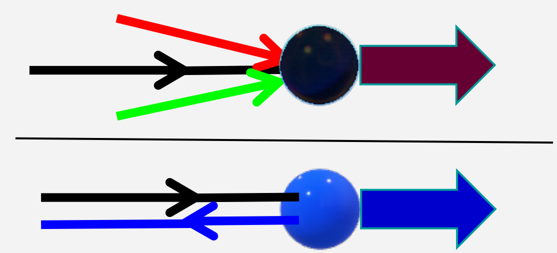


- Strange quarks in QGP enhance $\mathbf{D_s}$ via **recombination**

[He,Fries+RR '13]

Charm Baryon-to-Meson Ratio: Λ_c / D^0



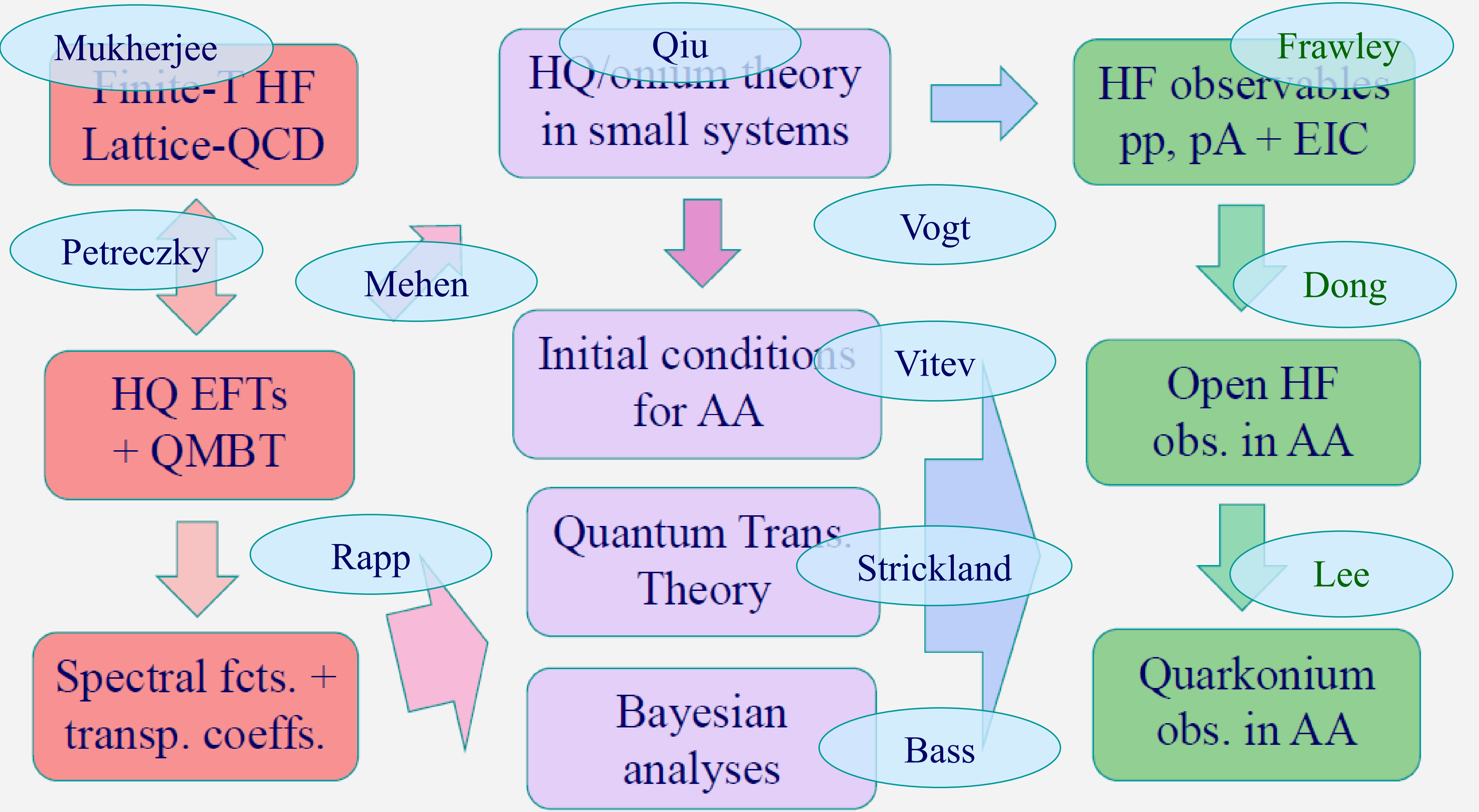


- **Recombination** + flow effect on Λ_c

5.) Summary

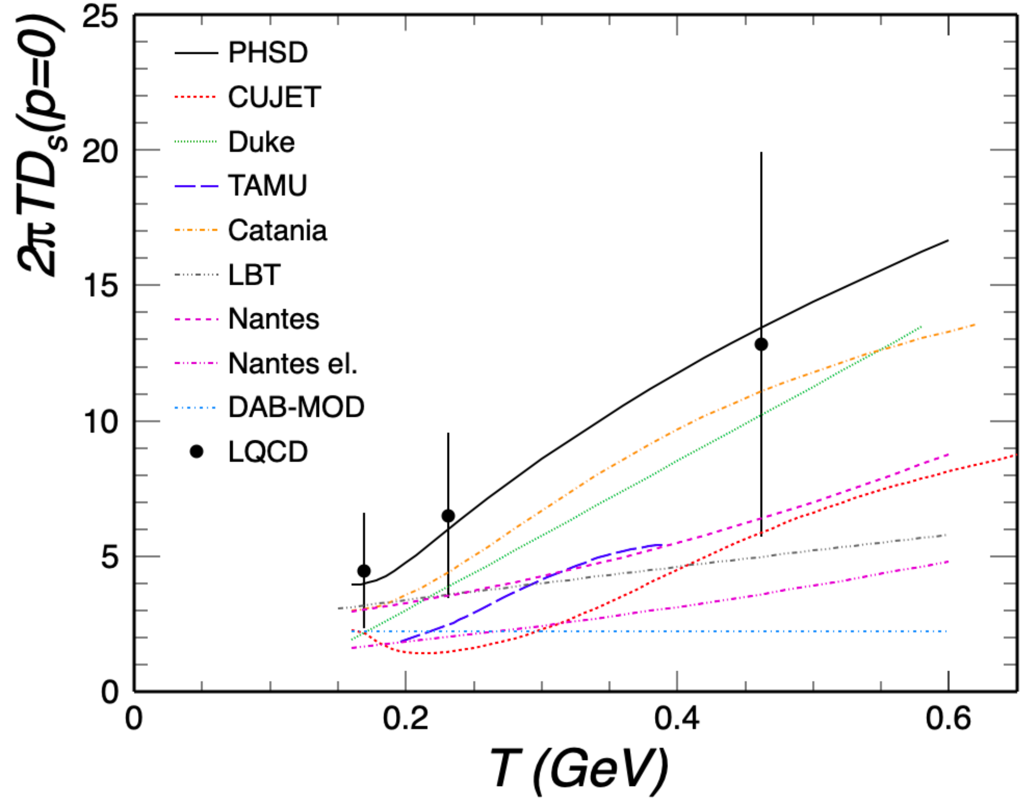
- Quantum Many-Body Theory of **s**QGP:
  - Accounts for key aspects of **strong coupling**:
    nonperturbative forces, resummation, quantum effects (large widths)
  - Input parameters constrained by lattice QCD, recover vacuum limit
- QGP structure driven by remnants of **long-range confining force**
  → - **melts** long-wavelength quasi-partons
  - forms **hadronic bound states**
  - generates **liquid properties** (small $\mathcal{D}_s$, η/s, …)
  - **quantum effects** ubiquitous
- $(2\pi T\mathcal{D}_s) / (4\pi\ \eta/s)$ as quantitative measure of "**strongly coupled**" QGP
- Self-consistency essential for quantum bounds!?

