Heavy Quark Radiative Energy Loss in T-matrix Approach

Shuai Liu, Ralf Rapp

Institute of Modern Physics & Texas A&M University

ETC* Heavy-Flavor Transport in QCD Matter Workshop, 2021, Online

Based on work: Liu and Rapp: JHEP 08 (2020) 168

Outline

1) Background and Motivation

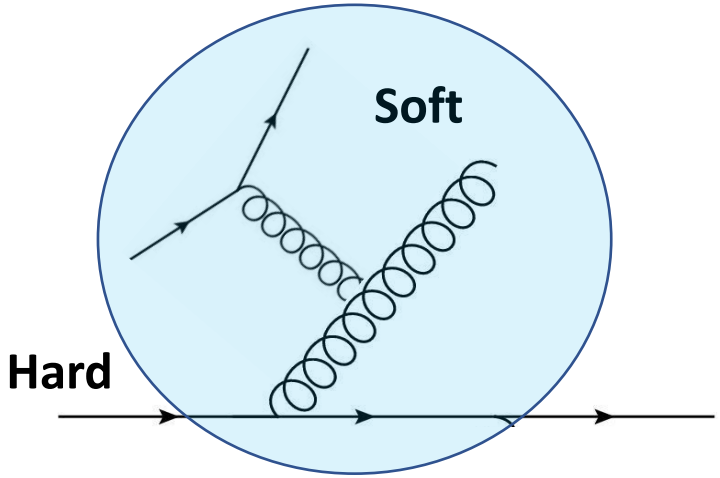
2) Many-Body Approach to Radiative Process

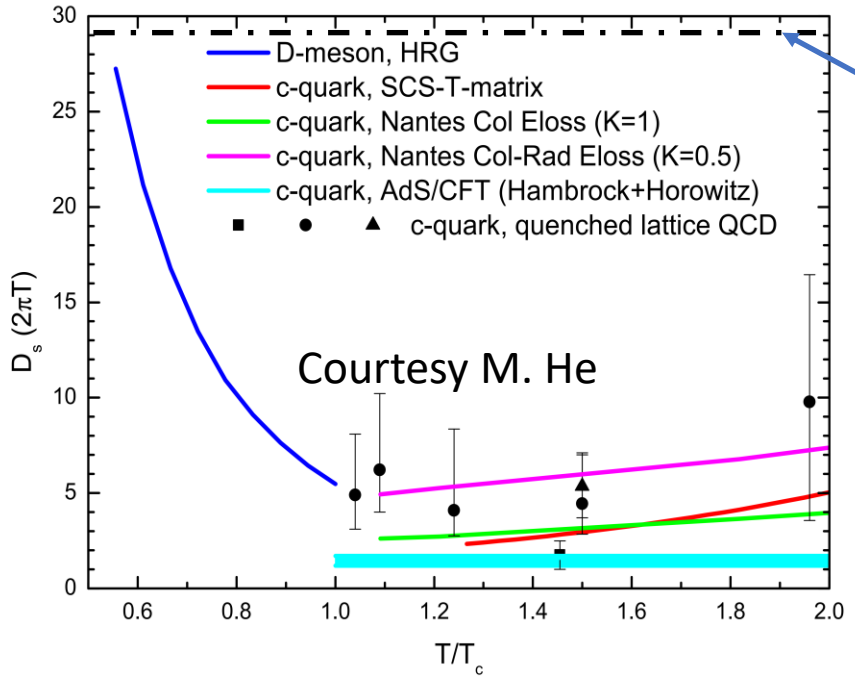
3) Study the Non-Perturbative (NP) Effects on Radiative Process

4) Conclusion

Non-Perturbative Effects for High Energy Partons?

- A multi-scale problem
- Gluons emitted at soft scale
- Interactions at soft scale, strong!

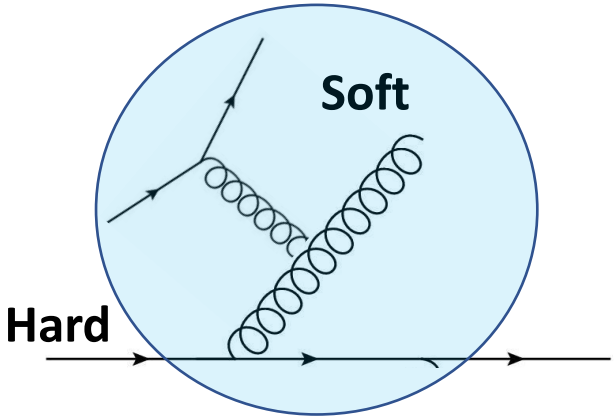




LO pQCD

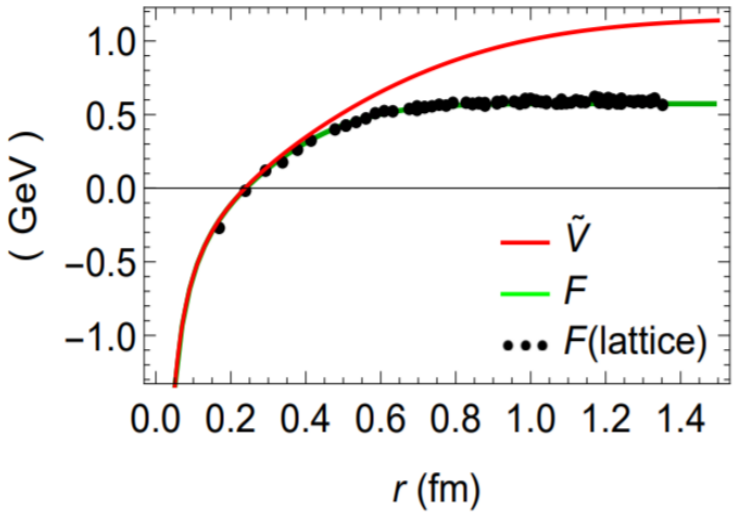
Non-Perturbative Effects for High Energy Partons?

- A multi-scale problem
- Gluons emitted at soft scale
- Interactions at soft scale, strong!



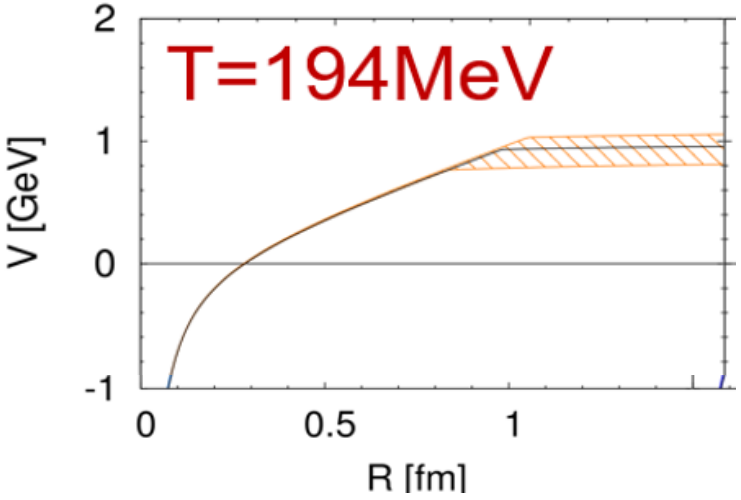
Not just Coulomb interaction

From Lattice&HF Phenomenology



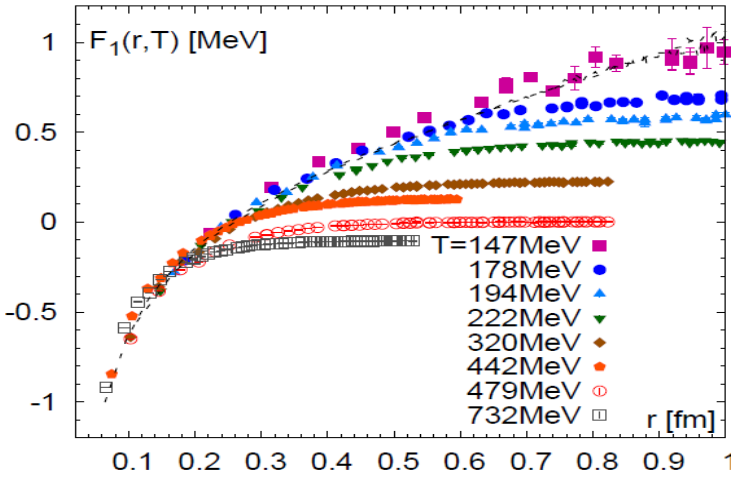
Liu, Rapp, 2018, 2019

From Quarkonium Phenomenology



Du, Liu, Rapp, 2019

Lattice Free Energy



Mocsy, Petreczky, Strickland,13

Non-Perturbative Effects for High Energy Partons?

