Probing the in-Medium QCD Force by Heavy-Flavor Observables

Shuai Liu, Texas A&M University

In collaboration with: Min He, Xiaojian Du, and Ralf Rapp

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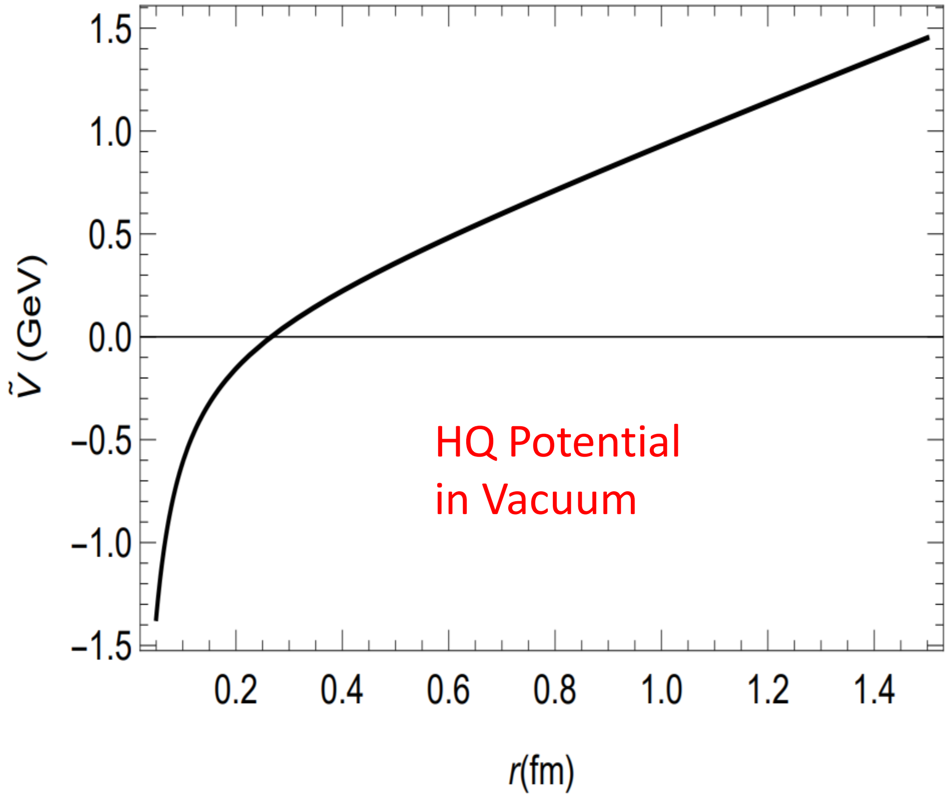
Outline

1) **Background and motivation**
2) **Constrain the force from heavy-flavor spectra**
3) **Constrain the force from quarkonium perspective**
4) **Conclusions and perspective**

Color Potential in Vacuum

- Include confinement at long range (soft scale)
- Recover pQCD at short distance (hard scale)



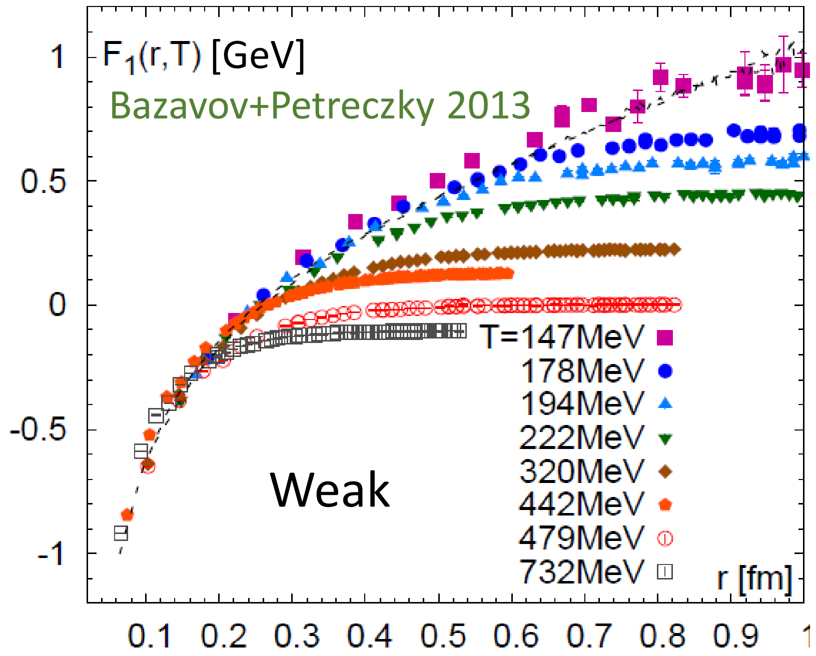
- Can be calculated in lattice QCD
- Successful in studying vacuum quarkonium physics
- Even work well for light hadrons (with relativistic effects)

Color Potential in Medium?

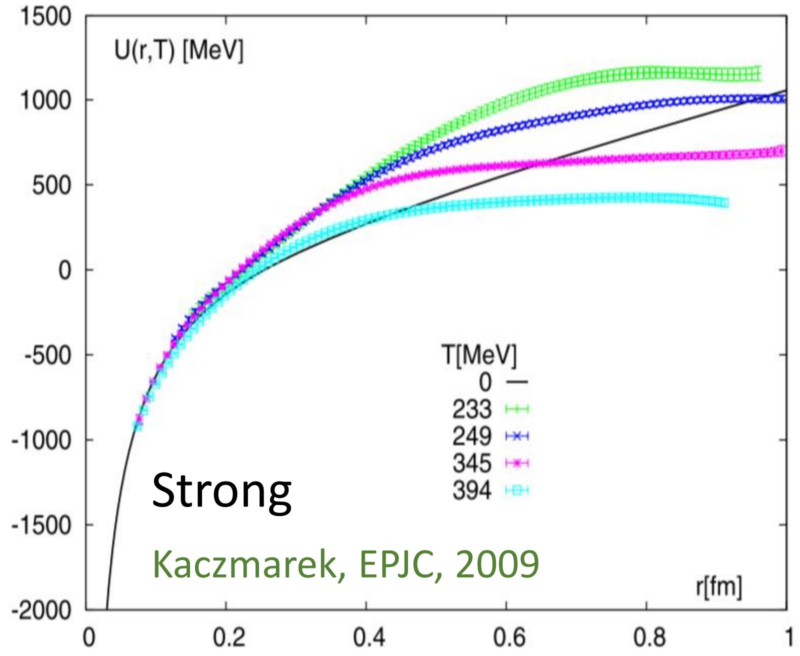
- Help us on: quarkonium properties, heavy-flavor transport, spectral properties, shear viscosity …