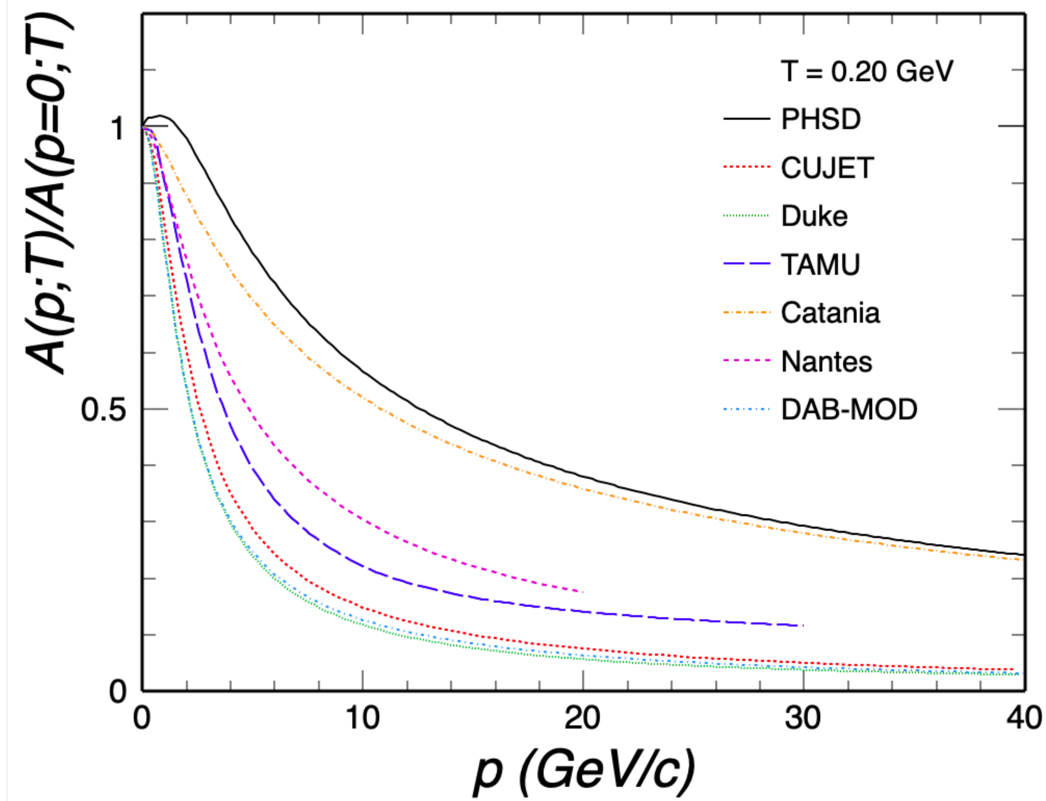
Topical Collaboration in Nuclear Theory: HEavy Flavor TheorY (HEFTY) for QCD Matter



3.5.2 Collective Progress II

[ECT* HF workshop ’21, RR et al]





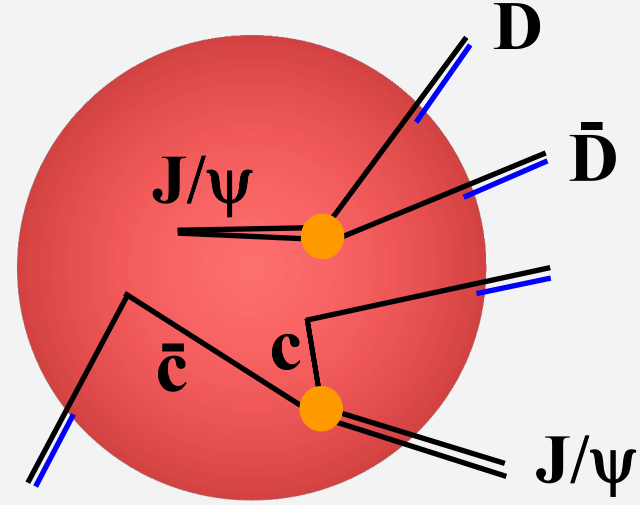
- correlation: large $\mathcal{D}_s$ $\leftrightarrow$ weak **p**-dependence
- need control over momentum dependence

2.1 Quarkonium Transport in Heavy-Ion Collisions

[PBM+Stachel '00, Thews et al '01, Grandchamp+RR '01, Gorenstein et al '02, Ko et al '02, Andronic et al '03, Zhuang et al '05, Ferreiro et al '11, …]

- **Inelastic reactions:**

  detailed balance: $J/\psi + g \rightleftarrows c + \bar{c} + X$

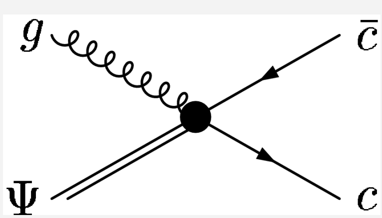


- **Rate equation:**

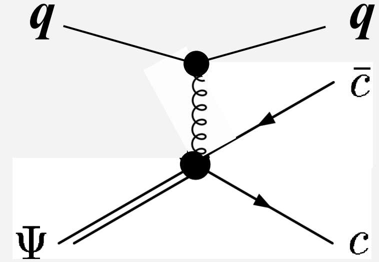
$$\frac{dN_\psi}{d\tau} = -\Gamma_\psi \left[N_\psi - N_\psi^{eq} \right]$$

- **Transport coefficients**
  - **Equilibrium limit** $N_\psi^{eq}(m_\psi, T; N_{cc})$
  - **Reaction Rate** $\Gamma_\psi \, (E_B(T))$

"Strong" binding $E_B \geq T$



"Weak" binding $E_B < m_D$



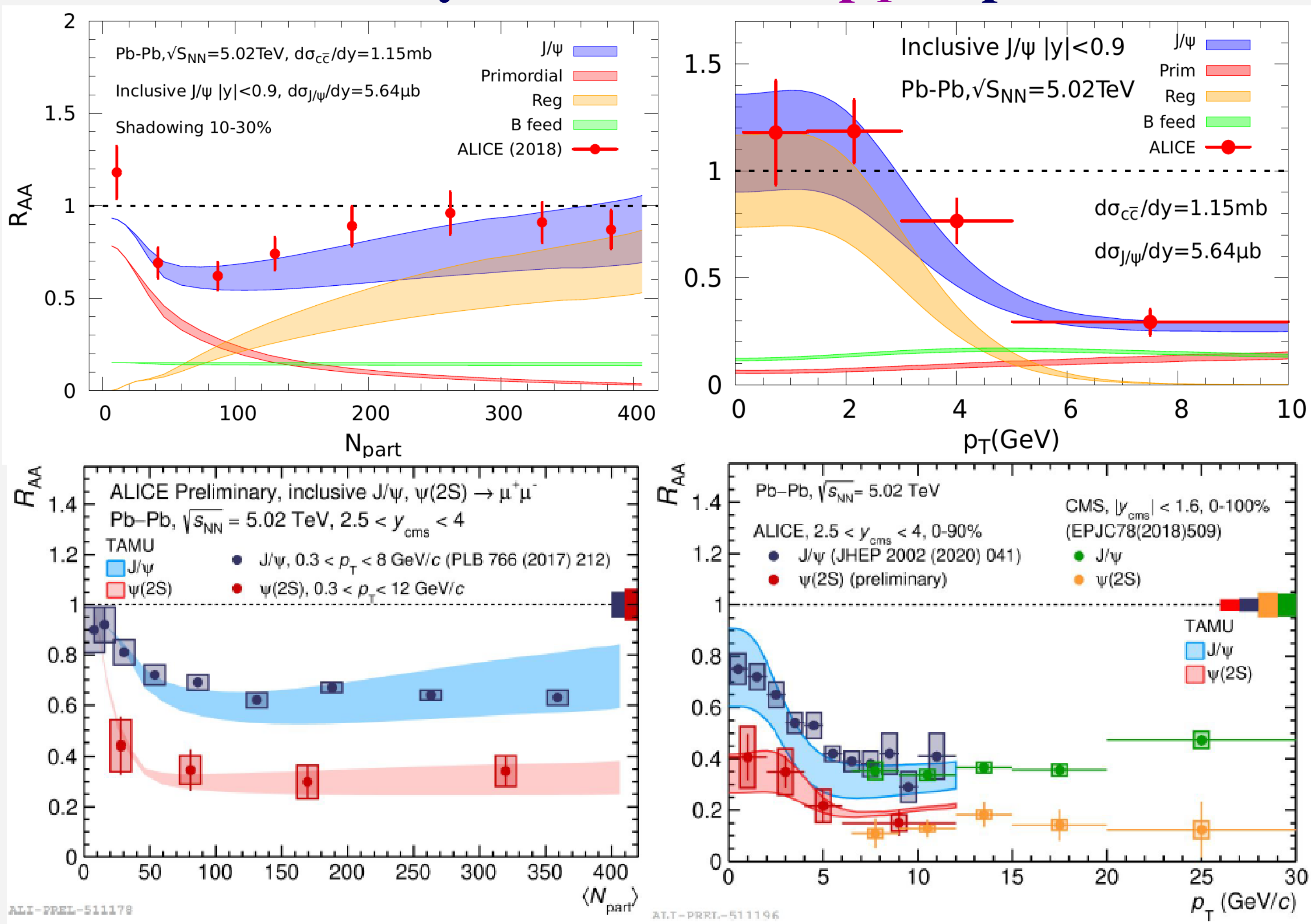
- gluo-dissosciation ("singlet-to-octet")
- "quasi-free"/ Landau damping