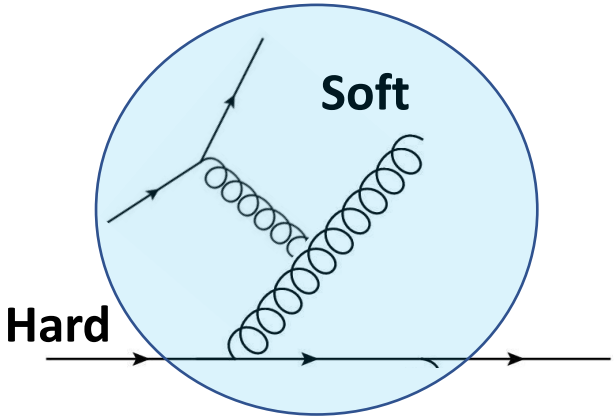
- A multi-scale problem
- Gluons emitted at soft scale
- Interactions at soft scale, strong!

Not just Coulomb interaction

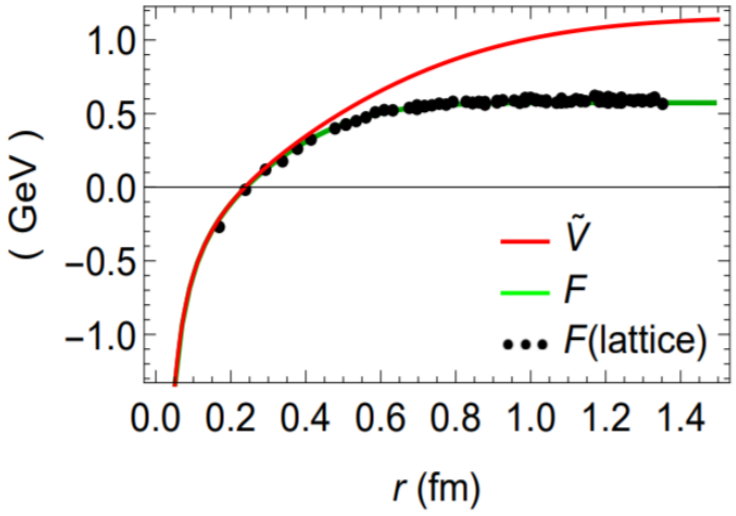
Remnant of confining force,

Resummation,

Non-quasiparticle

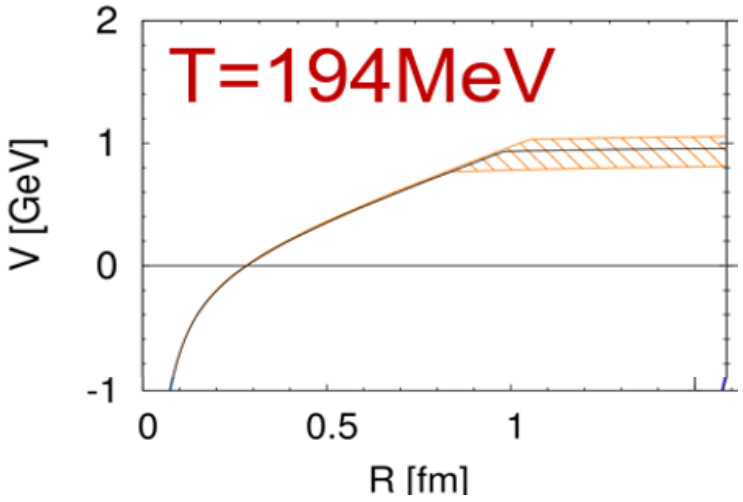


From Lattice&HF Phenomenology



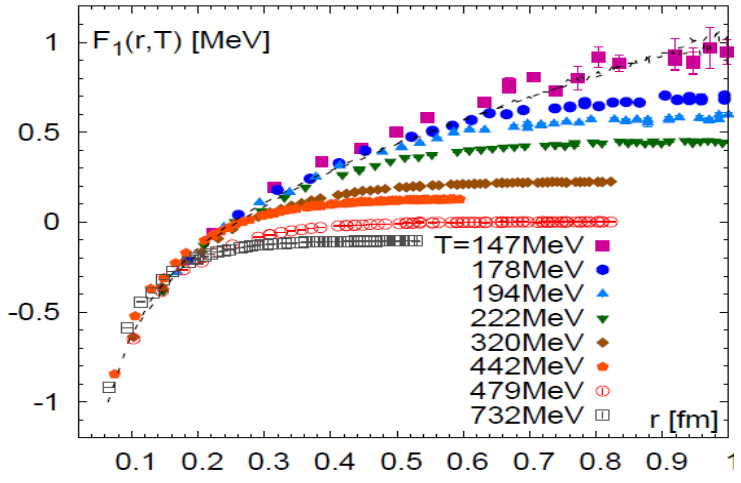
Liu, Rapp, 2018, 2019

From Quarkonium Phenomenology



Du, Liu, Rapp, 2019

Lattice Free Energy

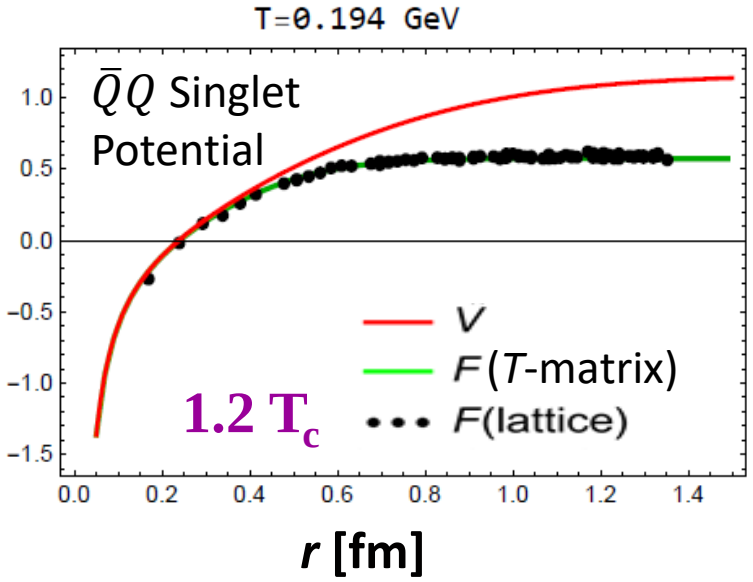


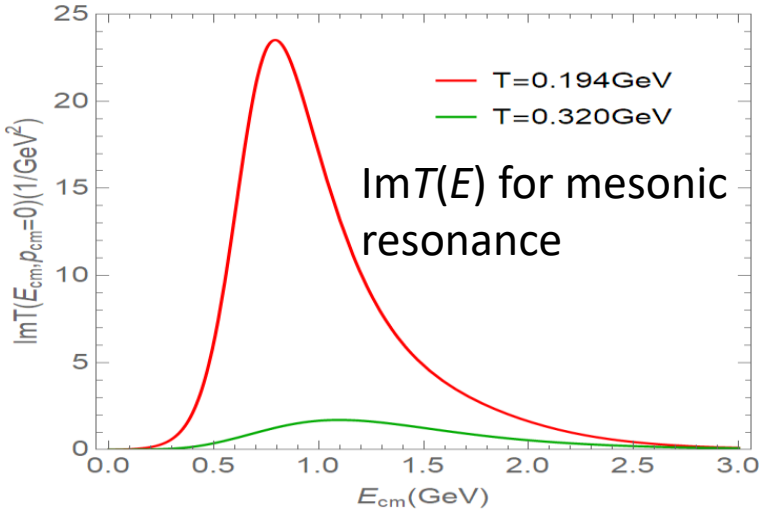
Mocsy, Petreczky, Strickland,13

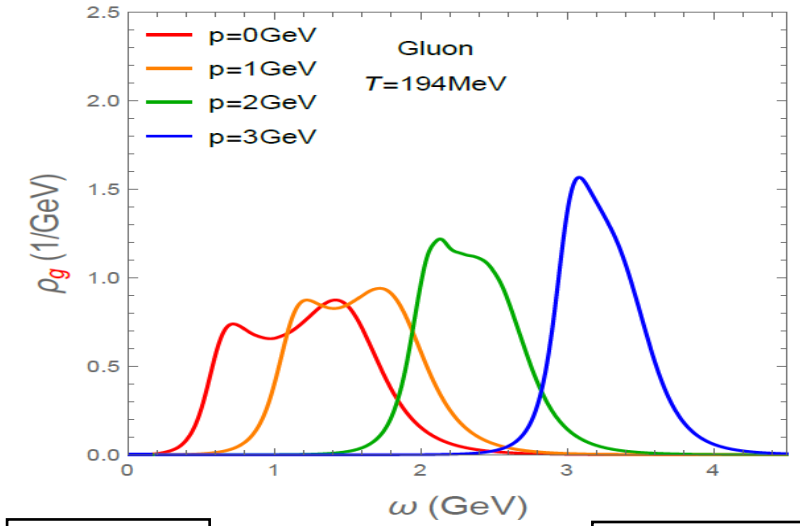
Liu, Rapp, 2018, 2019, 2020

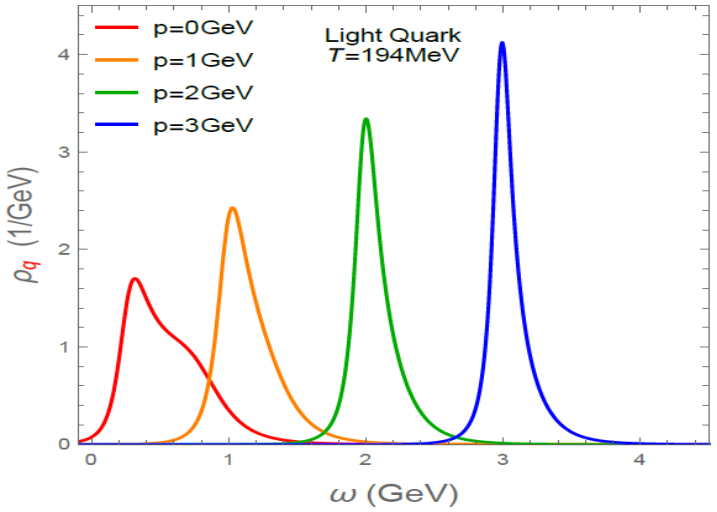