arXiv:1612.09138

Free energy $F_{\bar{Q}Q}$

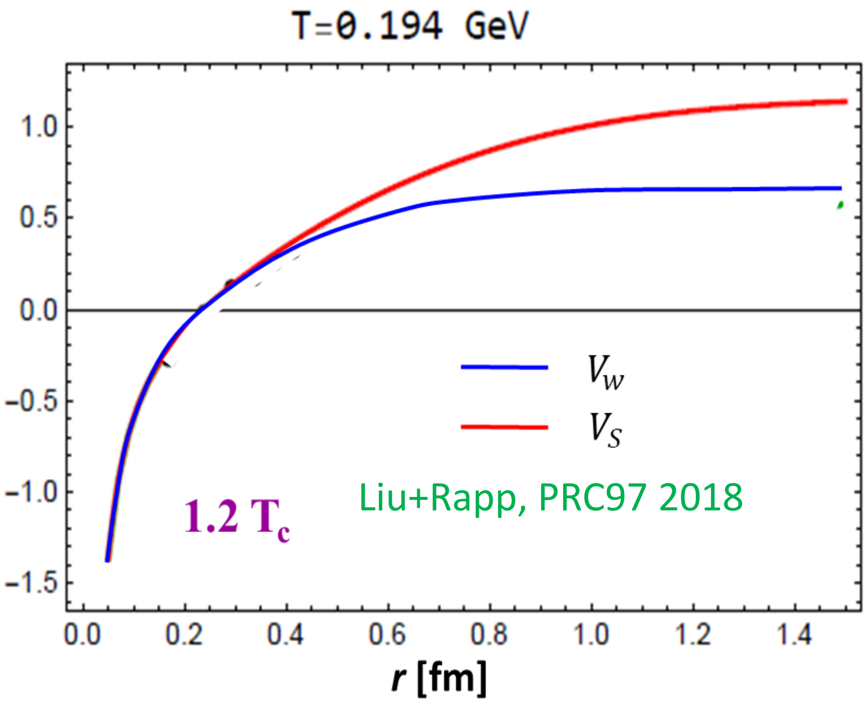


Internal energy $U_{\bar{Q}Q}$



"True potential" $V_{\bar{Q}Q}$?

(T-matrix extraction from lattice)



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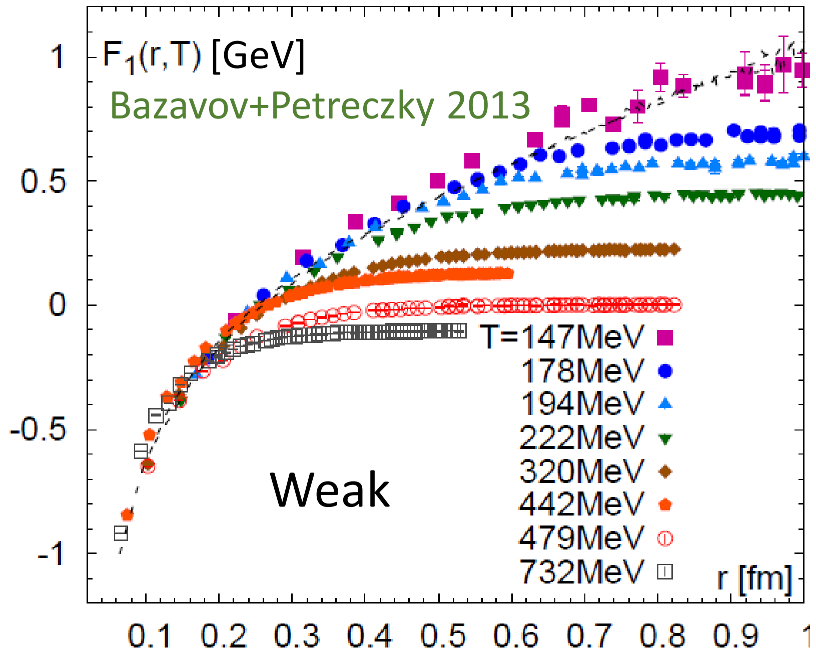
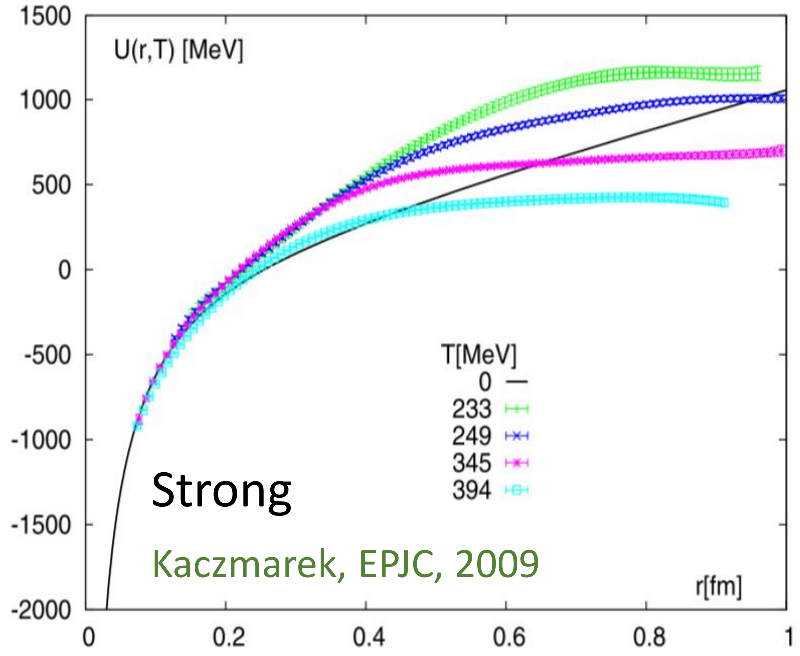
Free energy $F_{\bar{Q}Q}$



Internal energy $U_{\bar{Q}Q}$



"True potential" $V_{\bar{Q}Q}$?

(Data analysis on lattice data)

Weak V:

Burnier+Kaczmarek+Rothkopf 14

Petreczky+Rothkopf+Weber QM18

Strong V:

Bazavov+Burnier+Petreczky HP14

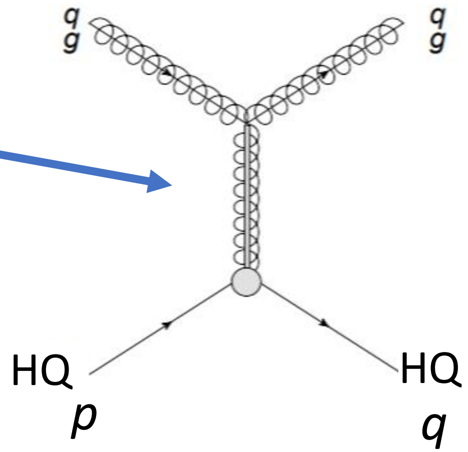
Petreczky QM17

How HF experiments help us?

Potentials for Heavy-Light Scattering?

- Propagator to potential:

$$\frac{1}{\left(\sqrt{M^2+p^2}-\sqrt{M^2+q^2}\right)^2-(\mathbf{p}-\mathbf{q})^2} \approx \frac{1}{(0)^2-(\mathbf{p}-\mathbf{q})^2} \to \frac{1}{4\pi}\frac{1}{r}$$



- Similar approximation can be applied to confining interaction
- Relativistic vertex structure:

