Spin-Induced Heavy-Quark Interactions and Transport in the QGP

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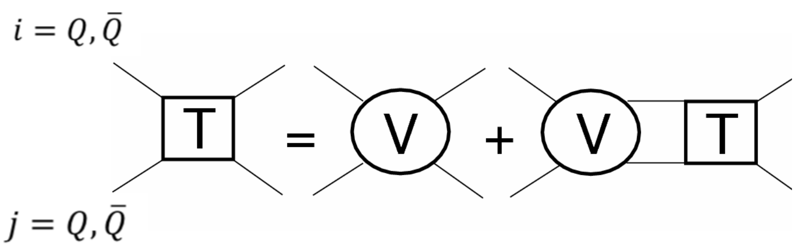
Outline

1. Introduction to T-matrix approach
2. Role of spin in vacuum spectroscopy of heavy-quarkonium
3. Impact on heavy-quark transport coefficient in QGP
4. Summary

1.1 T-Matrix Approach

[F. Riek+R. Rapp ’10]
[S. Liu+R. Rapp ’18]

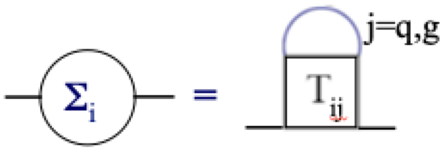
- **Quantum many-body approach to quarkonium in vacuum and medium**



$$T_{ij} = V_{ij} + \int V_{ij} G_i G_j T_{ij}$$

Dyson-Schwinger type self-consistent problem

- $G_i = 1/[\omega - \omega_k - \Sigma_i]$: 1-body propagator

Self-energy: 

- V_{ij}: potential (input of T-matrix)
  - Vacuum potential (Cornell): $V = -\frac{4}{3}\alpha_s \frac{1}{r} + \sigma r$
    - Coulomb (V_{Coul})
    - Confining (V_{conf})
  - In-medium potential constrained by $Q\bar{Q}$ free energy from lattice QCD
  - Motivation: introducing spin-dependent potentials to account for $Q\bar{Q}$ hyper-/fine splittings

1.2 Corrections to Potential

- **Relativistic corrections**

  - **Breit correction:** $V = RV^{vec} + V^{sca}$,

    with $R = \sqrt{\frac{\varepsilon_i(p)\varepsilon_j(p)}{M_i M_j}}\sqrt{1+\frac{p^2}{\varepsilon_i(p)\varepsilon_j(p)}}\sqrt{\frac{\varepsilon_i(p')\varepsilon_j(p')}{M_i M_j}}\sqrt{1+\frac{p'^2}{\varepsilon_i(p')\varepsilon_j(p')}}$ relativistic correction for the vector interaction

    $V^{vec} = V_{Coul}$

    Common assumption: $V^{sca} = V_{conf}$

    [N. Brambilla+A. Vairo '97] [A. Szczepaniak et al. '96, '97] [D. Ebert et al. '98, '03] ← Improved assumption: $V^{vec} = V_{Coul} + (1-\chi)V_{conf}$, $V^{sca} = \chi V_{conf}$

    ↓ mixing coefficient (proportion of scalar component in V_{conf})

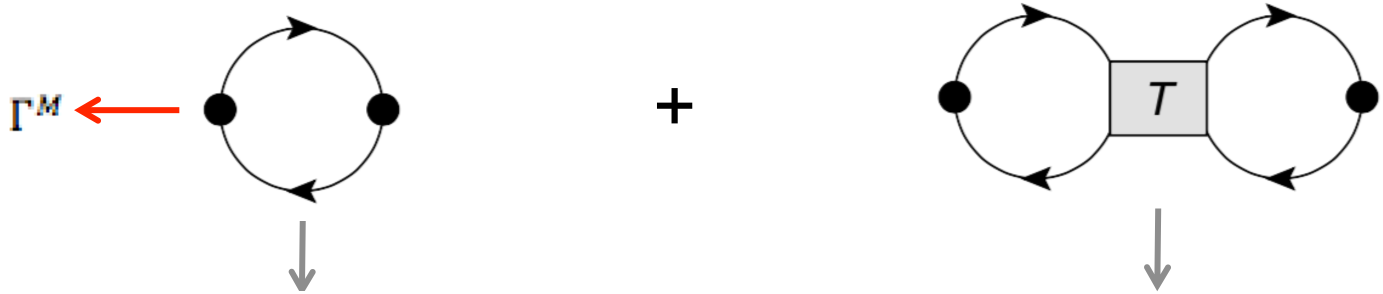
  - **Higher order in 1/M_Q:** $V = RV^{vec} + V^{sca} + V^{LS} + V^{SS} + V^T$