Non-Perturbative Effects in Strongly Coupled QGP

- Remnant of confining force
- Ladder resummation ⟹ resonances
- Melts low-momentum quasiparticles





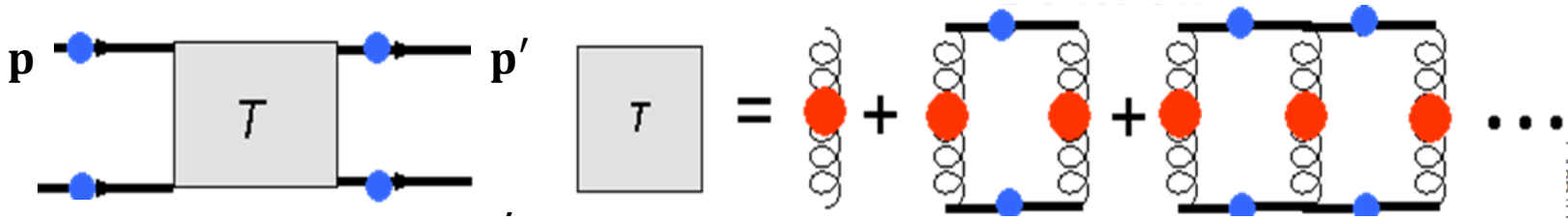




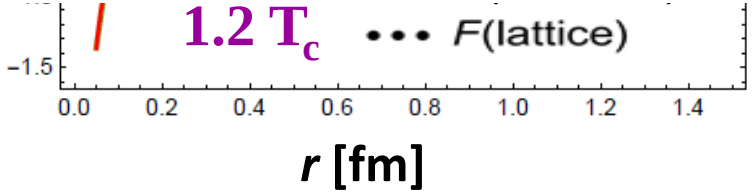
Liquid ⟹ Quasiparticle

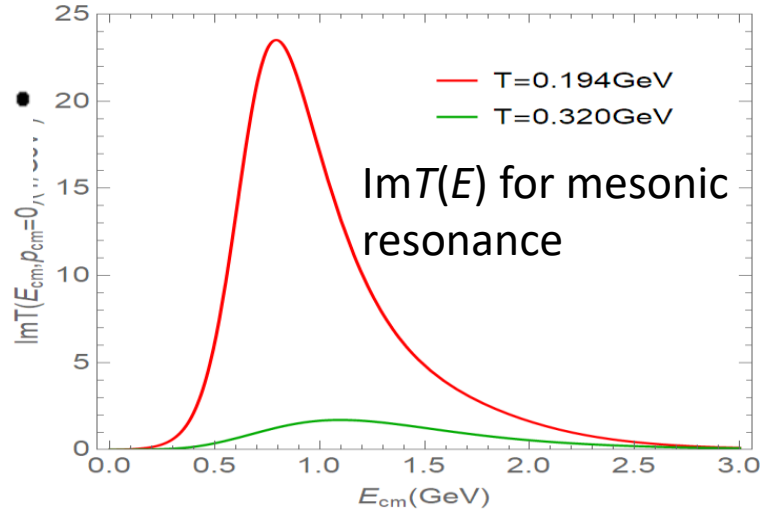
Liu, Rapp, 2018, 2019, 2020

Non-Perturbative Effects in Strongly Coupled QGP

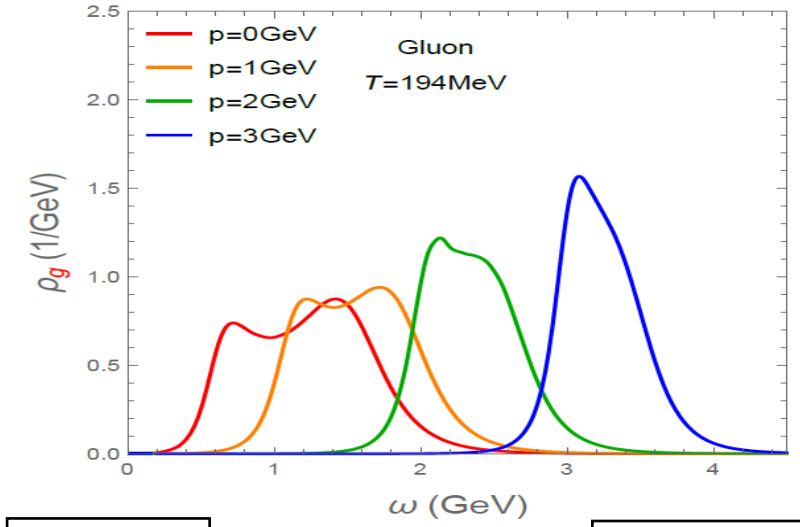


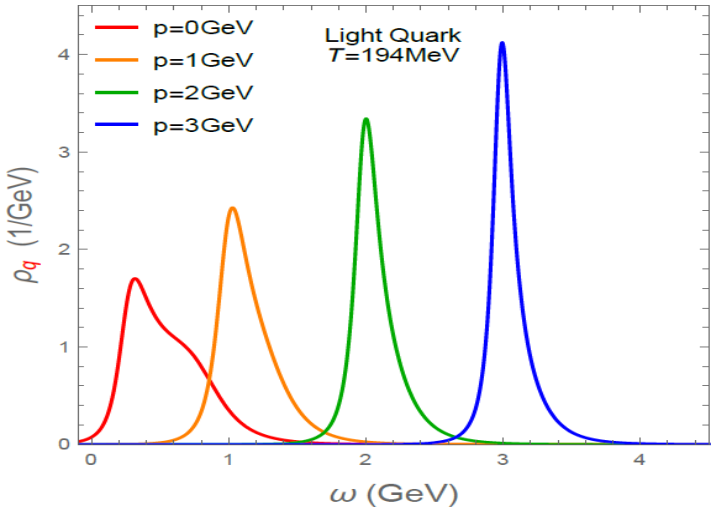
$$T(E,\mathbf{p},\mathbf{p}') = V(\mathbf{p},\mathbf{p}') + \int \frac{d^3p}{(2\pi)^3} V(\mathbf{p},\mathbf{k}) G_{(2)}(E,\mathbf{k}) T(z,\mathbf{p},\mathbf{p}')$$





- Remnant of confining force
- Ladder resummation
  ➡ resonances
- Melts low-momentum quasiparticles