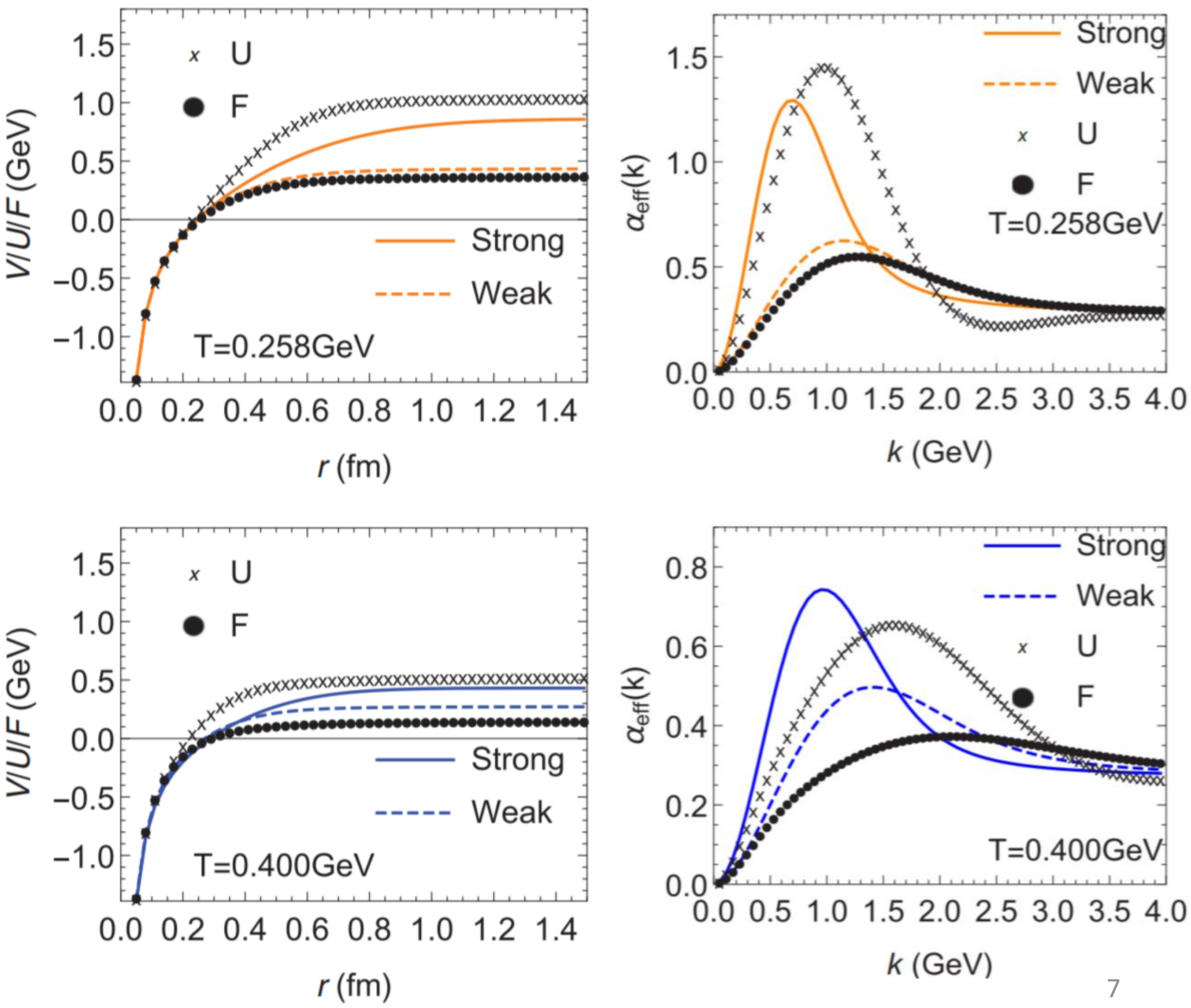
$$V_{ij}^{a}(\mathbf{p},\mathbf{p}') = \mathcal{R}_{ij}^{\mathcal{C}}\mathcal{F}_{a}^{\mathcal{C}}V_{\mathcal{C}}(\mathbf{p}-\mathbf{p}') + \mathcal{R}_{ij}^{\mathcal{S}}\mathcal{F}_{a}^{\mathcal{S}}V_{\mathcal{S}}(\mathbf{p}-\mathbf{p}')$$

- Recover full relativistic Born results at leading $1/M$ order
- Recover static potential if both quarks are heavy

In-Medium Potentials Based on Lattice QCD

- U: largest confining force, significant larger than vacuum
- F: smallest confining force
- V_s (Strong): large remnant of long-range confining force
- V_w (Weak): small confining force, close to F

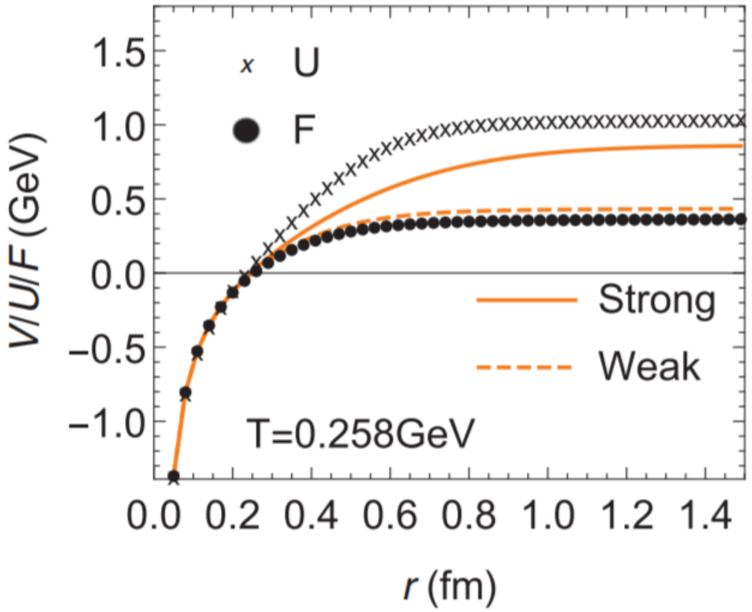
$$\alpha_{\rm eff}(k) \equiv \frac{3}{16\pi} k^2 V(k)$$

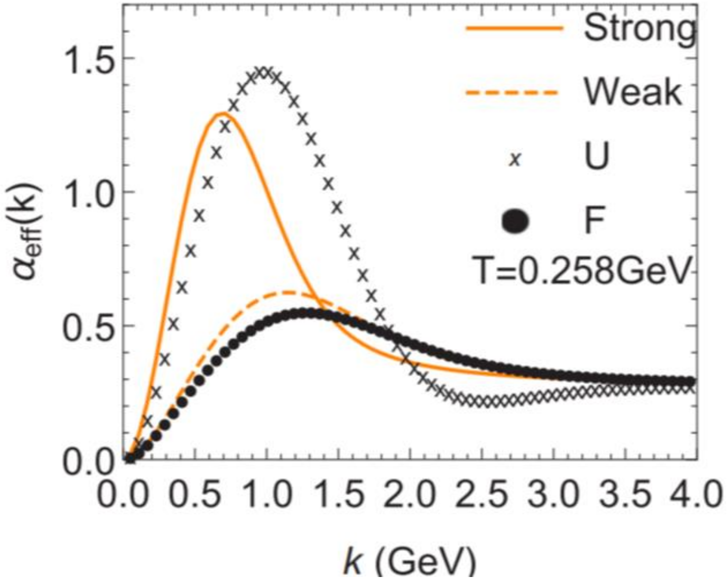


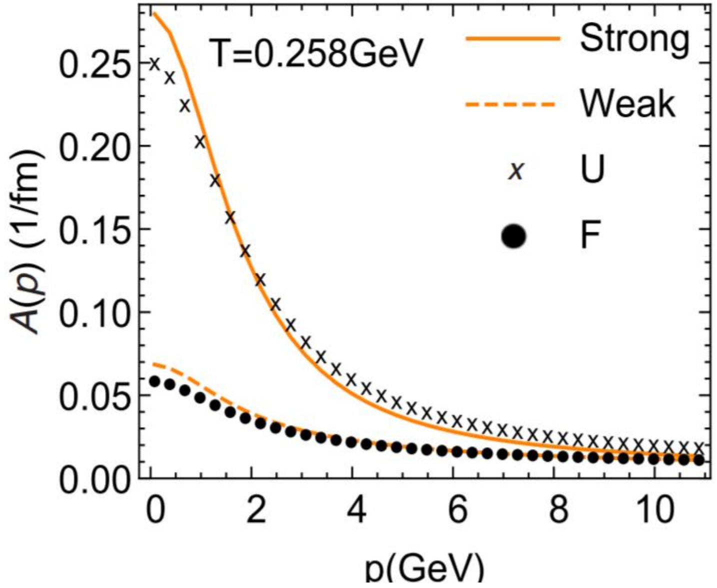
A Sensitivity Check at Born Level

- Born Formula for Drag:

$$A(p) = \int d^9\tilde{p}\, \delta^4 |V|^2 \left(1 - \frac{\mathbf{p}\cdot\mathbf{p}'}{p^2}\right) f_i(1 \pm f_i)(1 - f_Q)$$







Large long rang force → Large effective coupling at soft scale → Large enhancement in drag at small momentum

- Open HF transport is quite sensitive to underlying potential!