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

2.1 Correlation/Spectral Functions

- **Quakonium mass read from spectral functions**
- **Spectral functions:** $\sigma(E) = -\frac{1}{\pi}\mathrm{Im}[G_0(E) + G_{\mathrm{int}}(E)]$
- **Correlation functions:**



$G_0(E) \sim \Gamma^M G^0_{Q\bar{Q}}(E,p)\Gamma^M$

non-interacting (free) part

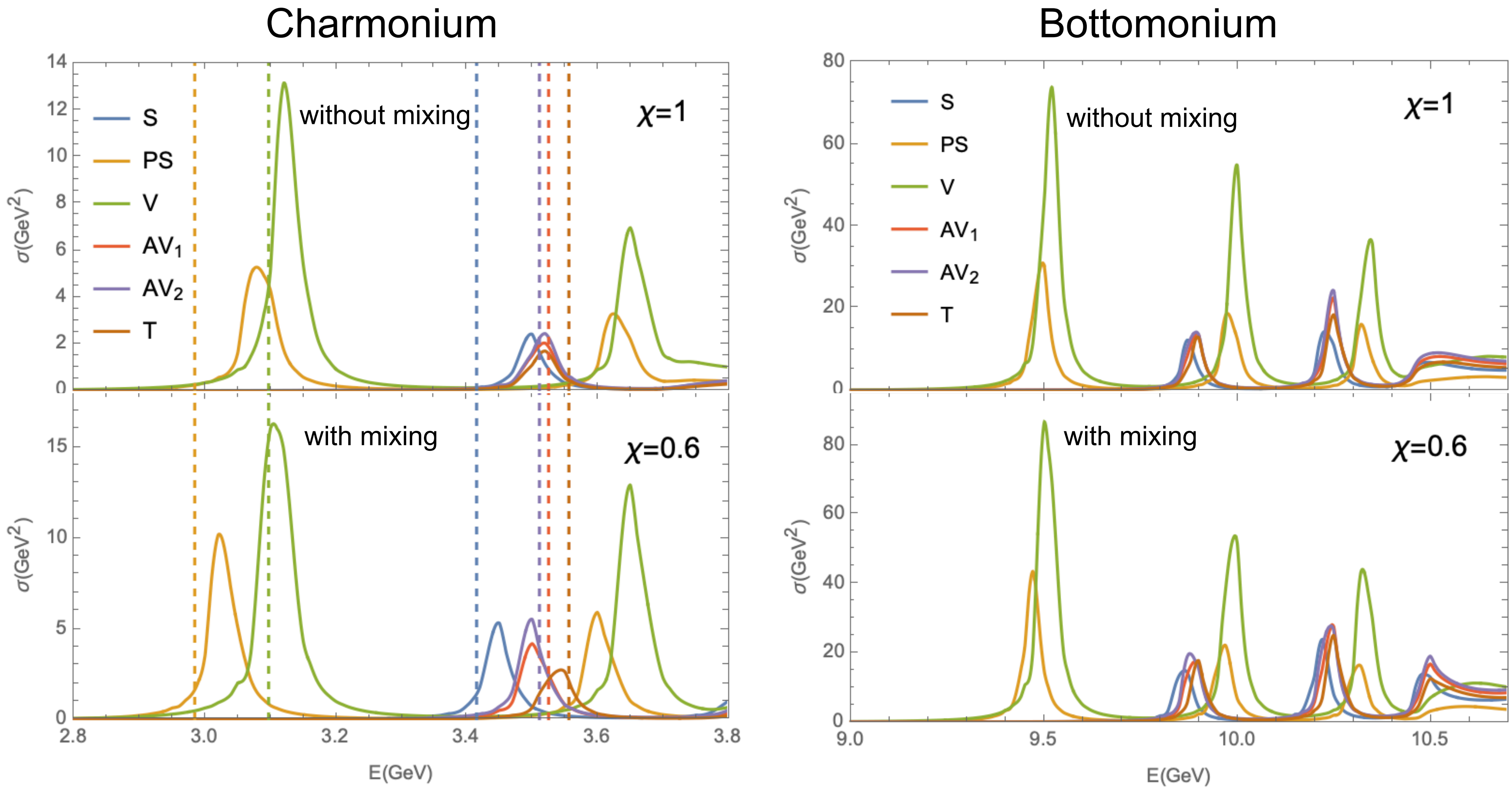
$G_{\mathrm{int}}(E) \sim \Gamma^M G^0_{Q\bar{Q}}(E,p) G^0_{Q\bar{Q}}(E,p')\Gamma^M T_{Q\bar{Q}}(E,p,p')$