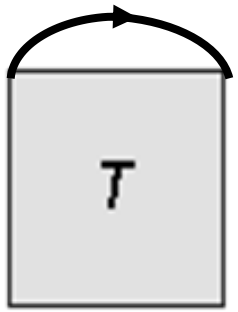
Liquid ➡ Quasiparticle

Liu, Rapp, 2018, 2019, 2020

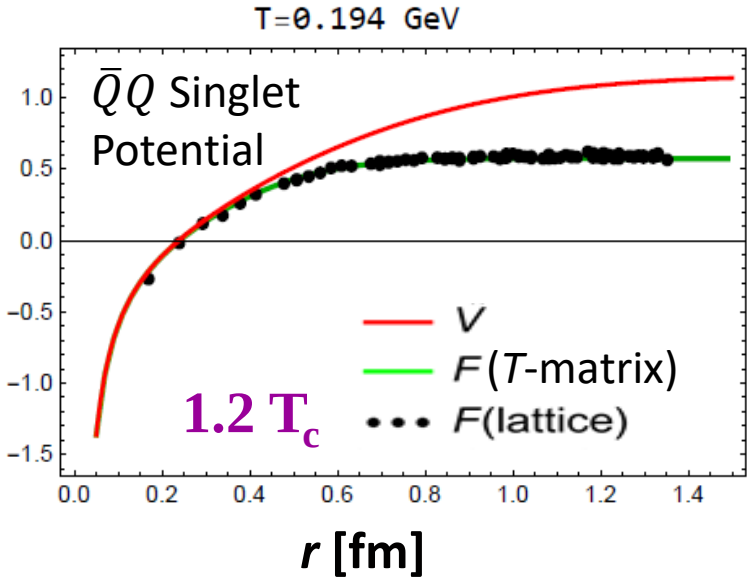
Non-Perturbative Effects in Strongly Coupled QGP

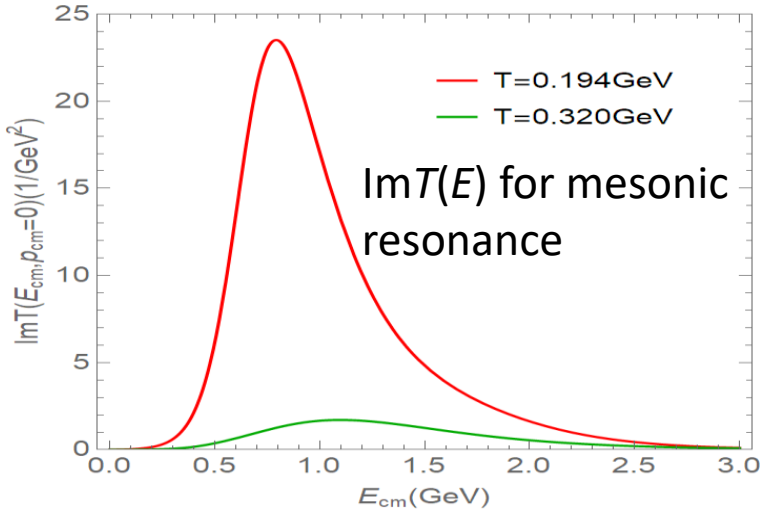
$$\Sigma = \sum_{s,c,f} \int \widetilde{d^4k}\, T(\mathrm{G})\, G$$

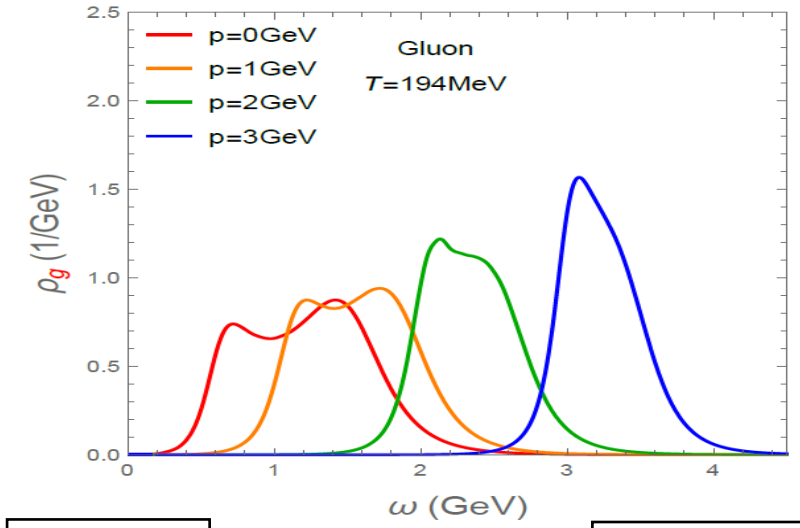
$$\rho(\omega) = \frac{1}{\pi} \mathrm{Im} \frac{-1}{\omega - \varepsilon_p - \Sigma}$$

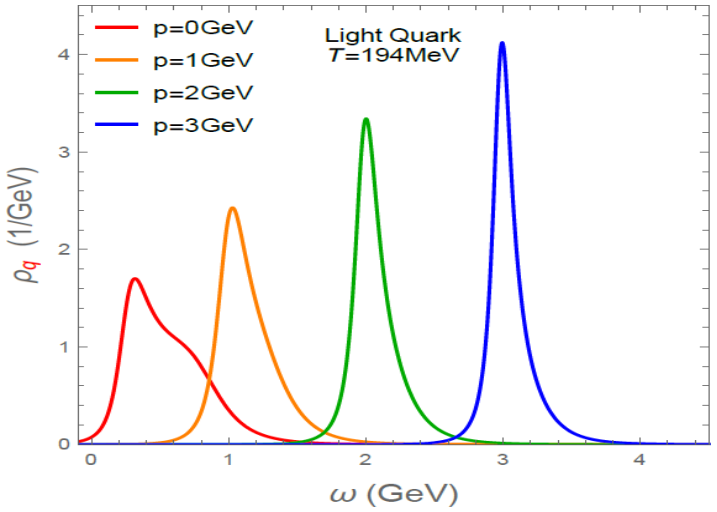


- Remnant of confining force
- Ladder resummation
  ⇒ resonances
- Melts low-momentum quasiparticles