Many-Body Formalism

- Kadanoff Baym equation

$$\frac{\partial}{\partial t}\left[\int d\omega\, G_Q^<(\omega,\mathbf{p},t)\right]=\int d\omega\{i\Sigma_Q^<(\omega,\mathbf{p},t)G_Q^>(\omega,\mathbf{p},t)-i\Sigma_Q^>(\omega,\mathbf{p},t))G_Q^<(\omega,\mathbf{p},t)\}$$

- Reducing to Fock-Plank:

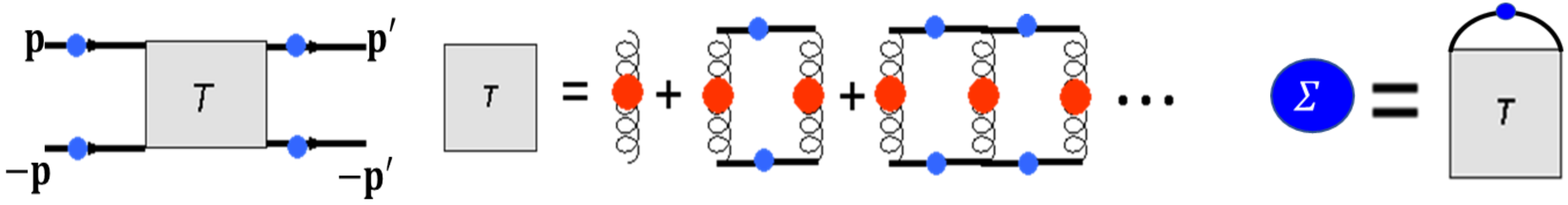
Liu+He+Rapp, PRC 99, 2019

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

- Transport coefficients with off-shell effects

$$A(p)=\int d^9\tilde{p}d^3\omega\,\delta^4|T_{Qi}|^2\left(1-\frac{\mathbf{p}\cdot\mathbf{p}'}{p^2}\right)f_i\rho_i(1\pm f_i)\rho_i(1-f_Q)\rho_Q$$

- Self-consistent *T*-matrix formalism

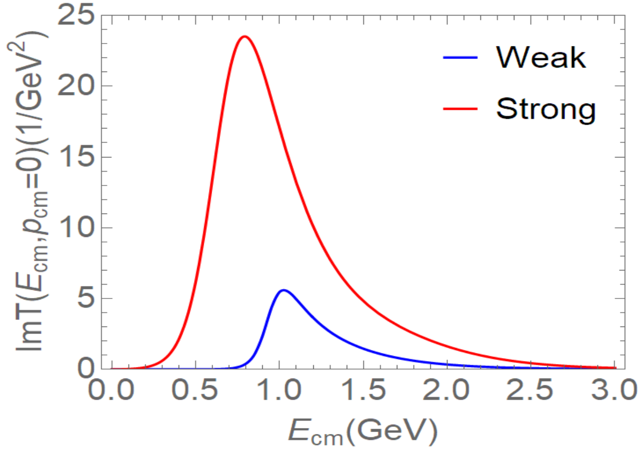


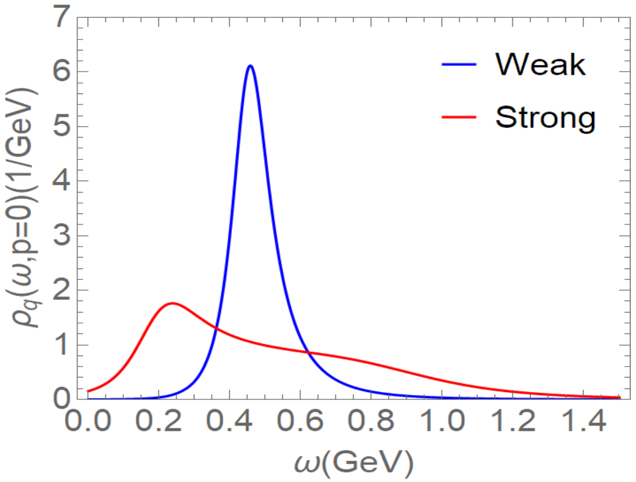
Liu+Rapp PRC 97, 2018

Strongly/Weakly Coupled Solutions

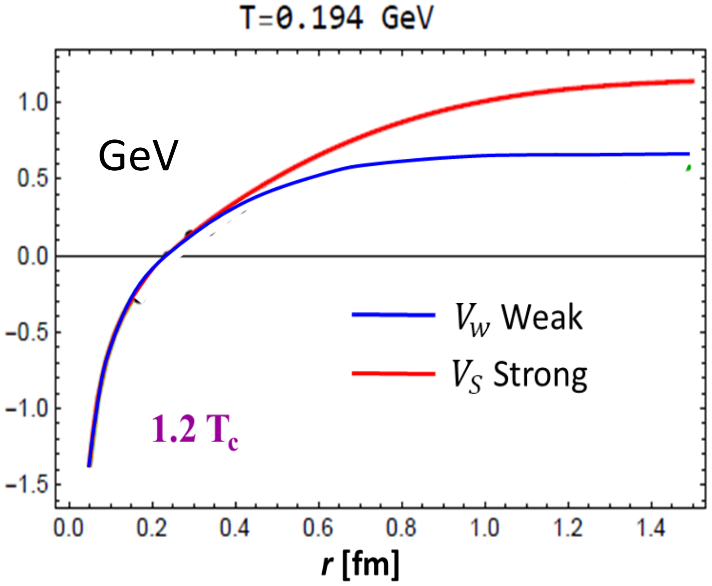
- Drag coefficients:

$$A(p) = \int d^9\tilde{p}\, d^3\omega\, \delta^4 \left|T_{Qi}\right|^2 \left(1 - \frac{\mathbf{p}\cdot\mathbf{p}'}{p^2}\right) f_i \rho_i (1 \pm f_i) \rho_i (1 - f_Q) \rho_Q$$