interacting part

	scalar (S)	pseudoscalar (PS)	vector (V)	axial-vector (AV)	tensor (T)
Γ^M	1	$i\gamma_5$	γ^μ	$\gamma^\mu\gamma_5$	$i[\gamma^\mu,\gamma^\nu]/2$

- S-wave (PS, V) and P-wave (S, AV, T) states degenerate without spin-related ($1/M_Q$) corrections

2.2 Quarkonium Vacuum Spectroscopy



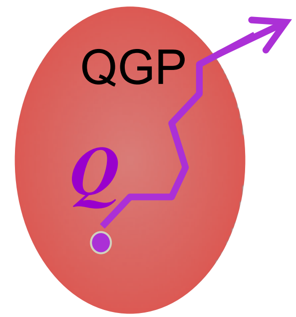
- Mass splittings significantly improved by mixing effect
- Less significant for bottomonium ($1/M_b<1/M_c$)

3.1 In-Medium Charm-Quark Transport

- Fokker-Planck equation

$$\frac{\partial}{\partial t} f(p,t) = \frac{\partial}{\partial p_i}\left\{A(p) p_i f(p,t) + \frac{\partial}{\partial p_j}\left[B_{ij}(p) f(p,t)\right]\right\}$$

thermal relaxation rate (friction coefficient) — momentum diffusion coefficient

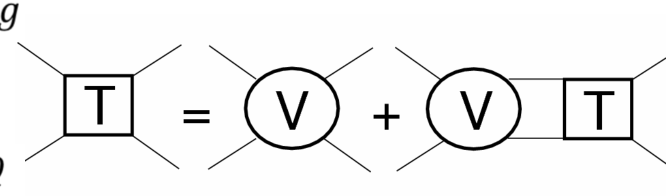


Brownian motion for heavy quarks through the QGP

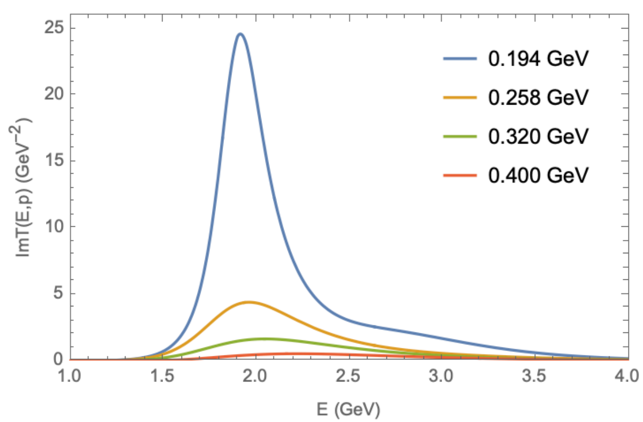
$$A(p) \sim \sum_i \int d^4p' d^4q\, d^4q' |T_{Qi}|^2 \left(1 - \frac{\boldsymbol{p}\cdot\boldsymbol{p}'}{\boldsymbol{p}^2}\right)$$