2.3 Differential Charmonium Transport: LHC

Centrality | **p_T Dependence**

Mid-Rapidity

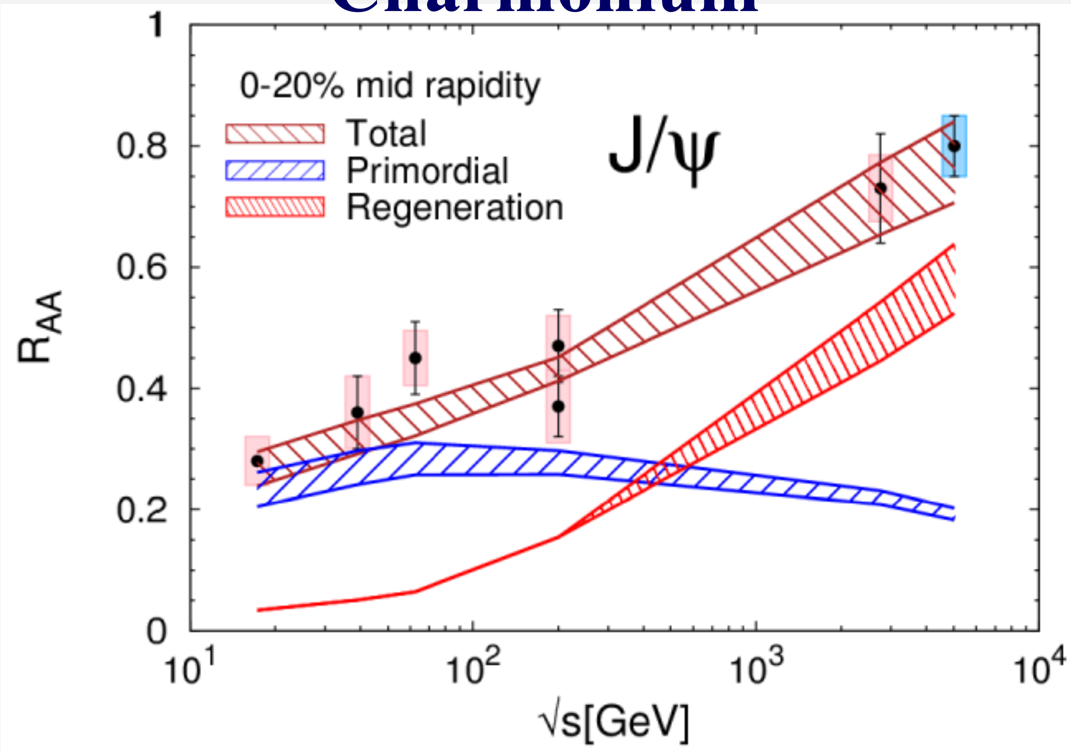
Forward Rapidity



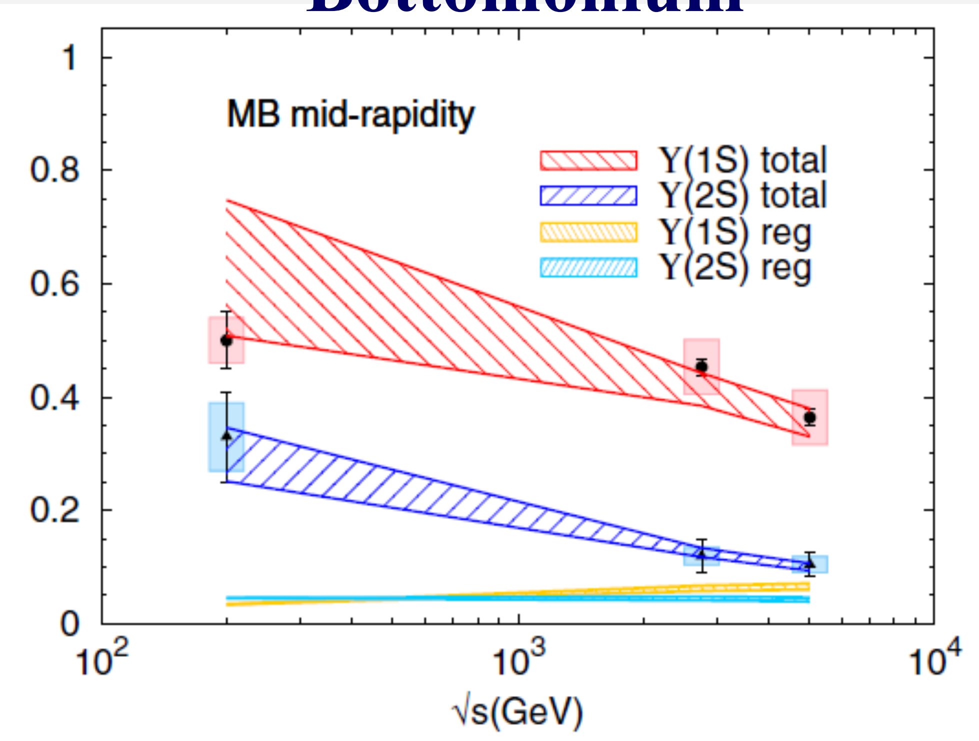
• substantial regeneration, concentrated at low p_T

2.5 Excitation Functions: SPS-RHIC-LHC

Charmonium



Bottomonium



- Gradual **increase** of total **J/ψ** **R_{AA}**
- Regeneration **and** suppression increase
- Regeneration concentrated at low **p_T**!

- Gradual **suppression**
- Regeneration (**N_Υ^{eq}**) small
- Qualitative difference from **J/ψ**

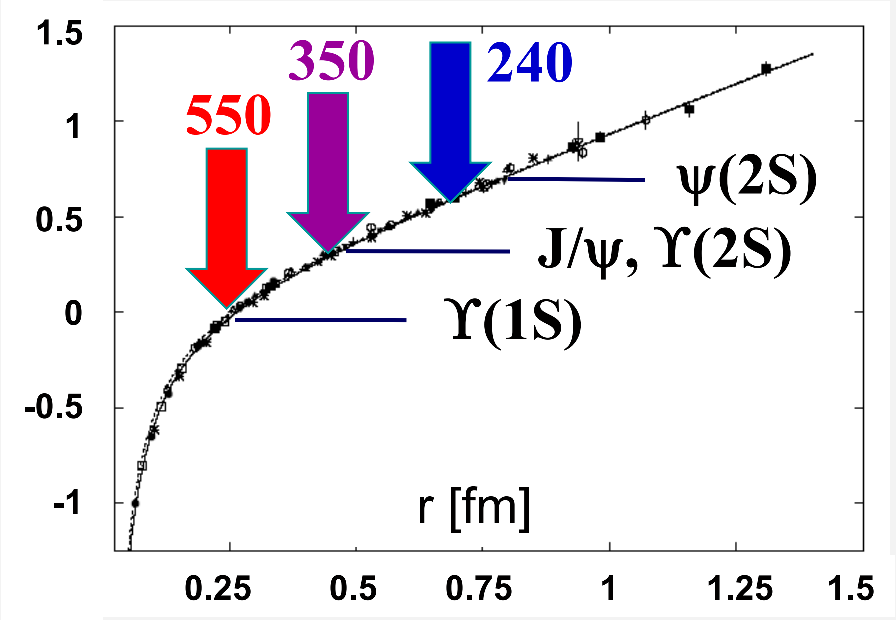
[**data**: **NA50, PHENIX, STAR, ALICE, CMS**]