T-matrix



T-matrix Fit to

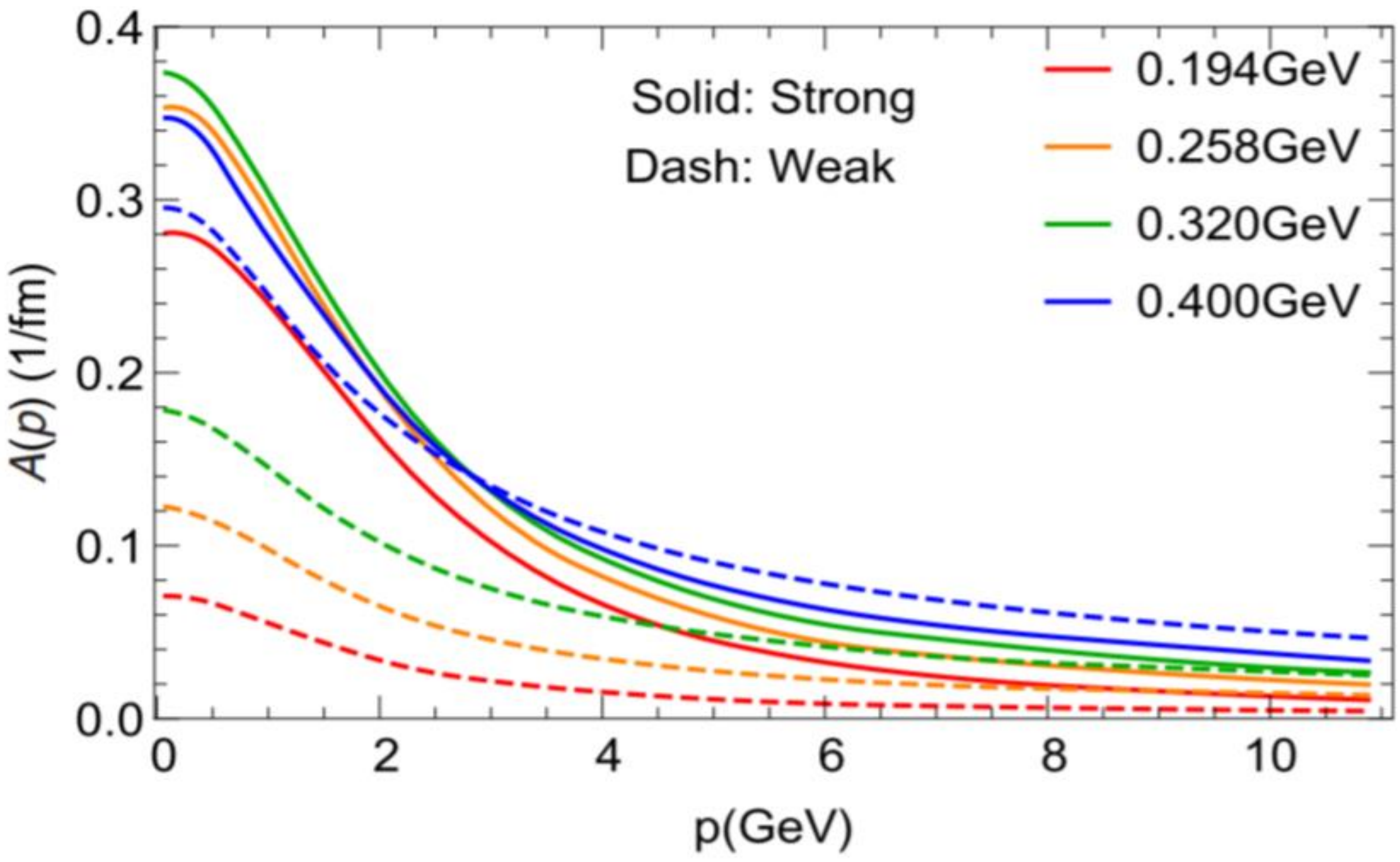
Lattice QCD:
EoS, $F_{\bar{Q}Q}$, Quarkonium Correlator

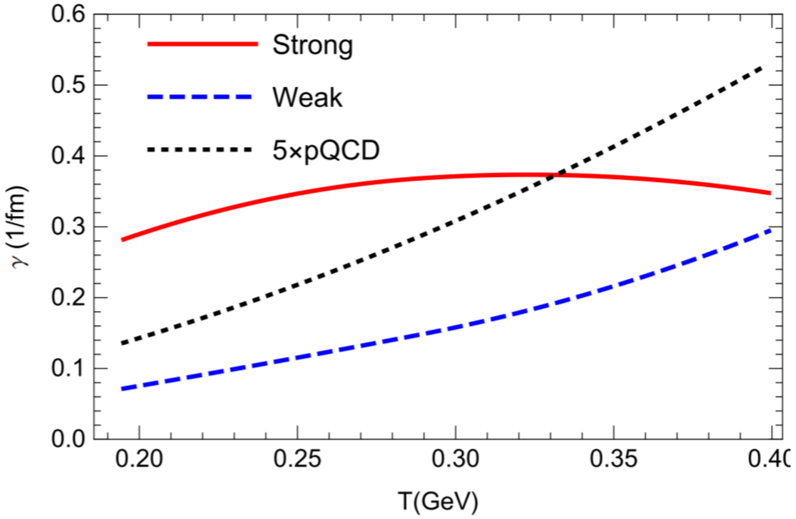
Liu+Rapp PRC 97, 2018

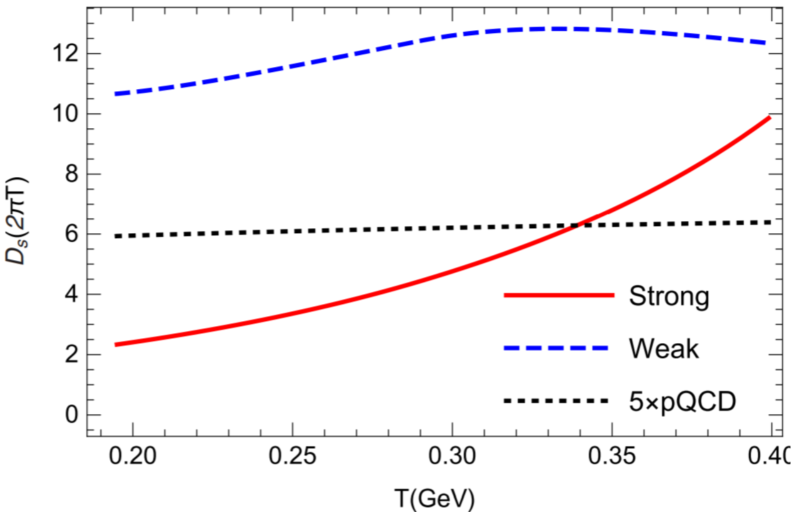
- F and U: NOT the solutions
- V_w similar to Lattice Results：
  Burnier+Kaczmarek+Rothkopf 14

Drag Coefficients from the Many-Body Theory

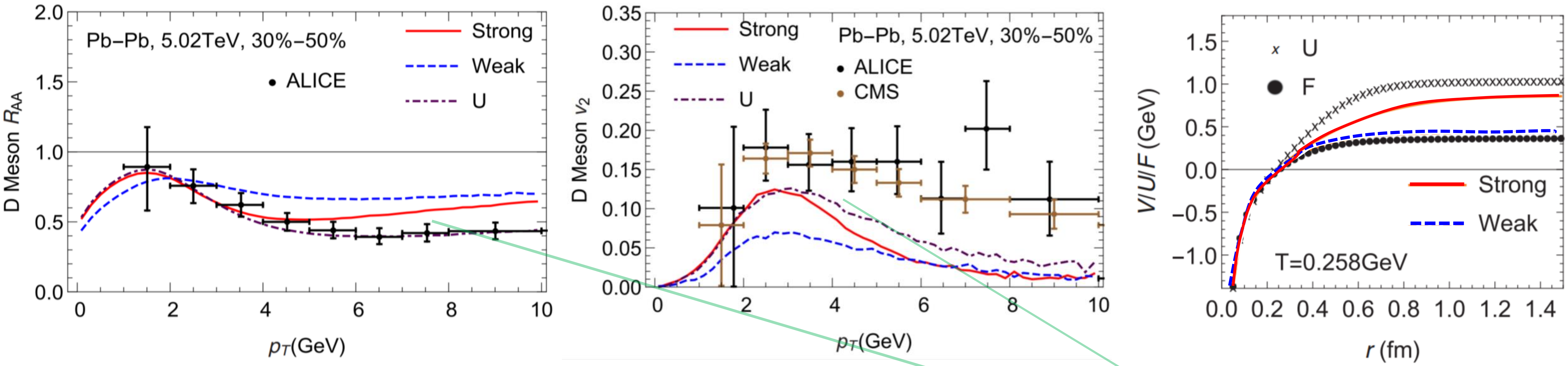
- V_S: Overall large drag, flat T dependence
- V_w : Overall small drag, perturbative-like T dependence







Langevin Simulation and Comparison to Experiments



Need radiative energy loss

- U: consistent with HF experiments BUT NOT consistent with lattice QCD and many-body physics
- V_w: consistent with lattice QCD and many-body physics BUT NOT with HF experiments
- V_S: consistent with both