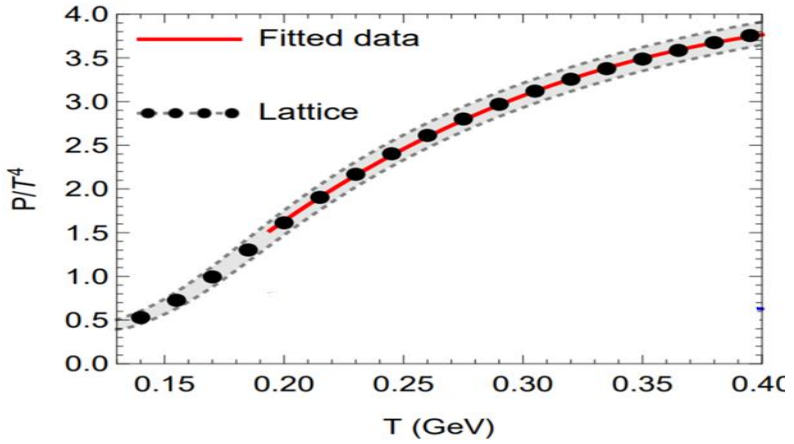


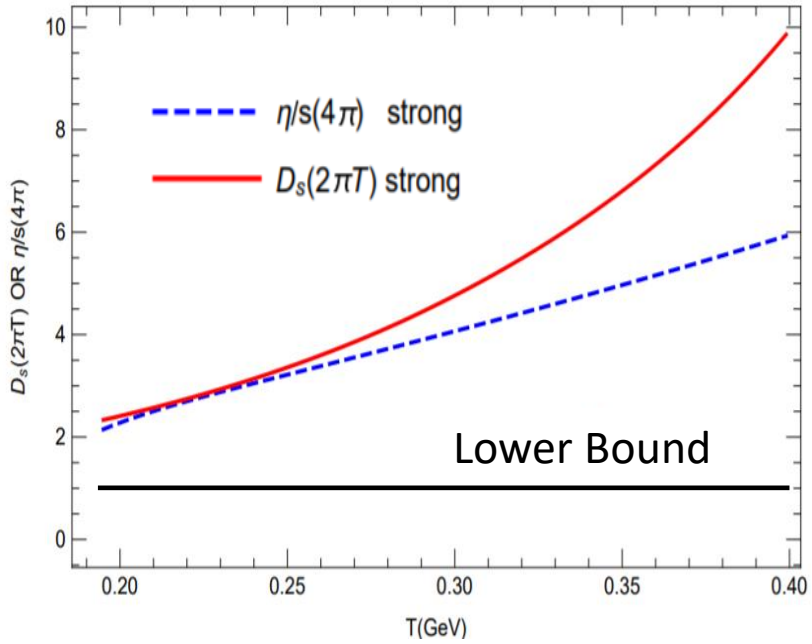
Liquid ⇒ Quasiparticle

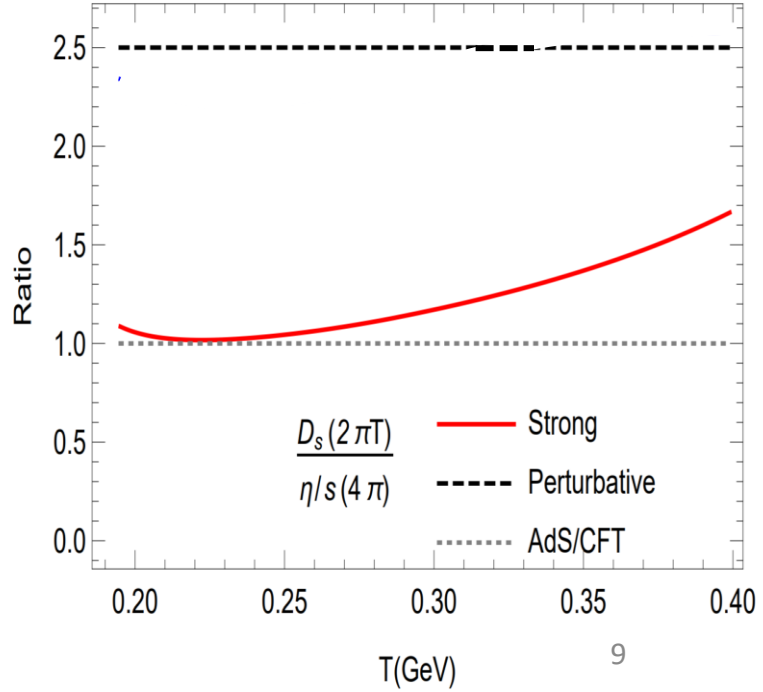
Liu, Rapp, 2018, 2019, 2020

Non-Perturbative Effects in Strongly Coupled QGP

- Remnant of confining force
- Ladder resummation
  ⟹ resonances
- Melts low-momentum quasiparticles

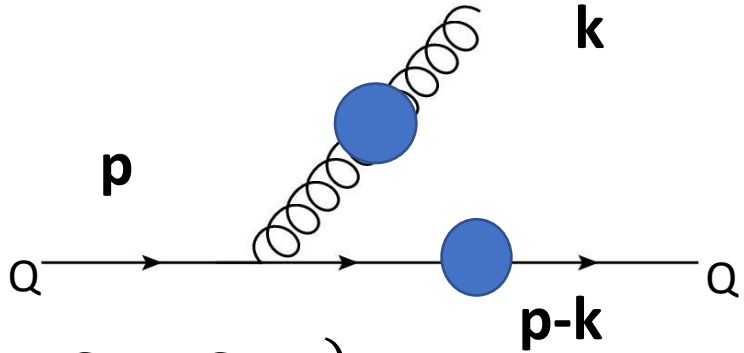


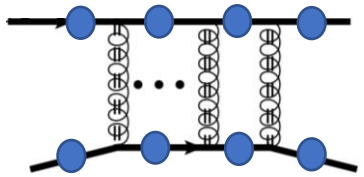




T-matrix Approach for Energy Loss

- Leading skeleton order radiation:





- Main idea:

$$\textbf{OnShell}\ \delta(\varepsilon_{\boldsymbol{p}} - \varepsilon_{\boldsymbol{k}} - \varepsilon_{\boldsymbol{p-k}})$$

$$\textbf{OffShell}\ \int d\omega dv \delta\left(\varepsilon_{\boldsymbol{p}} - \omega - v\right)\rho(\omega, k)\rho(v, \boldsymbol{p-k})$$

- Momentum transition rate:

$$w(\mathbf{p},\mathbf{k}) = \int d^4\tilde{q}d\omega'(2\pi)^4\delta^{(4)}|M_{Q\leftrightarrow Qg}|^2\rho_Q\left[1-n_Q\right]\rho_g\left[1+n_g\right]$$

$$\boxed{\sum|u(\bar{p}')\gamma_\mu u(p)\epsilon^\mu(k)|^2}$$

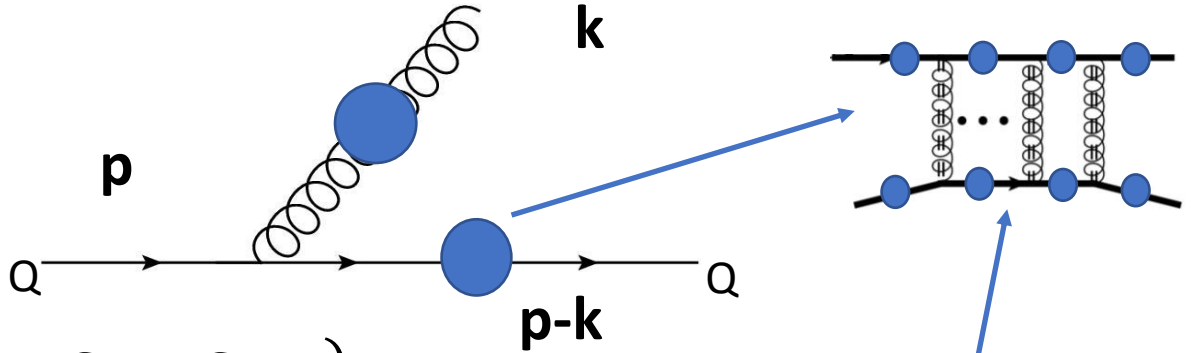
- Spectral functions

$$\rho(\omega) = \frac{1}{\pi}\mathrm{Im}\frac{-1}{\omega - \varepsilon_{\boldsymbol{p}} - \Sigma}$$

Encode Medium Effects

T-matrix Approach for Energy Loss

- Leading skeleton order radiation:



- Main idea:

$$\textbf{OnShell}\ \delta(\varepsilon_{\boldsymbol{p}} - \varepsilon_{\boldsymbol{k}} - \varepsilon_{\boldsymbol{p-k}})$$

$$\textbf{OffShell}\ \int d\omega dv \delta\left(\varepsilon_{\boldsymbol{p}} - \omega - v\right)\rho(\omega, k)\rho(v, \boldsymbol{p-k})$$

- Momentum transition rate:

$$w(\mathbf{p},\mathbf{k}) = \int d^4\tilde{q}d\omega'(2\pi)^4\delta^{(4)}|M_{Q\leftrightarrow Qg}|^2\rho_Q\left[1-n_Q\right]\rho_g\left[1+n_g\right]$$

$$\boxed{\sum |u(\bar{p}')\gamma_\mu u(p)\epsilon^\mu(k)|^2}$$

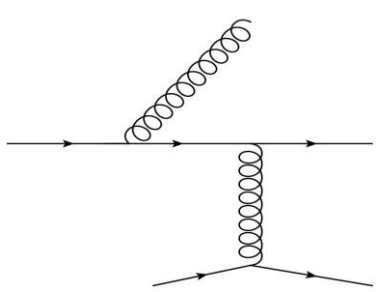
- Spectral functions

$$\rho(\omega) = \frac{1}{\pi}\mathrm{Im}\frac{-1}{\omega - \varepsilon_{\boldsymbol{p}} - \Sigma}$$

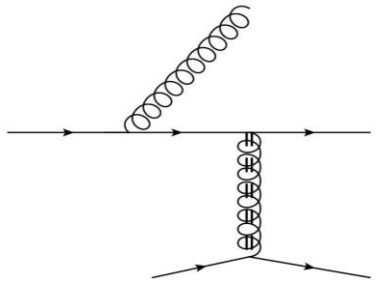
Encode Medium Effects

Four Cases with Different NP Effects

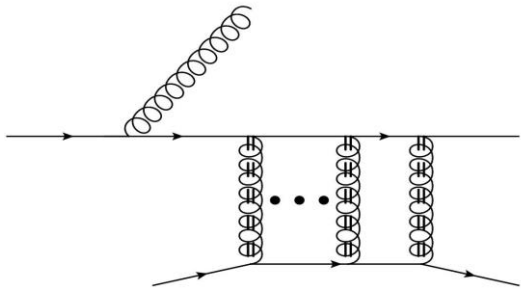
(1) V_C Born	(2) V_{CS} Born	(3) Tmatrix Onshell	(4) Tmatrix Offshell
Coulomb	Coulomb+String	Coulomb+String	Coulomb+String
Leading-order	Leading-order	All order	All order
quasi-particle	quasi-particle	quasi-particle	off-shell spectra