spatial diffusion coefficient: $D_s = \frac{T}{M_Q A(p \to 0)}$

- T_{Qi}: heavy-light T-matrices



Prediction for D-meson from T-matrix approach



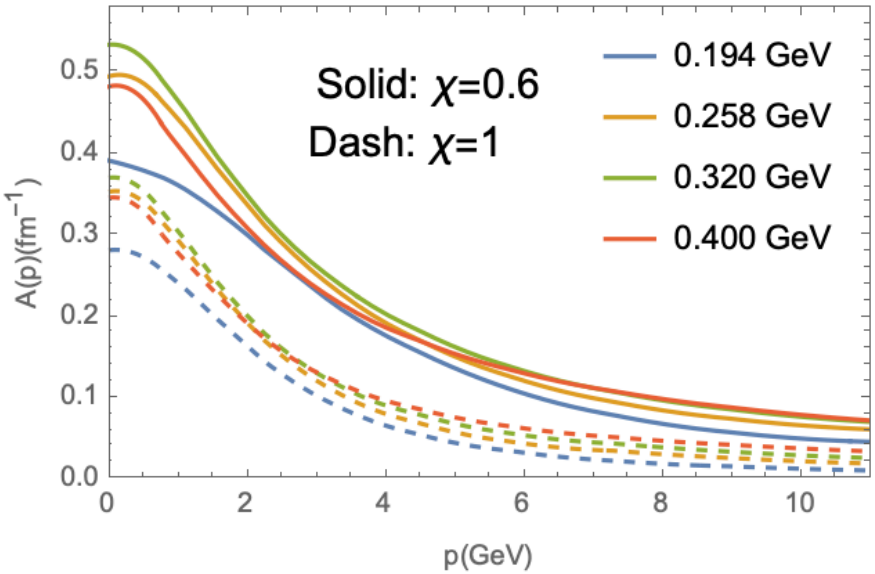
As temperature decreases…

- Screening for potential decreases
- Confining force appears
- D-meson emerges (with reasonable mass at $\sim T_c$)

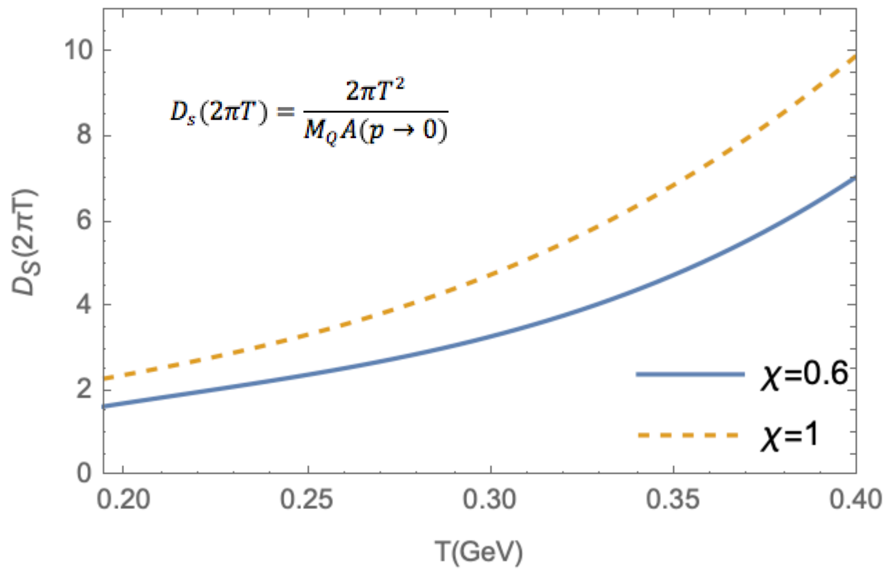
→ important for D_S at $\sim T_c$

3.2 In-Medium Charm-Quark Transport

- Transport coefficients :