Extracting Potential from Bottomonium Observables

Du+Liu+Rapp, arXiv:1904.00113

- Rate equation for quarkonium transport

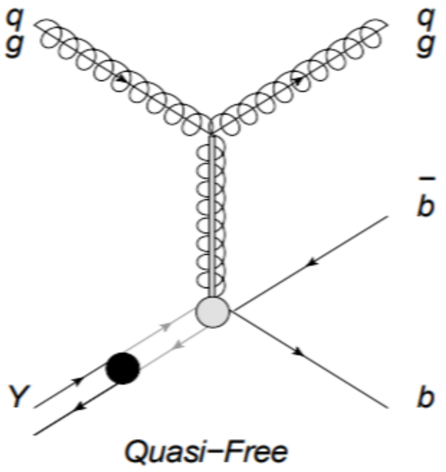
$$\frac{dN_\Upsilon(\tau)}{d\tau} = -\Gamma(T(\tau))\left[N_\Upsilon(\tau) - N_\Upsilon^{\rm eq}(T(\tau))\right]$$

Suppressed in $b\bar{b}$

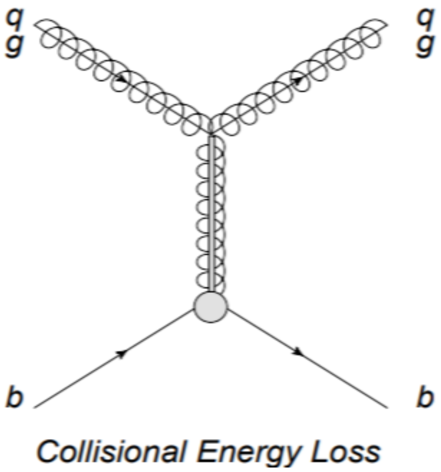
Binding energy & size ← Potential V

Interactions with medium ← Open HF physics

Bound states scattering



Individual HF scattering



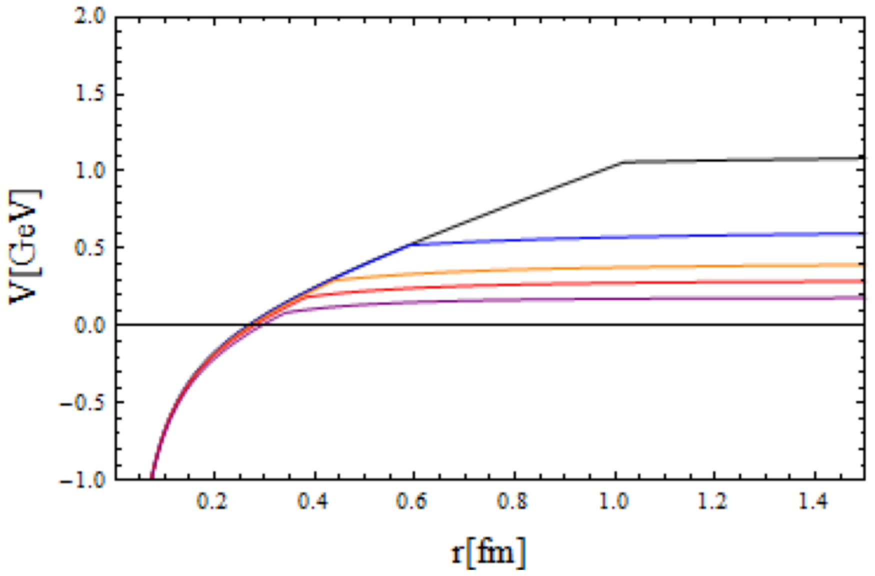
- Open and hidden flavor physics are intrinsically related!
- *K* factor to mimic non-perturbative effects

Ansatz, Parameters and Comparison to Experiments

Du+Liu+Rapp, arXiv:1904.00113

- The potential ansatz (independent from *V* in open HF section):

$$V = \begin{cases} -\frac{4}{3}\alpha_s\left(\frac{e^{-m_d r}}{r} - m_d\right) + \sigma\, r, & r < \frac{1}{m_s} \\ -\frac{4}{3}\alpha_s\left(\frac{e^{-m_d r}}{r} - m_d\right) + \frac{\sigma}{m_s}, & r > \frac{1}{m_s} \end{cases}$$



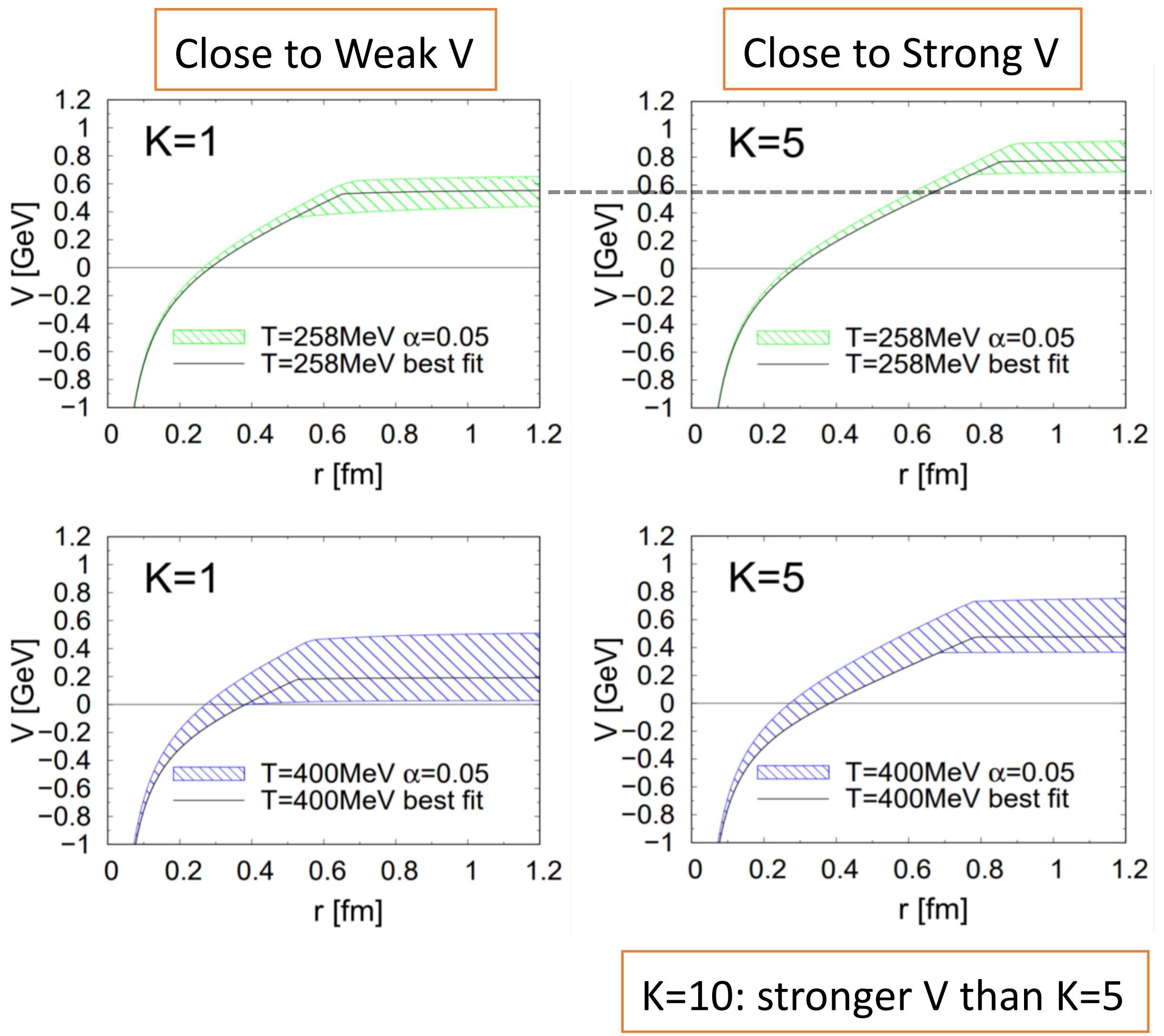
- α_s and σ: fix by vacuum bottomonium state
- Fit parameters: m_d and m_s
- Three scenarios: *K*=1, 5, 10
- Calculate the R_{AA} and compare with experiments