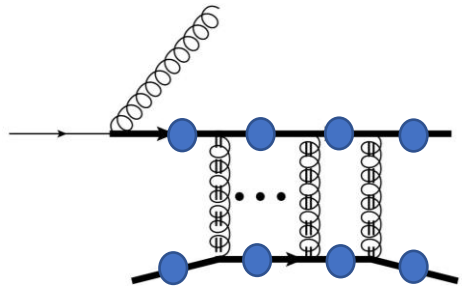
Close to pQCD



Add confining interaction



Add the t-channel resummation



Add off-shell medium partons; our full T-matrix prediction

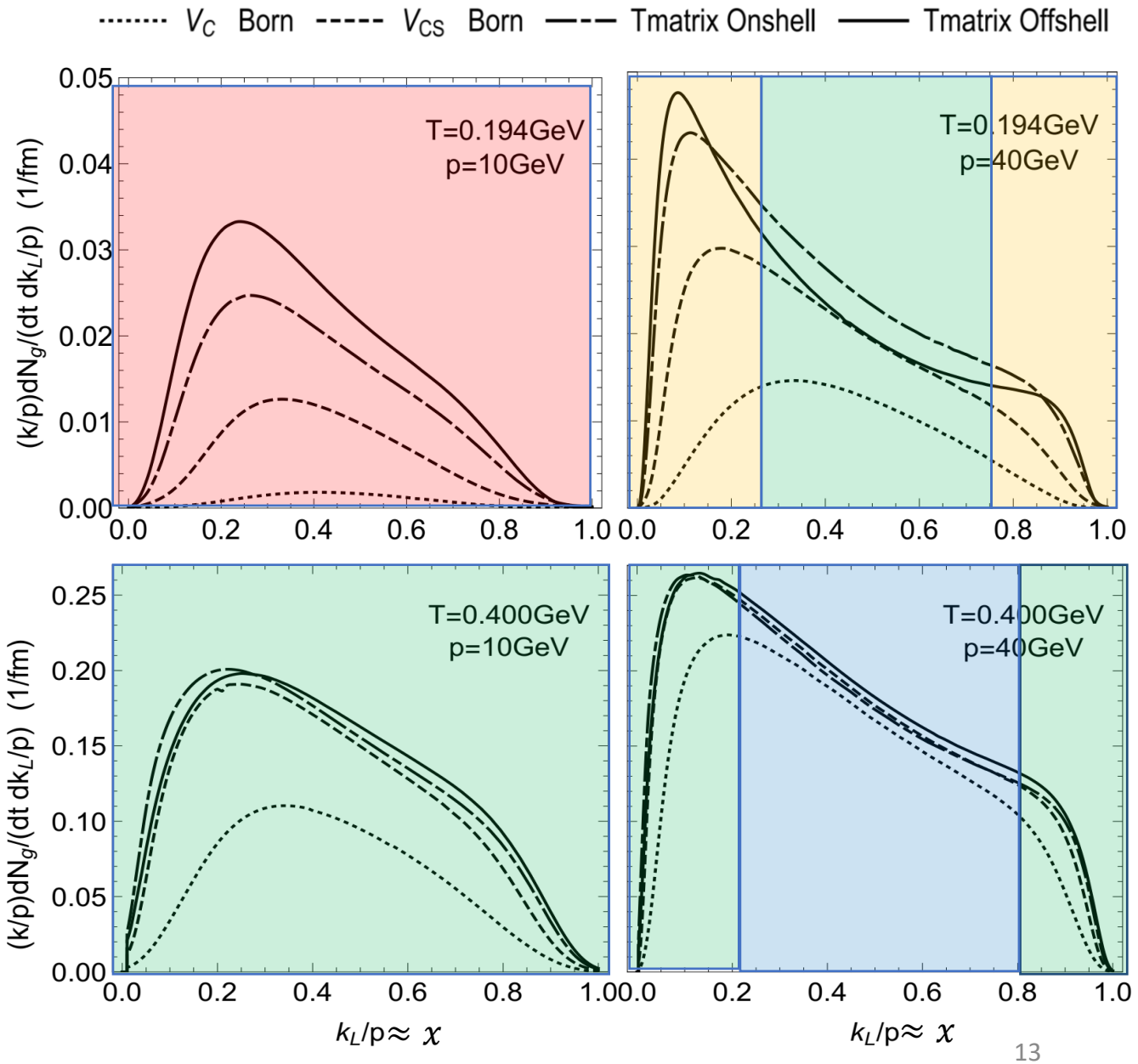
- Similar diagrams for rescattering of the outgoing gluons
- Similar medium parton density in all cases (fixed by lattice EoS)

Radiative Power Spectrum

- Power spectrum $\frac{(k/p)dN_g}{dt\ d(k_L/p)} \approx \frac{xdN_g}{dt\ dx}$

- **Red region**: Confining interaction, Resummation, Off-shell medium
- **Yellow region :** Confining interaction, Resummation, Off-shell medium
- **Green region**: Confining interaction, Resummation, Off-shell medium
- **Blue region**: Confining interaction, Resummation, Off-shell medium

Perturbative



Radiative Power Spectrum

- Adding confining interaction is quite helpful in lots of phase space

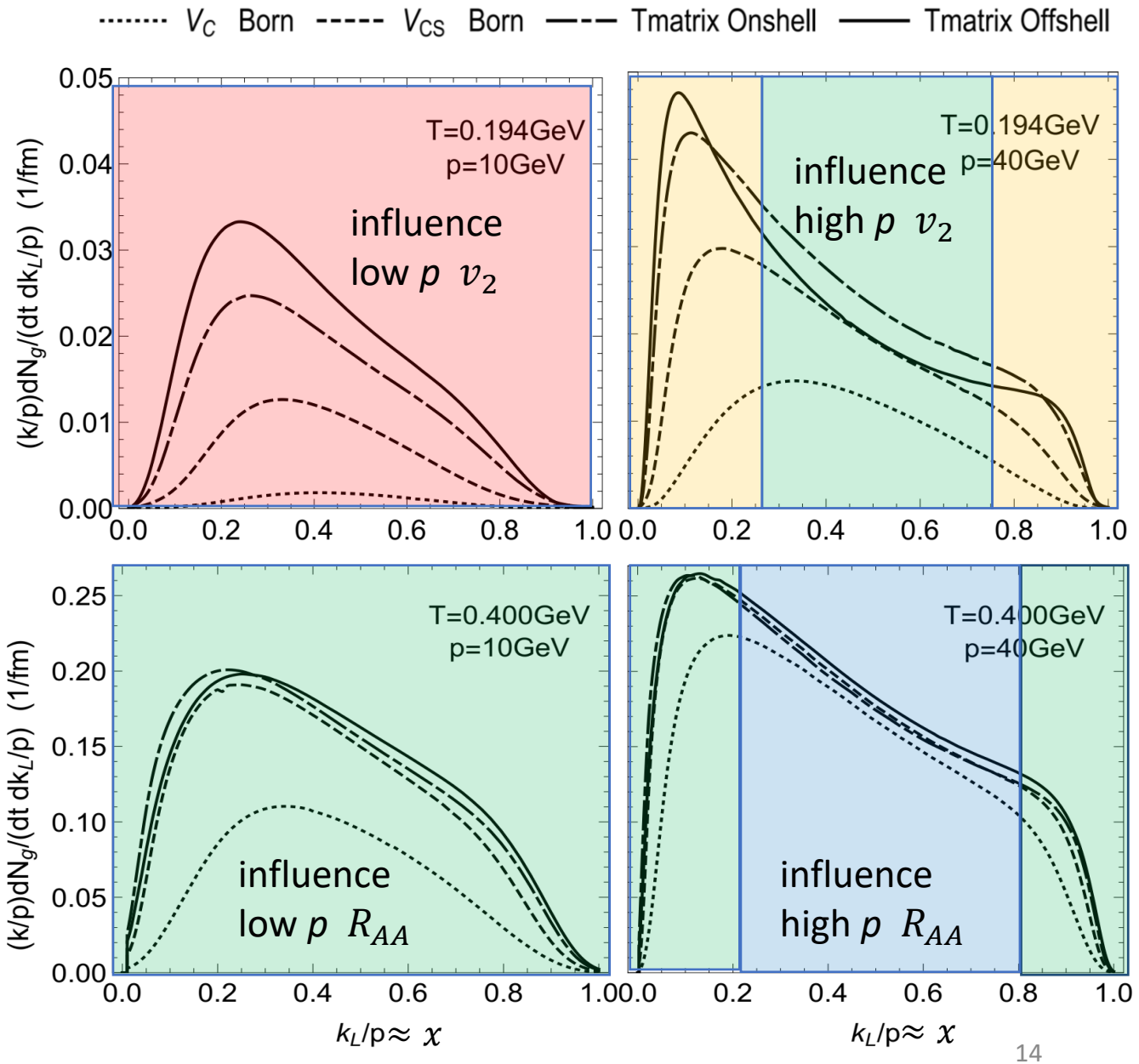
- **Red region**: Confining interaction, Resummation, Off-shell medium