Friction coefficients



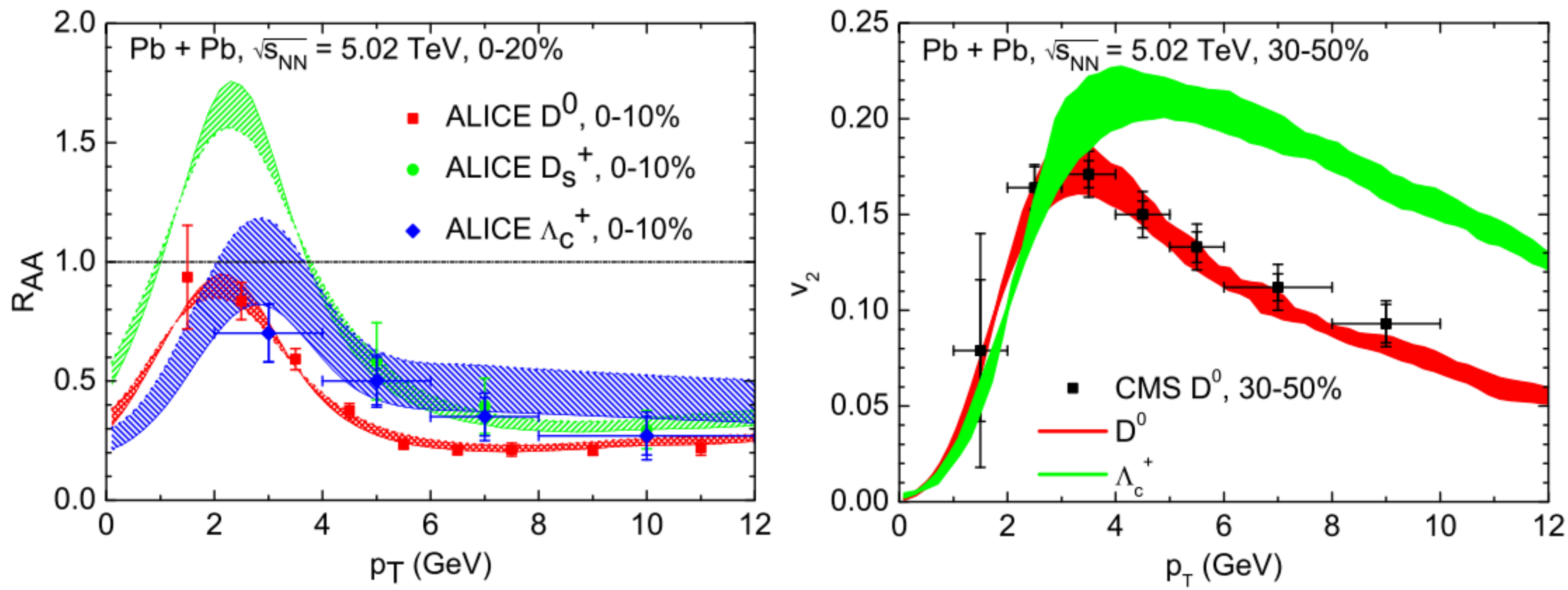
Spatial diffusion coefficients

- Increase in A(p) + harder dependence on momentum

→ important ramifications for the phenomenology of open heavy flavor probes in URHICs.

3.3 Connection to Experimental Observables

- A good description of D, D_s and Λ_c observables in heavy-ion collisions



[M. He+R. Rapp '20]

- Using T-matrix with U-potential as input + an extra K≈1.6
- Mixing effect (larger A(p)) promising to explain K factor

4. Summary

- **Extending T-matrix approach to include spin-induced interactions in vacuum**

- **Introducing vector component in confining potential V_{conf}**

- **Vacuum charmonium and bottomonium mass splittings improve**

- **Friction coefficients for charm quarks in the QGP enhanced, especially at high momenta (consequence of the enhancement from extra relativistic correction factor for the vector component of V_{conf})**

Thanks for Your Attention!