2.3 Upshot of Quarkonium Phenomenology

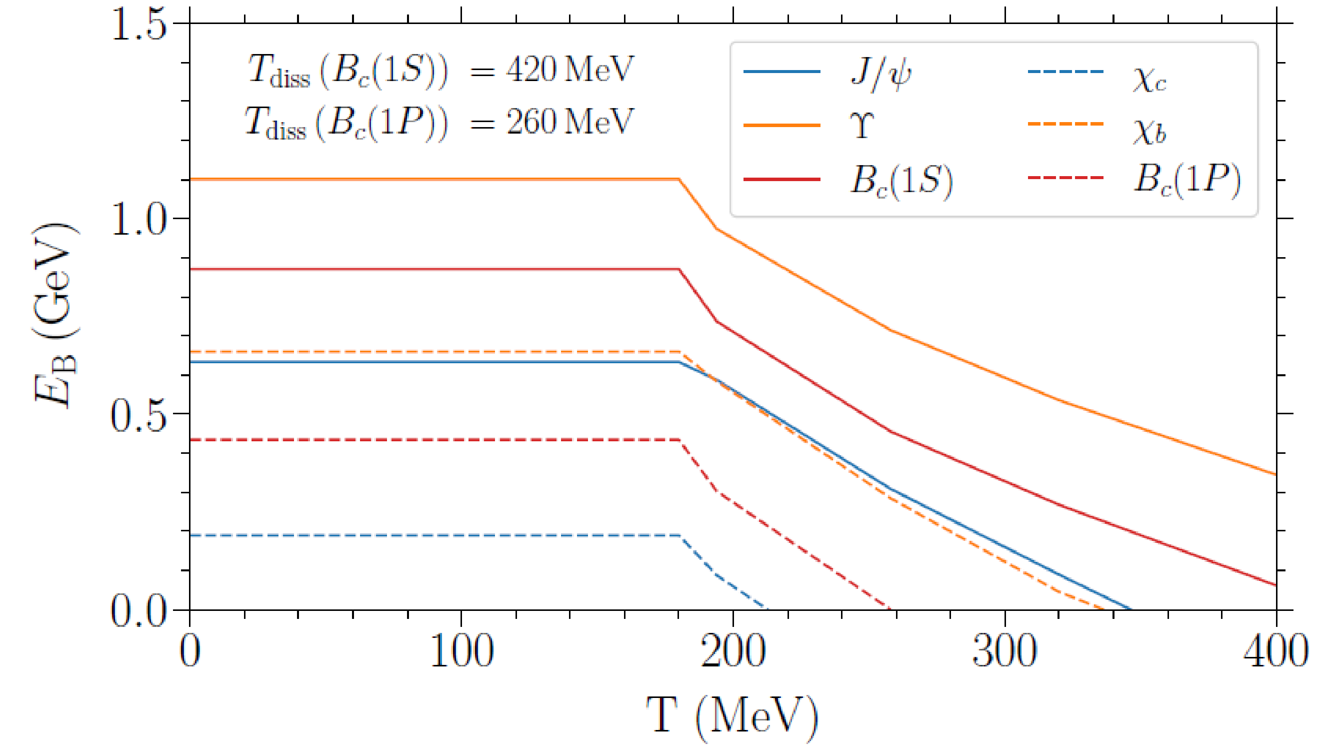
Use temperature estimates from hydro/photons/dileptons to infer:

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

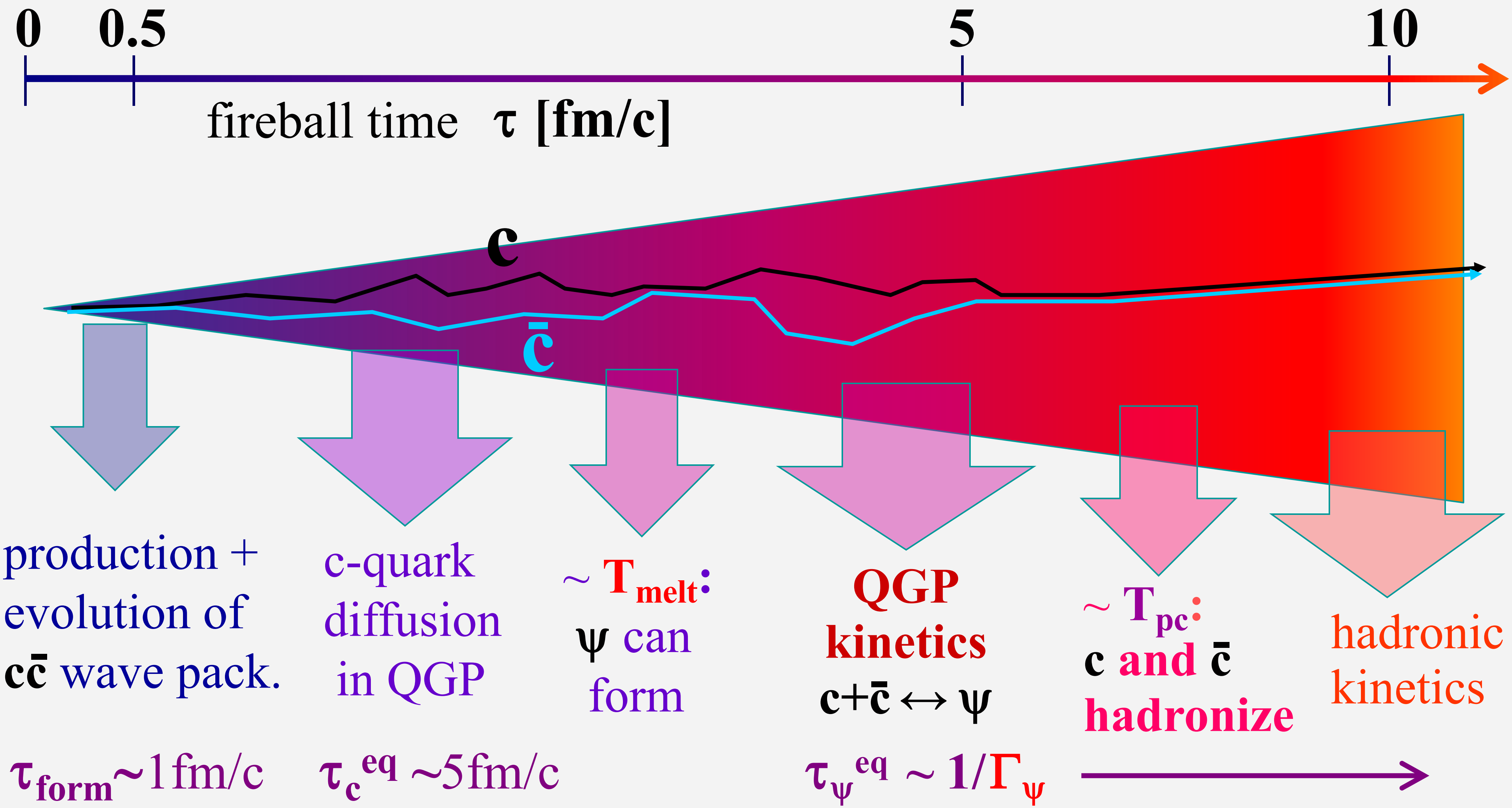
- **Remnants of confining force survive at SPS** [hold **J/ψ** together]
- **Confining force screened at RHIC+LHC** [“melts” **J/ψ+ϒ(2S)**]
- **Color-Coulomb screening at LHC** [**ϒ(1S)** suppression]
- **Thermalizing charm quarks recombine at LHC** [large **J/ψ** yield]



4.5 In-Medium Quarkonium Binding Energies



2.1 Quarkonium Transport in URHICs

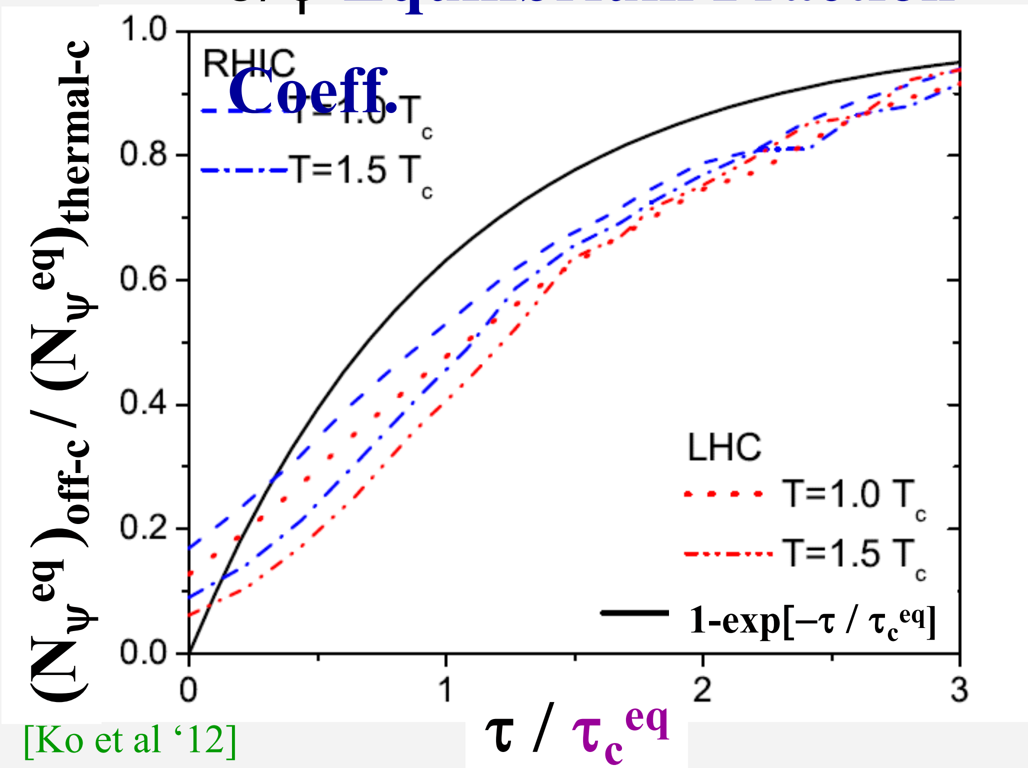


[Satz et al, Capella et al, Spieles et al, PBM et al, Thews et al, Grandchamp et al, Ko et al, Zhuang et al, Zhao et al, Chaudhuri, Gossiaux et al, Young et al, Ferreiro et al, Strickland et al, Brambilla et al, …]