- **Yellow region :** Confining interaction, Resummation, Off-shell medium

- **Green region**: Confining interaction, Resummation, Off-shell medium

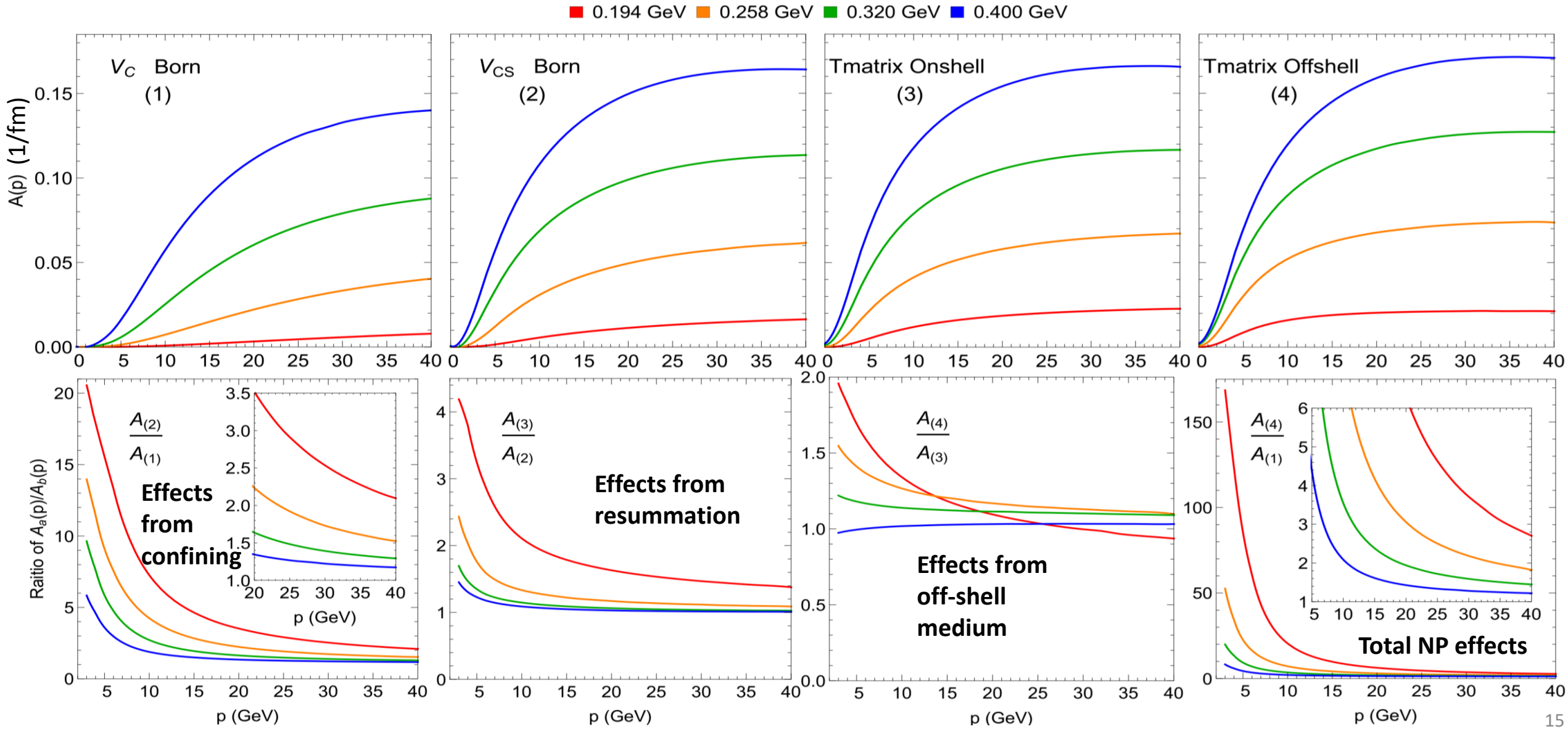
- **Blue region**: Confining interaction, Resummation, Off-shell medium

Perturbative



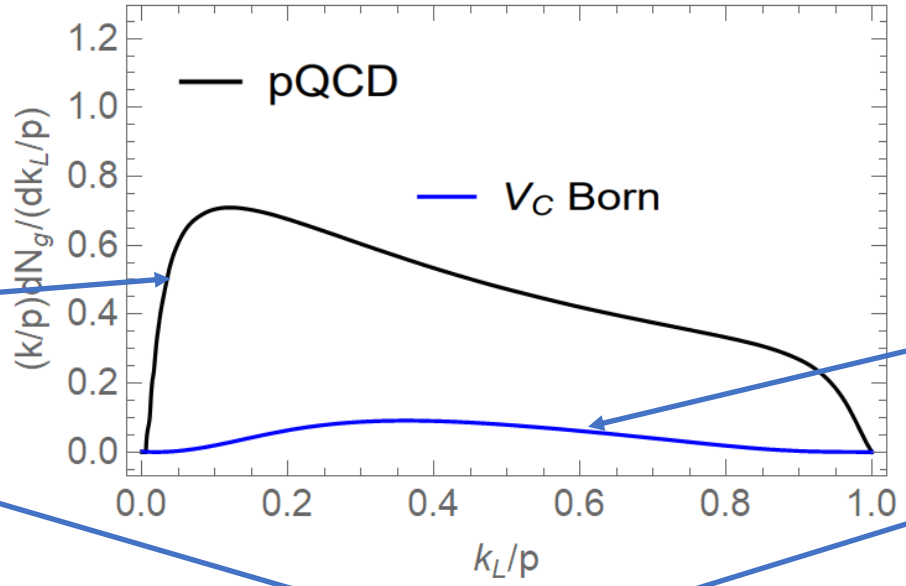
Radiative Contribution to Drag Coefficients

- $\mathrm{A(p)} \approx \left(E^{-1}dE\right)/dt \;\; (1/\mathrm{fm})$ percentage of energy loss per (fm) time