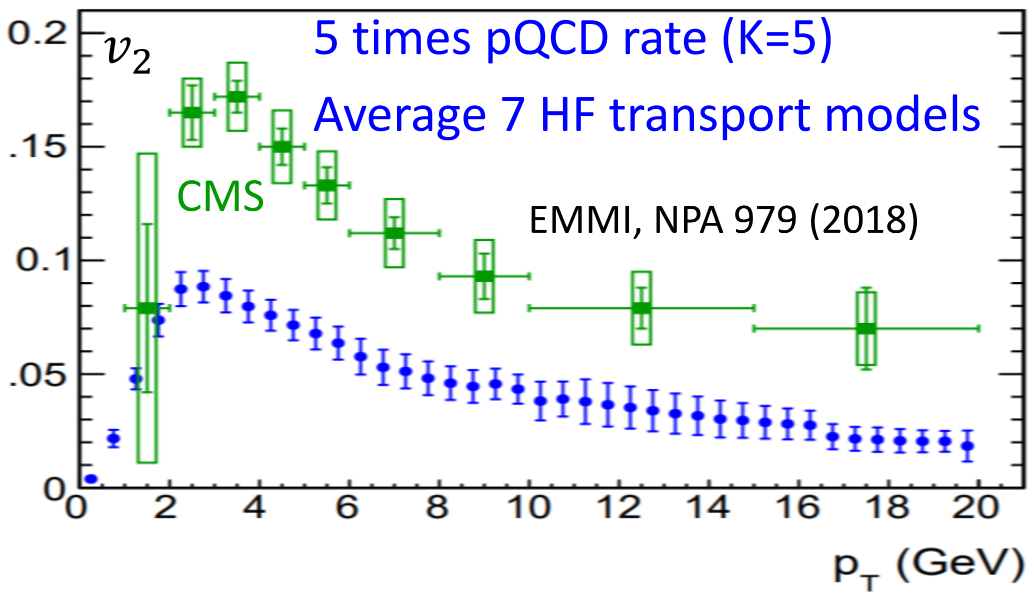
χ^2 analysis

Experiment	Rapidity	Data (R_{AA})	Reference
193 GeV U-U	$\lvert y\rvert < 1.0$	1S, 1S+2S+3S	STAR [59]
200 GeV Au-Au	$\lvert y\rvert < 0.5$	1S, 2S+3S, 1S+2S+3S	STAR [60]
2.76 TeV Pb-Pb	$\lvert y\rvert < 2.4$	1S, 2S	CMS [35]
2.76 TeV Pb-Pb	$2.5 < y < 4.0$	1S	ALICE [61]
5.02 TeV Pb-Pb	$\lvert y\rvert < 2.4$	1S, 2S, 3S	CMS [37]
5.02 TeV Pb-Pb	$2.5 < y < 4.0$	1S	ALICE [38]

Results for Extracting the Potential

Du+Liu+Rapp, arXiv:1904.00113





- Large *K* factor is preferred by open heavy flavor physics
- Combining open and hidden HF, a strong *V* is preferred

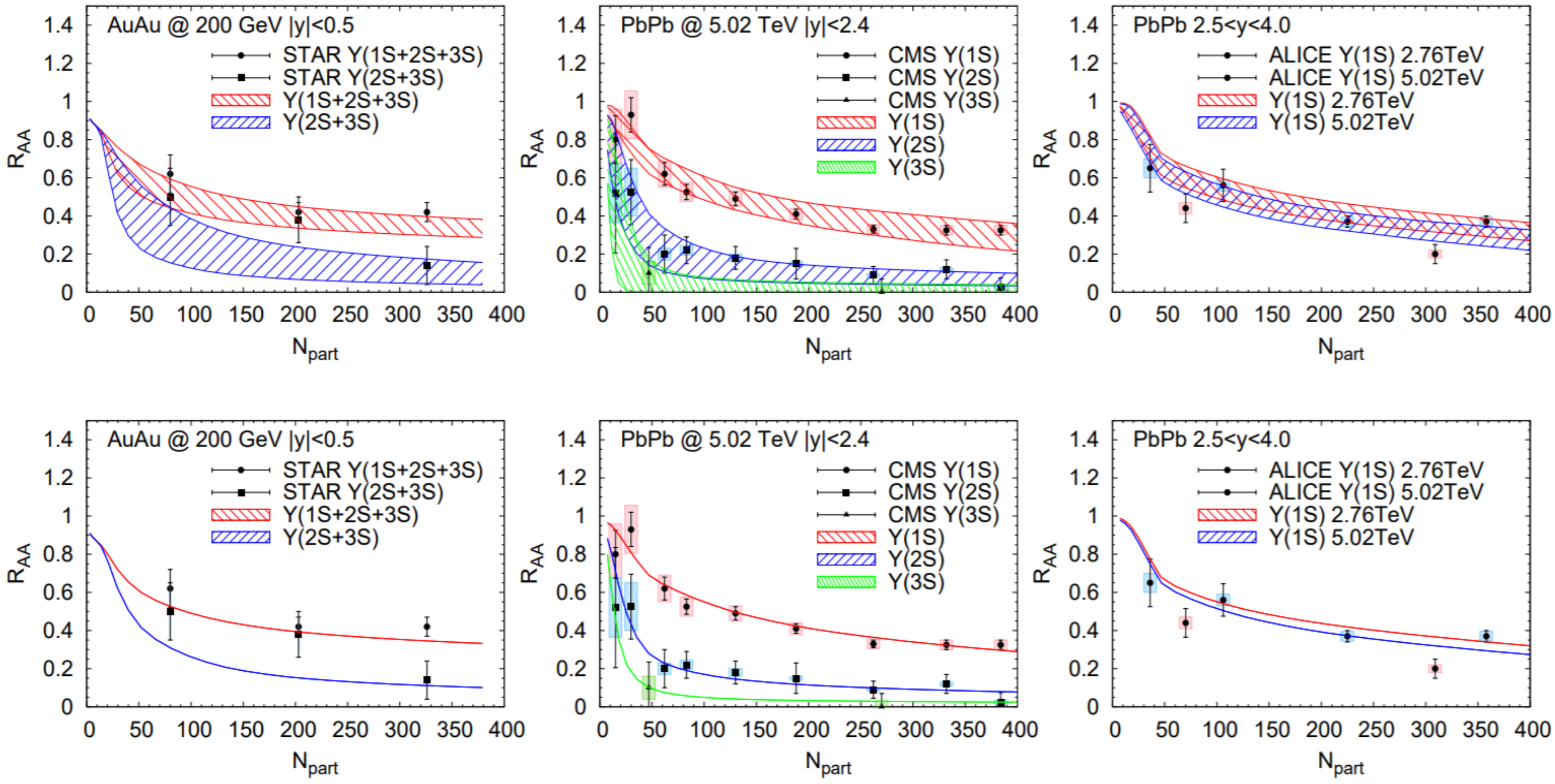
Conclusion & Perspective

- Combining open HF experiments, lattice QCD, and requirements of many-body physics, a strongly coupled potential closer to V_S is preferred