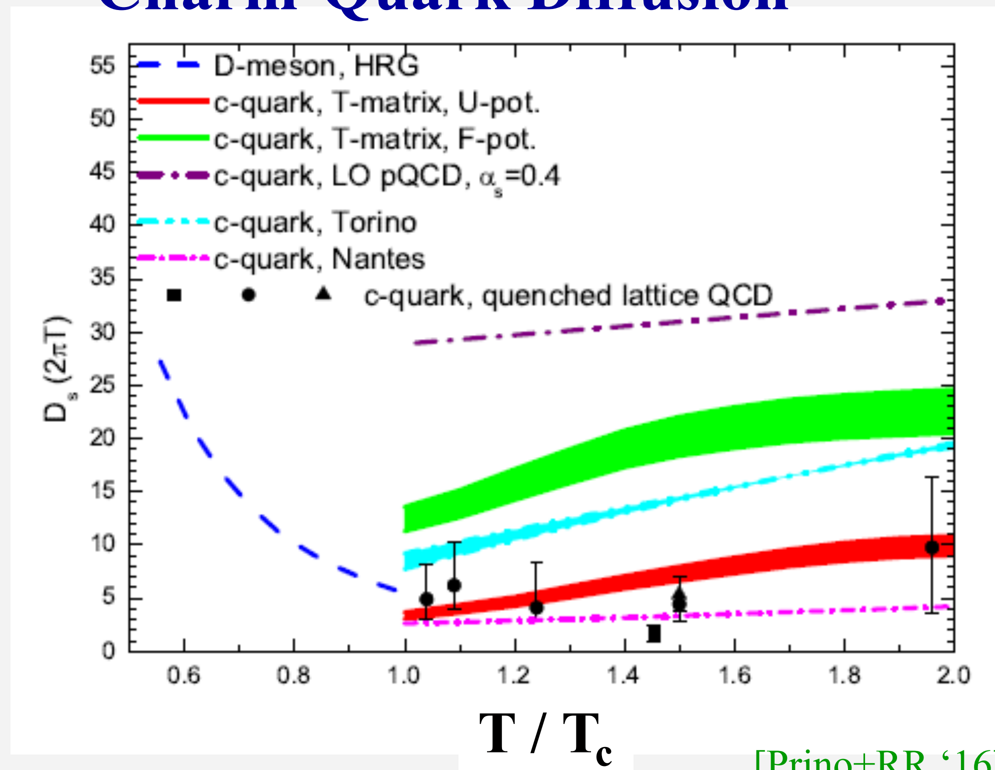
4.1 Charm Thermalization + J/ψ Regeneration

→ Softening of charm-quark spectra facilitates regeneration

J/ψ Equilibrium Fraction **Charm-Quark Diffusion Coeff.**



[Ko et al '12]

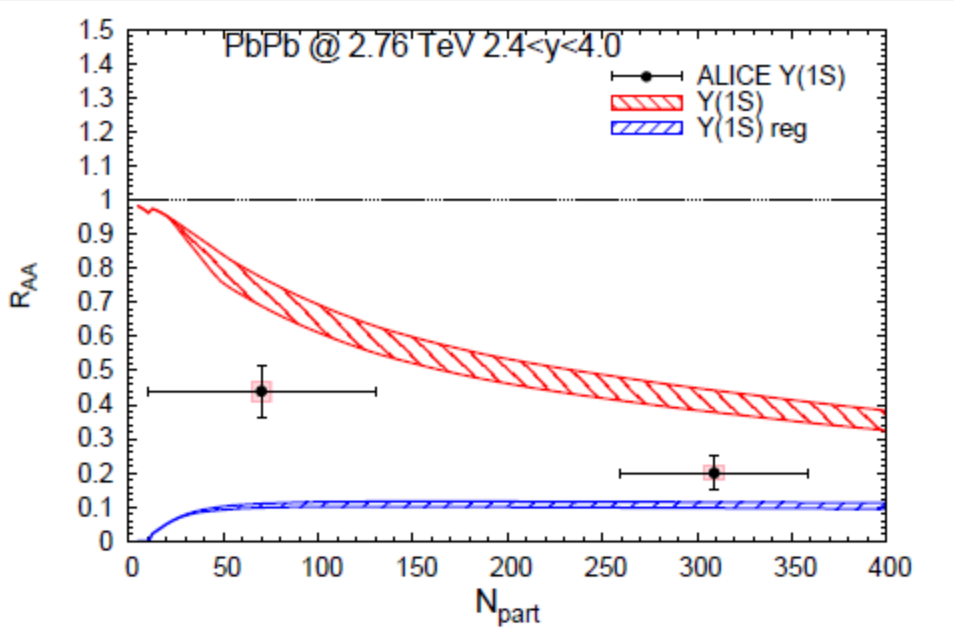


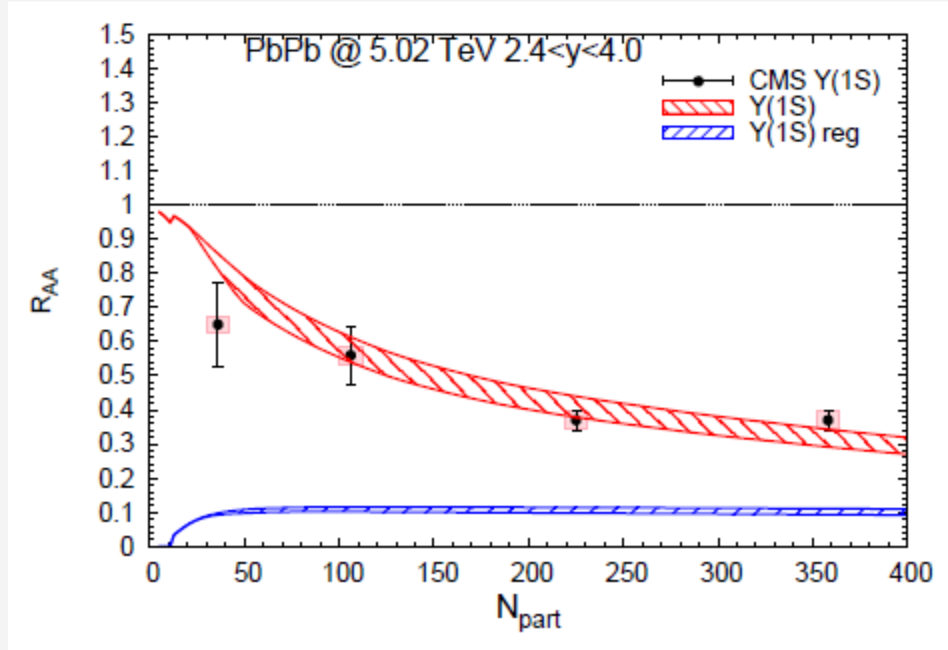
[Prino+RR '16]

- Charmonium phenomenology favors $\tau_c^{eq} \leq 5$ fm/c ("**strong**" coupling)