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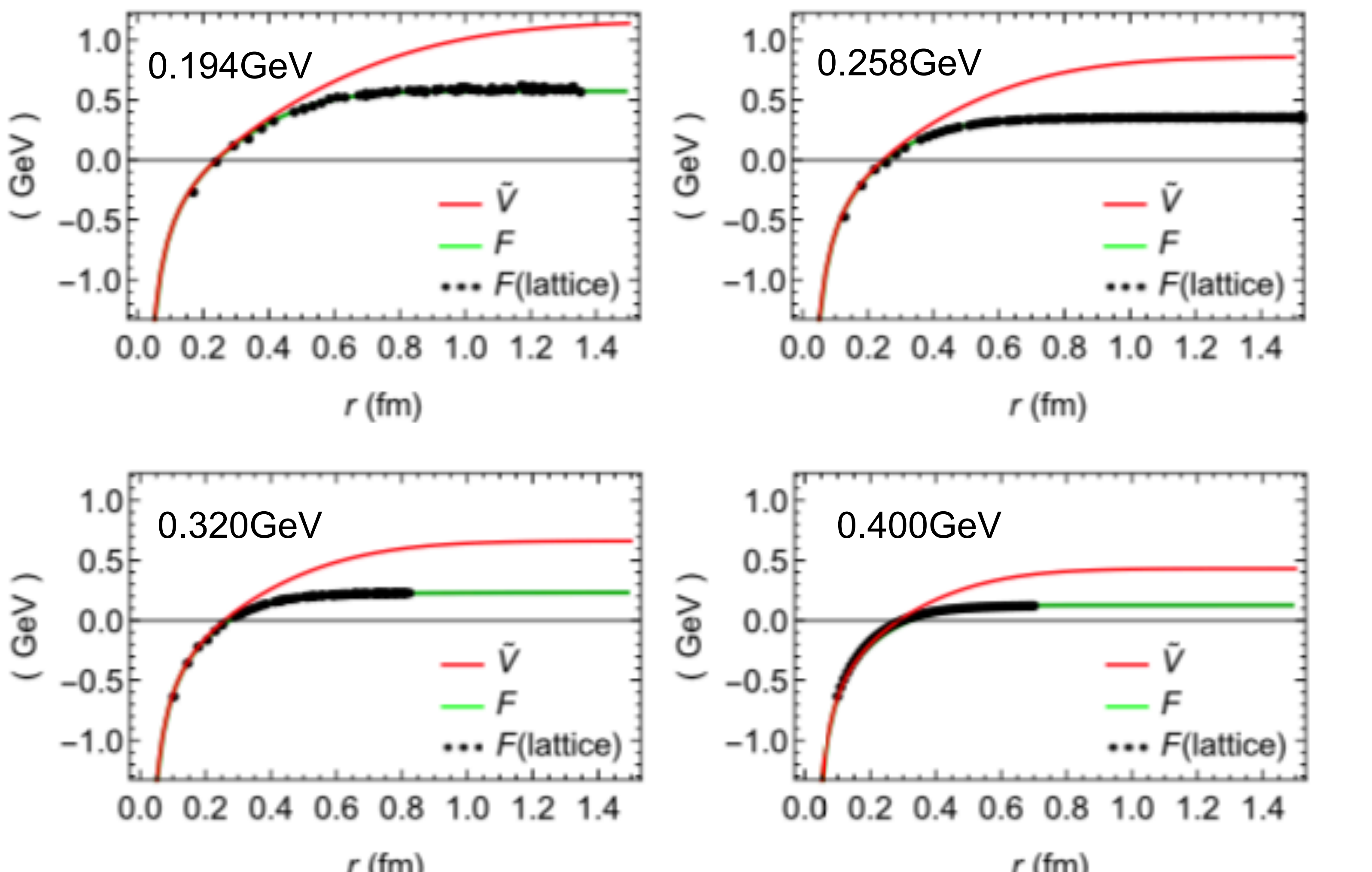
Fit to $Q\bar{Q}$ Free Energy



[S. Liu+R. Rapp '18]

D^0-D^* Splitting in Vacuum