- Including the insights from open HF physics (strong heavy-light scattering), bottomonium experiments also prefer a strongly coupled potential closer to V_S

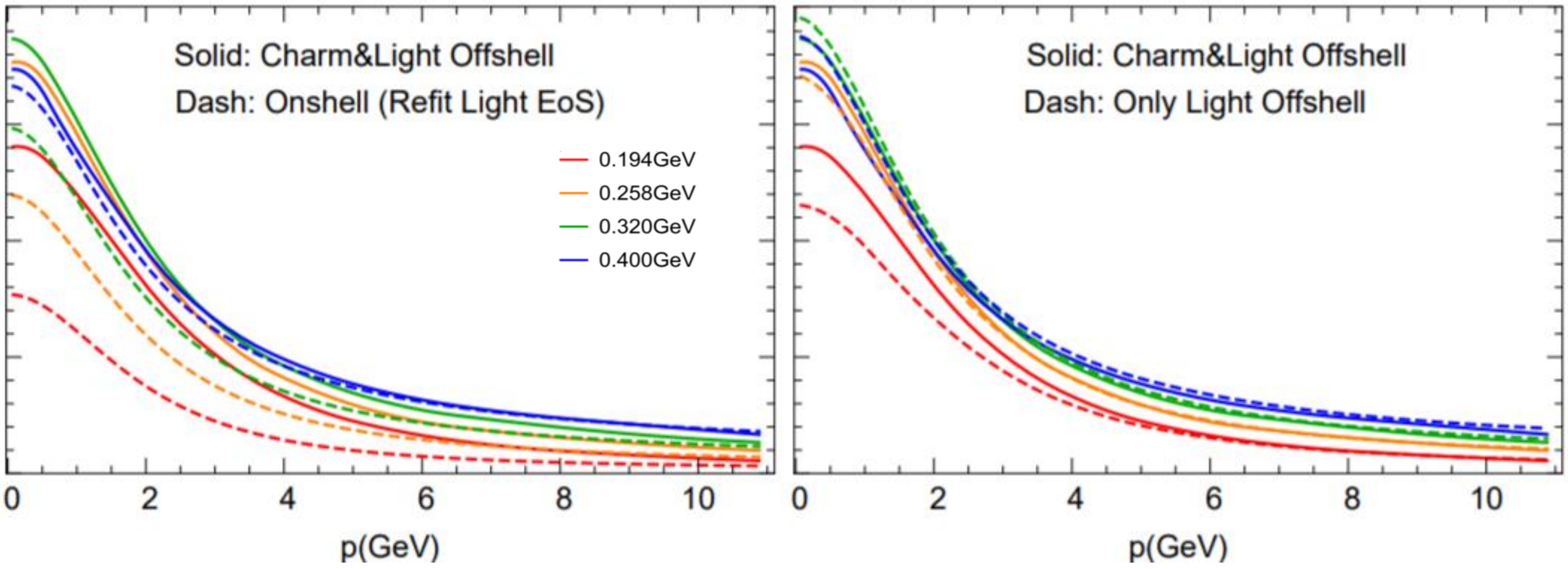
- The future analysis encompass both open and hidden HF observables in a unified framework can further narrow down the uncertainties

Compare to Bottomonium Data



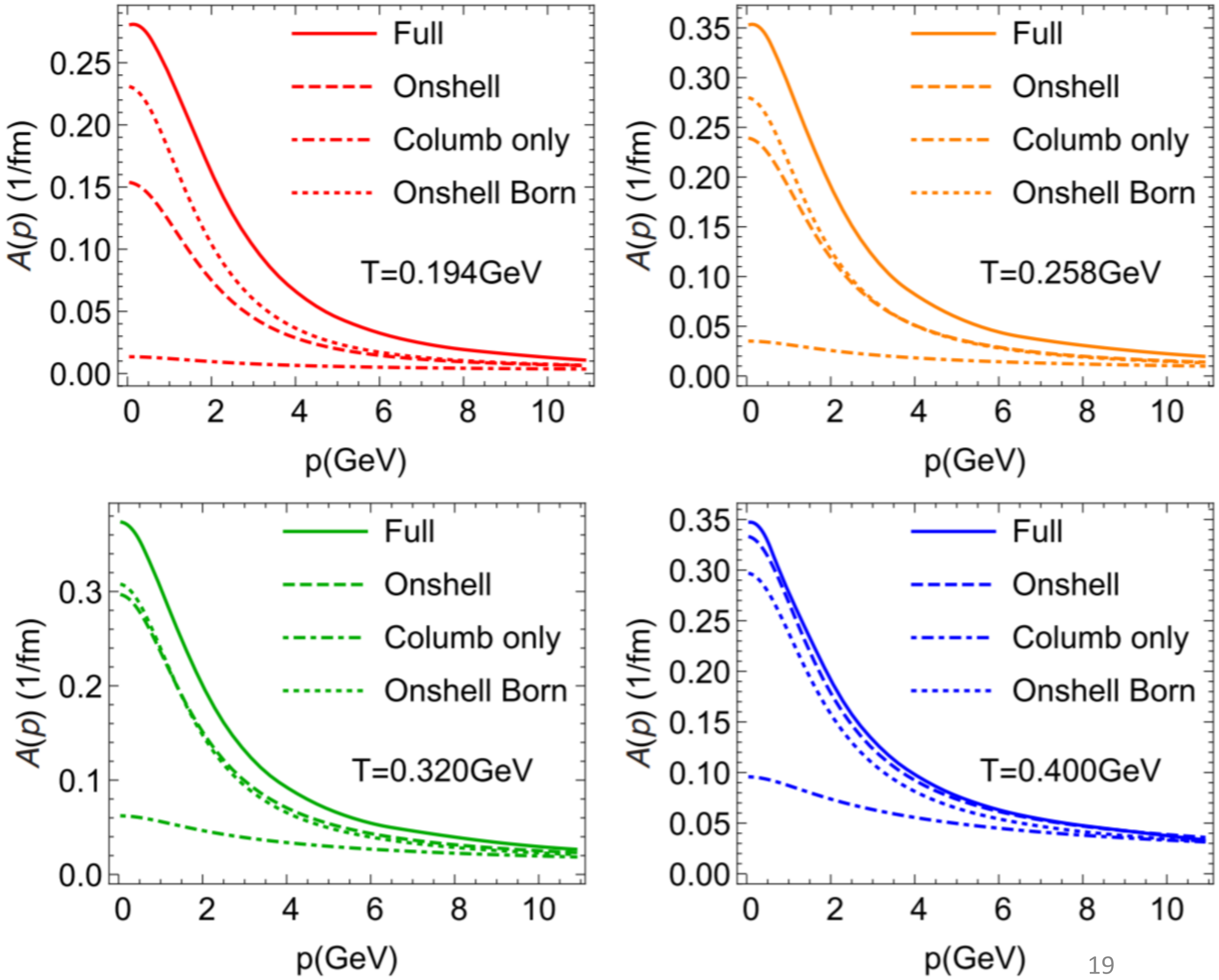
Off-shell Effects

- Largest at low temperature where the resonance is significant below the threshold



Scrutinizing Non-perturbative Effects

- Long range confining term makes the largest difference, as large as 15 times of perturbative contribution



How Force Contribute to Drag

- Slice the contribution to A(p) by momentum exchange

$$\bar{K}(k;p)dk \equiv A(p)^{-1}dA(k)$$

$$\bar{A}(k;p) \equiv \int_0^k dk' \bar{K}(k';p) \qquad k = |\vec{p}_{\rm cm} - \vec{p}'_{\rm cm}|$$

- Low T and small Charm p*:* larger percentage of contribution to A_p from low momentum
- High T and large Charm p , larger contribution to A_p from high momentum