$$D_s = \tau_c^{eq}\, T/m_Q \leq (4\text{-}8)\,/(2\pi T)$$

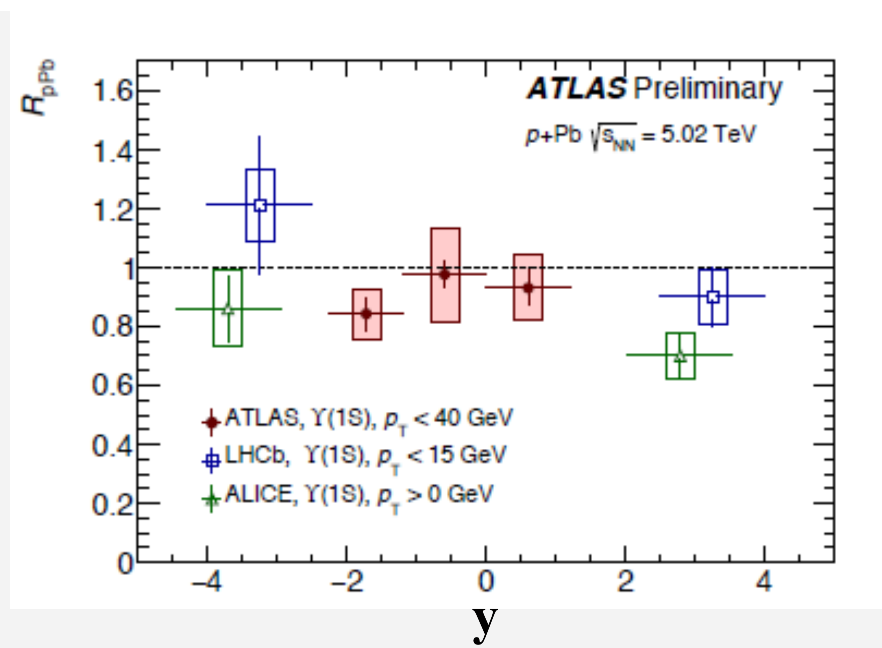
4.3 $\Upsilon(1S)$: Rapidity Puzzle





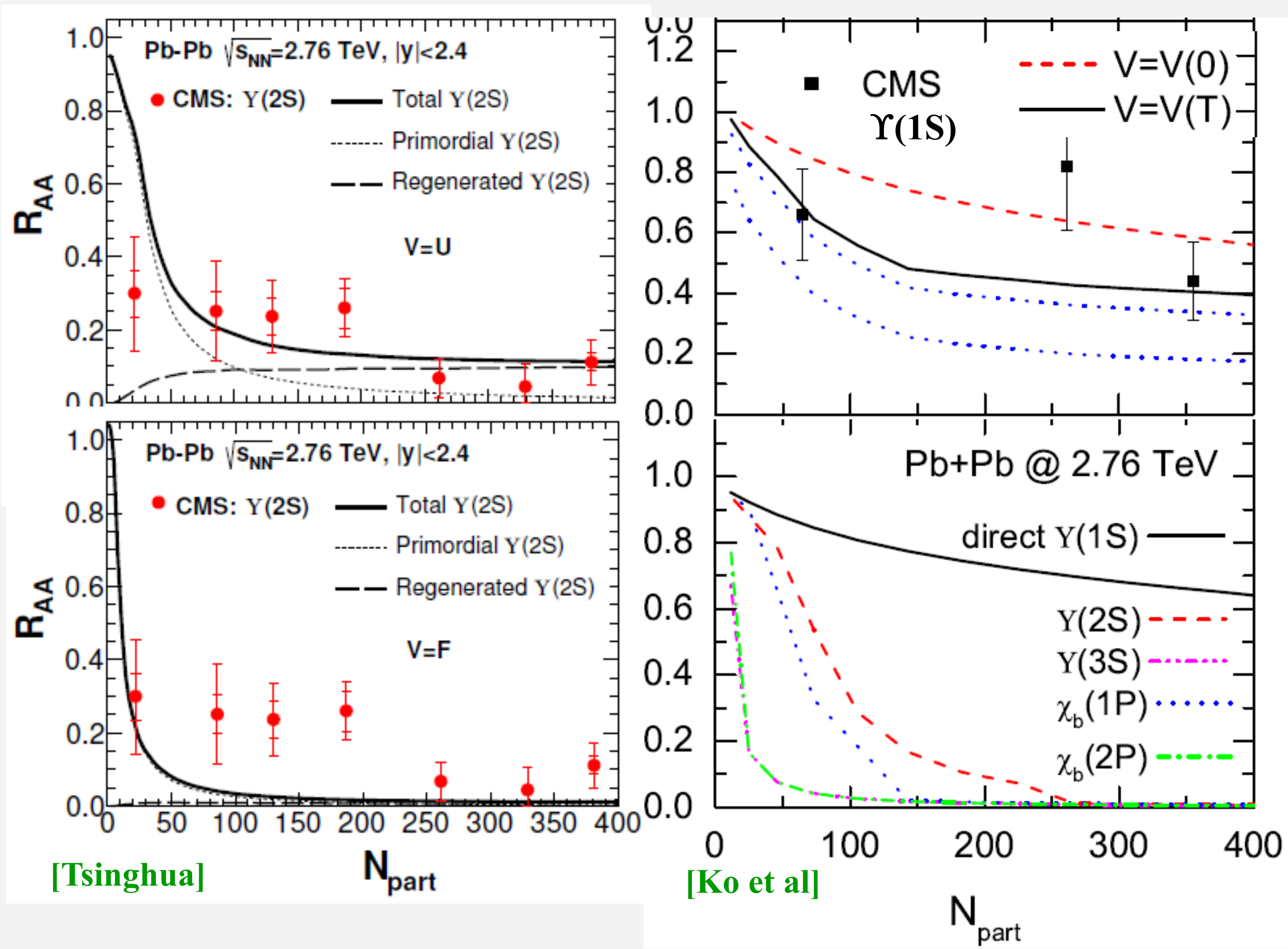
- problem of large(r) suppression in 2.76 TeV **ALICE** data
- beware of cold nuclear matter effects
- Regeneration: $\mathbf{N_{bb} \sim 1}$ for central PbPb

  $\Rightarrow$ canonical limit $\mathbf{N_Y \sim (N_{bb})^1}$



4.2 ϒ(1S) and ϒ(2S) Transport cont'd

… as implemented in current transport approaches

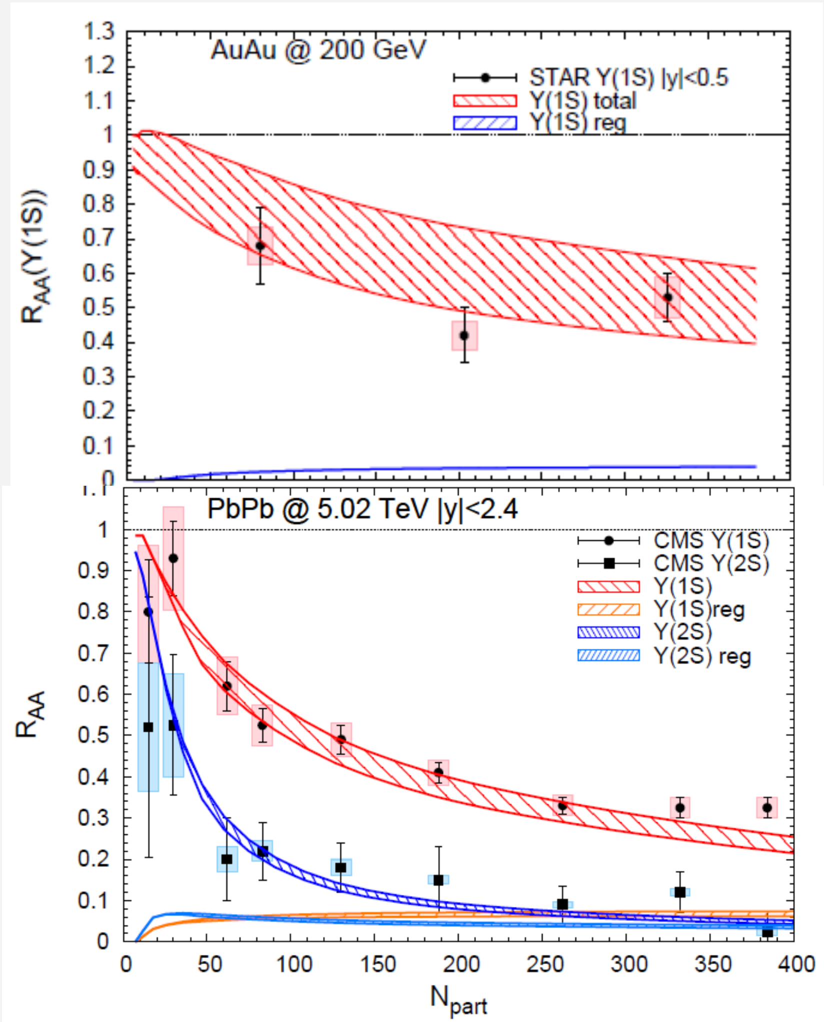


- **ϒ(2S)** more sensitive sensitive to in-medium potential

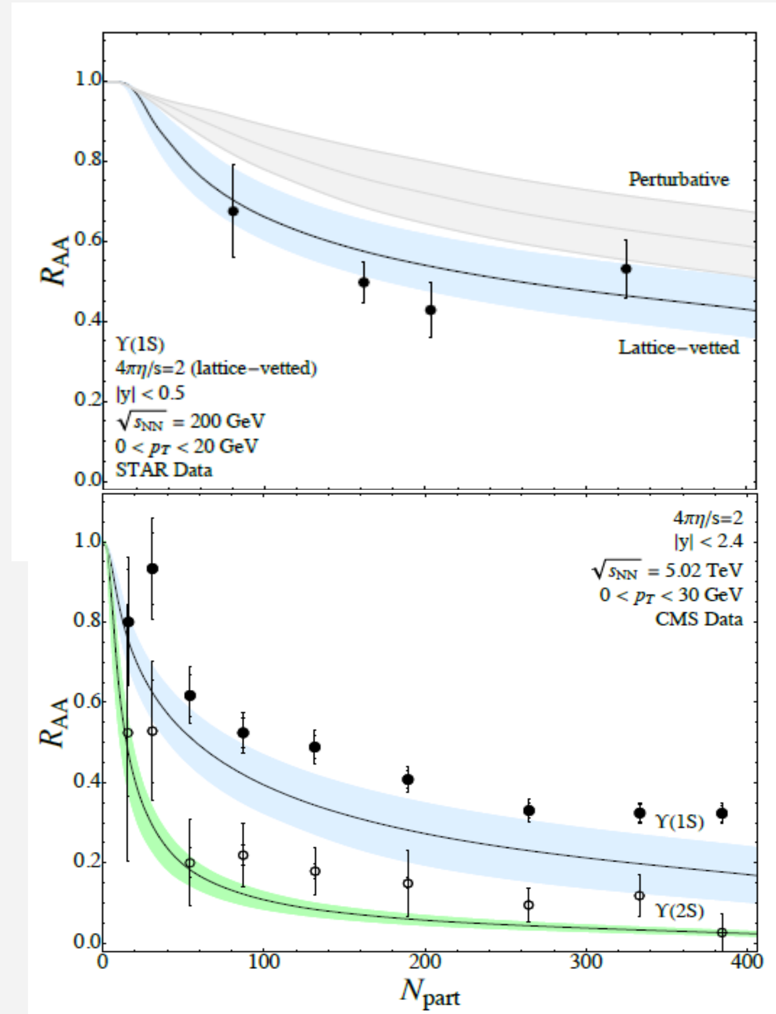
2.4 Heavy-Quark Potential + Regeneration

Lattice-based potentials

[TAMU ‘11,’17]



[Kent St ‘17]

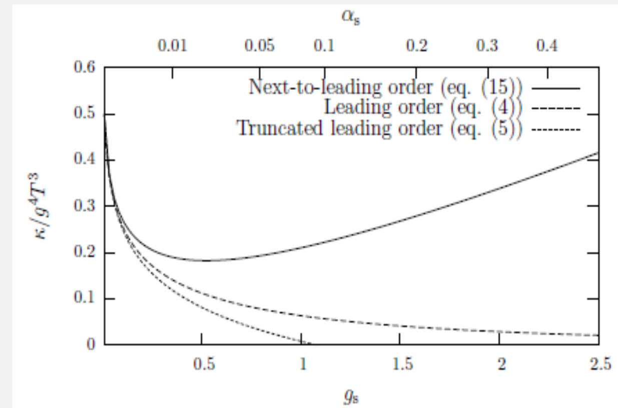


- **Υ(1S)** suppression at **RHIC** → regeneration at **LHC**
- Regeneration dominant for **Υ(2S)** in central **PbPb** at **LHC**?

3.3 Heavy-Quark Interactions in QGP

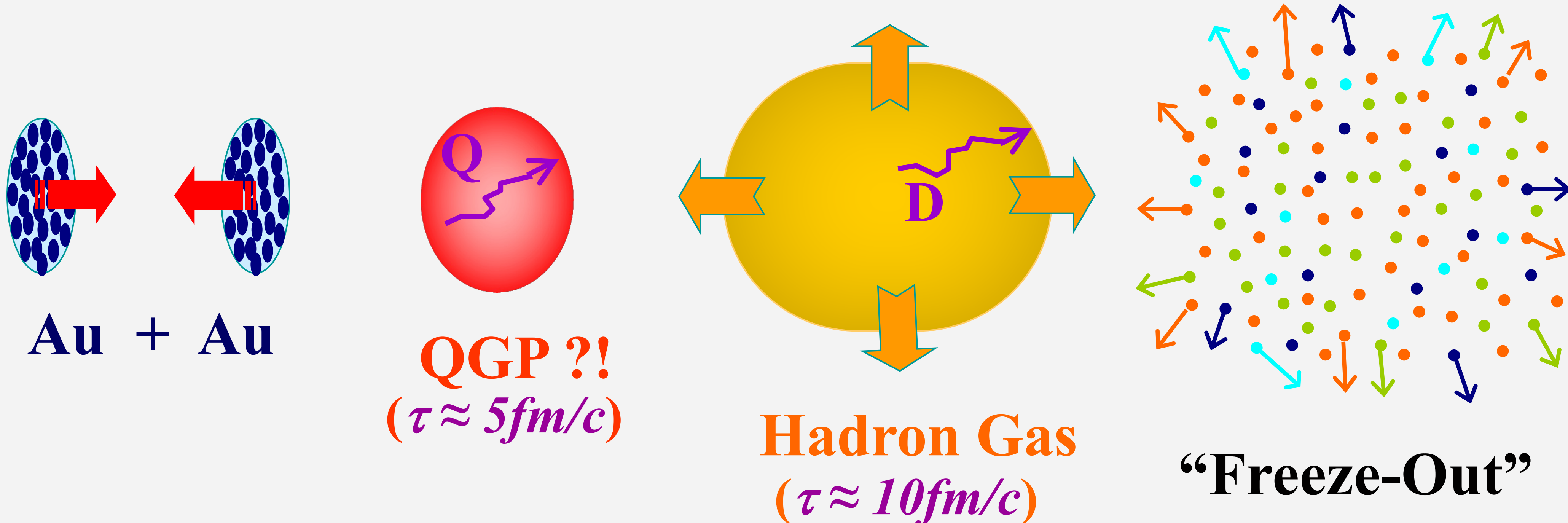
Minimal / Desirable Ingredients and Features

- **Microscopic** description of scattering **amplitude**
- Realistic in-medium **interaction kernel** (screening)
- **Nonperturbative** interactions
  (color-Coulomb / pQCD not enough)
- **Resummation** (strong coupling)
- **Hadronization** approaching T_c from above
  (bound states)
- Elastic + radiative processes (low / high p_T)
- Realistic **medium partons**:
  quasiparticles, widths, parton spectral functions, …? Equation of state?
- Quantitatively rooted in **constraints from lattice QCD**



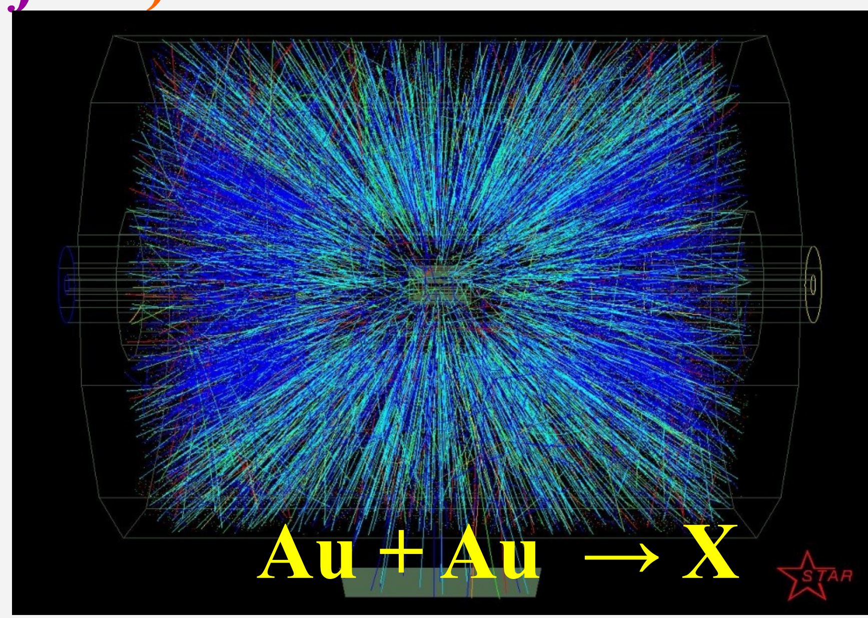
[Caron-Huot+Moore '08]

3.1 The "Little Bang" in the Laboratory

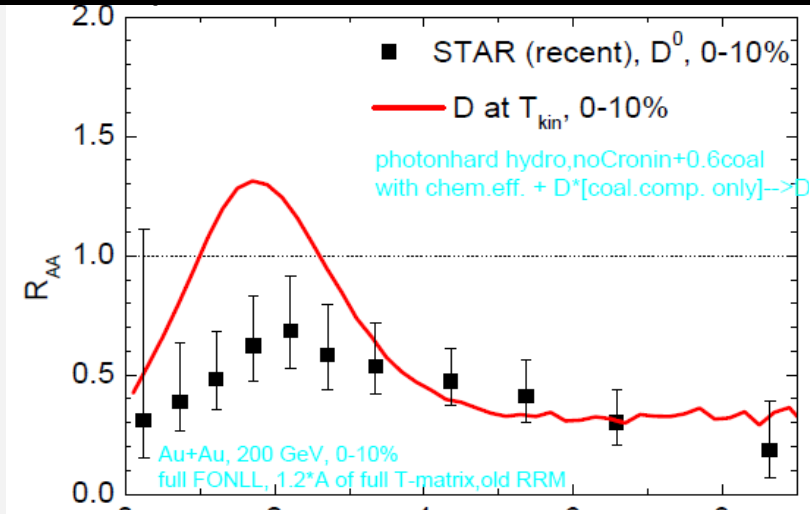


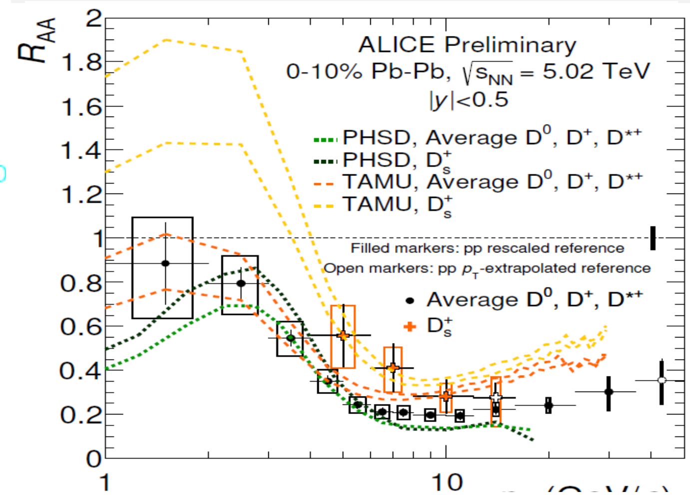
Idea

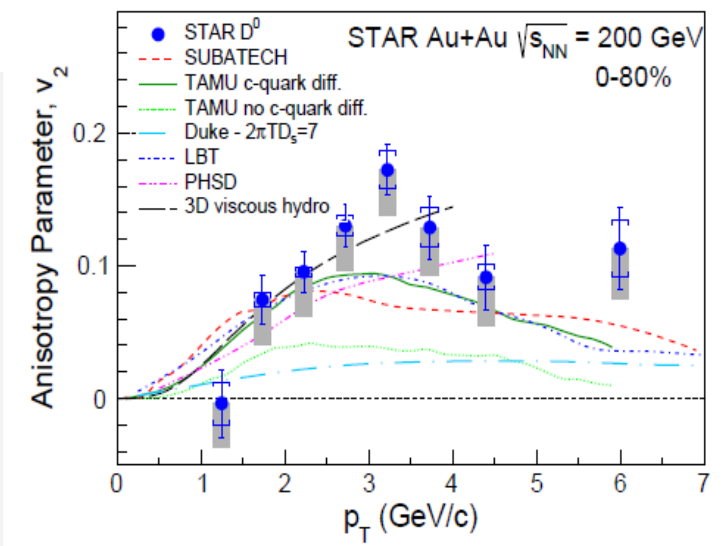
- Heavy quarks as "Brownian markers" of coupling strength to QCD medium
- Requires transport approach

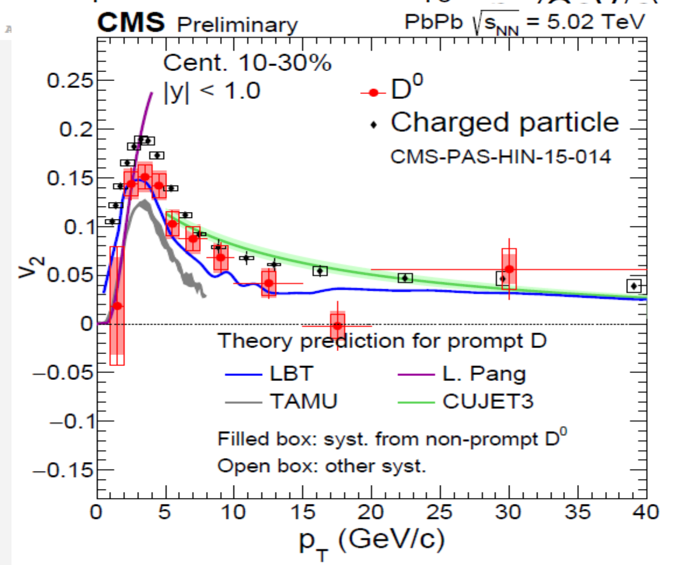


3.3 Heavy-Flavor Phenomemology at RHIC + LHC



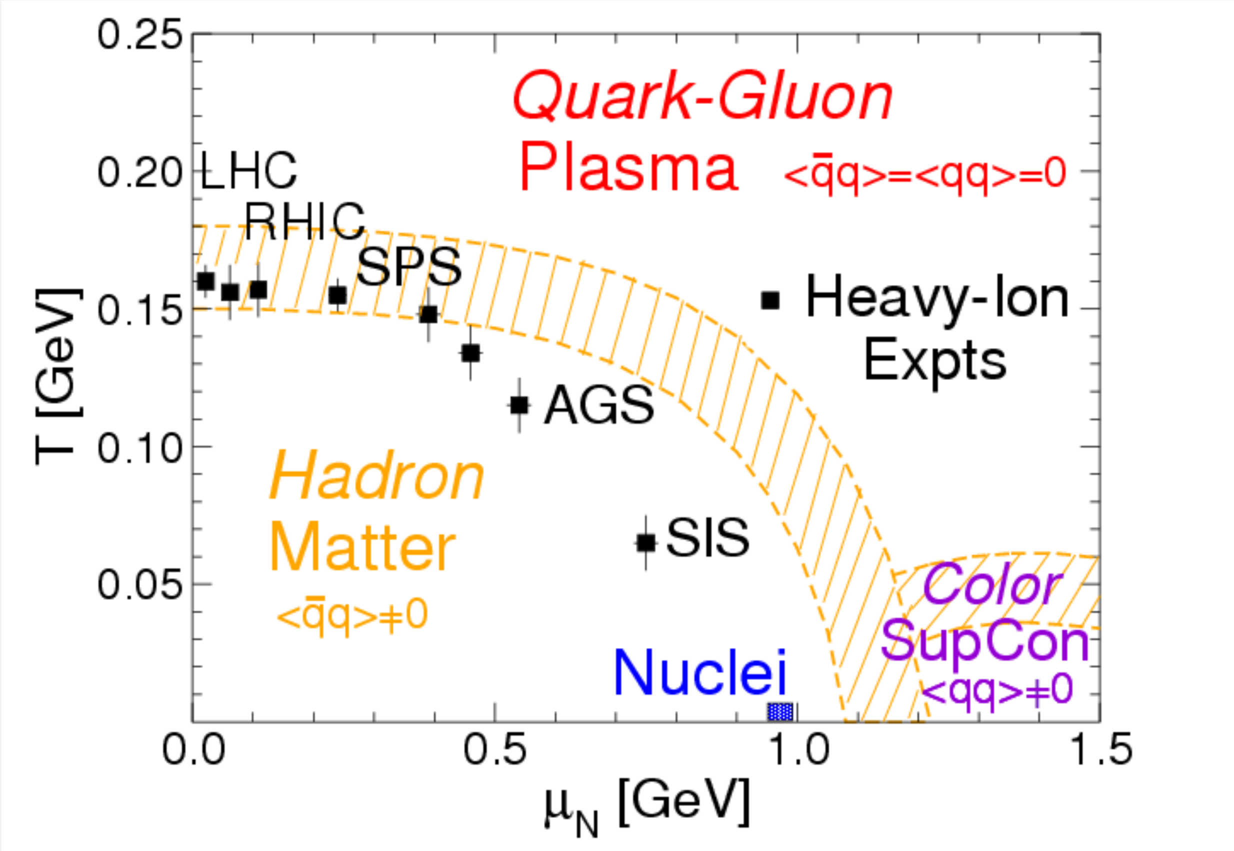






- Flow bump in **R_{AA}** + large **v_2** ↔ strong coupling near **T_{pc}** (**recombination**)
- Importance of **T**- + **p**-dependence of transport; $\mathcal{D}_s(2\pi T)$ ~ **2-4** near **T_{pc}**
- High-precision **v_2**: transition from elastic to radiative regime

1.2 QCD Matter



- De-/confinement and mass de-/generation
- From heavy-ion collision phenomenology:
  strongly coupled medium; **η/s, ($\mathcal{D}_s 2\pi T$)**,… near lower quantum bound

Microscopic structure and interactions at strong coupling?