Masses are Important

$$p_Q = 20\text{GeV}, T = 225\text{MeV}, L = 5\text{fm}$$



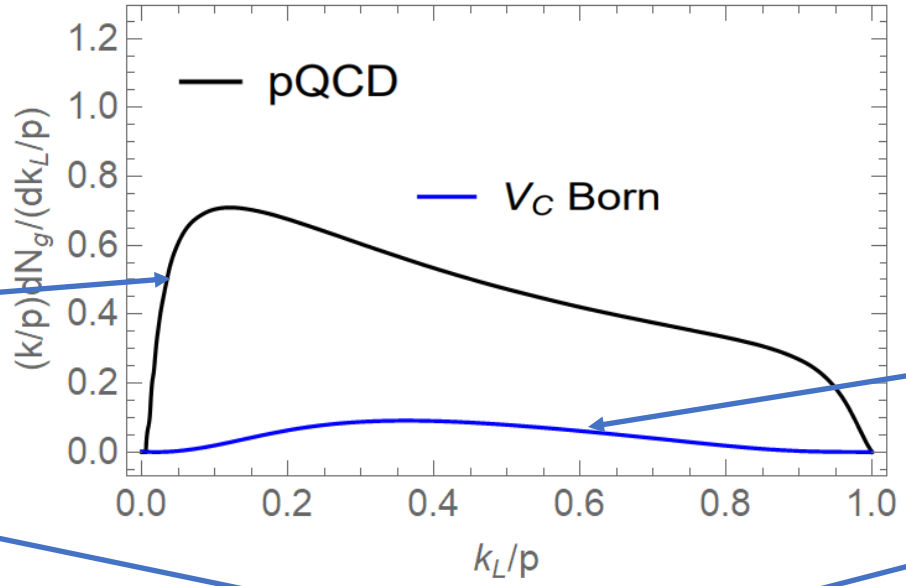
pQCD approach, Djordjevic 08

V_C Born, perturbative baseline of our approach

- **Both are perturbative calculation Why different?**

Masses are Important

$p_Q = 20\text{GeV}, T = 225\text{MeV}, L = 5\text{fm}$



pQCD approach, Djordjevic 08
M_q, M_g close to 0 GeV

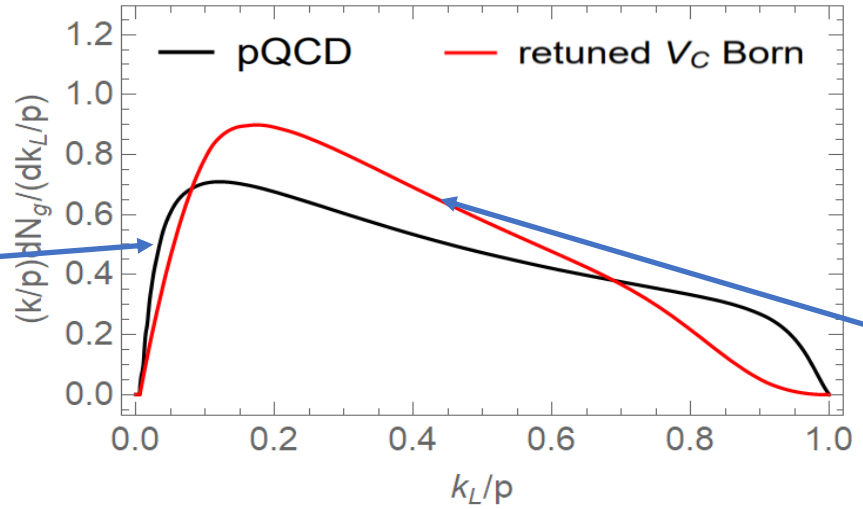
V_C Born, perturbative baseline of our approach
$M_q \sim 0.5$ GeV, $M_g \sim 1$ GeV

- **Masses are different**

Masses are Important

$$p_Q = 20\text{GeV}, T = 225\text{MeV}, L = 5\text{fm}$$

pQCD approach, Djordjevic 08
M_q, M_g close to 0 GeV

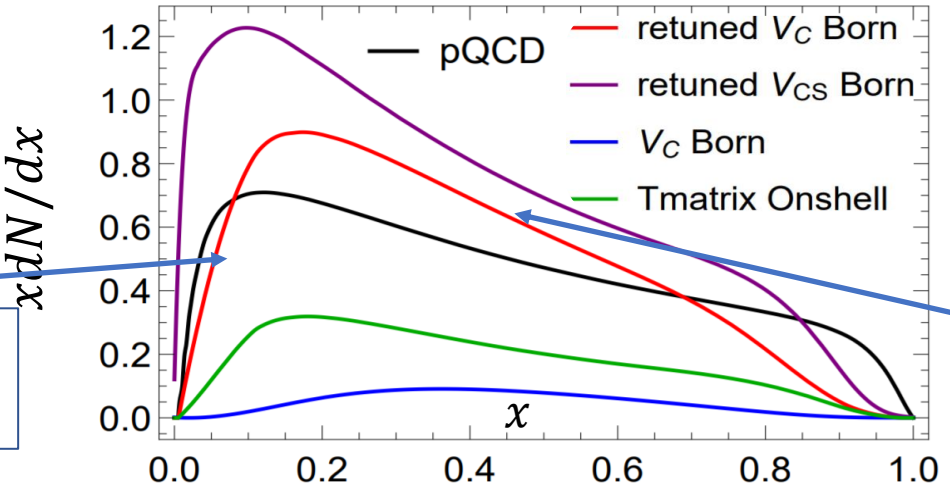


Retuned V_C Born, Perturbative baseline of our approach with same mass as pQCD that M_q, M_g close to 0 GeV

- **Similar if masses are tune to be the same**

Masses are Important

$$p_Q = 20\text{GeV}, T = 225\text{MeV}, L = 5\text{fm}$$



pQCD approach, Djordjevic 08
M_q, M_g close to 0 GeV

- **Retuned** means pQCD mass
- Otherwise, NP masses

- Green line: pQCD interaction + pQCD masses > NP interactions + NP masses

Which picture is more correct for radiative energy loss at intermediate/low momentum?

Apply to Heavy-ion Collisions

T-matrix elastic only

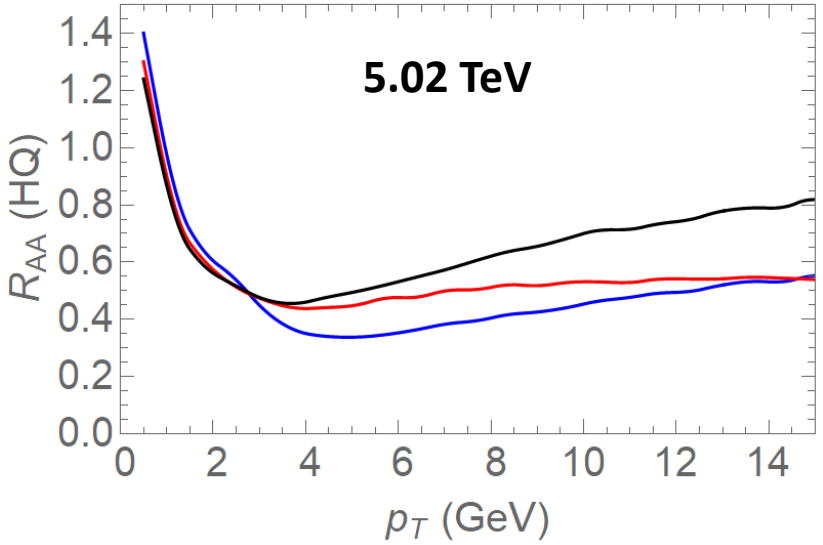
T-matrix elastic+ radiation in this work

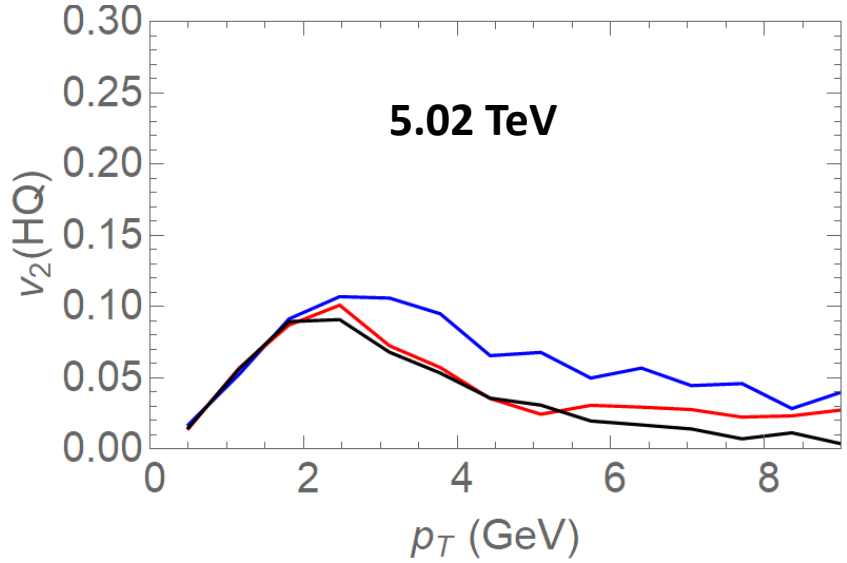
T-matrix elastic + High Twist radiation using NP $\hat{q}$ (>5 $\times$ $\hat{q}_{\mathrm{pQCD}}$ at small T, p) from T-matrix

Hybrid, High Twist + NP interactions

Code used in Cao, Sun, Li, Liu, Xing, Qin PLB, 2020

- Radiation is important for R_{AA} and v_2 at low energy~5 GeV, where NP effects are unavoidable
- **Gluon** (radiative) **Mass** (Large(~1GeV)/small) leads to a difference between red and blue
- Could we use these to understand/constrain the NP gluon masses experimentally?





Apply to Heavy-ion Collisions

T-matrix elastic only

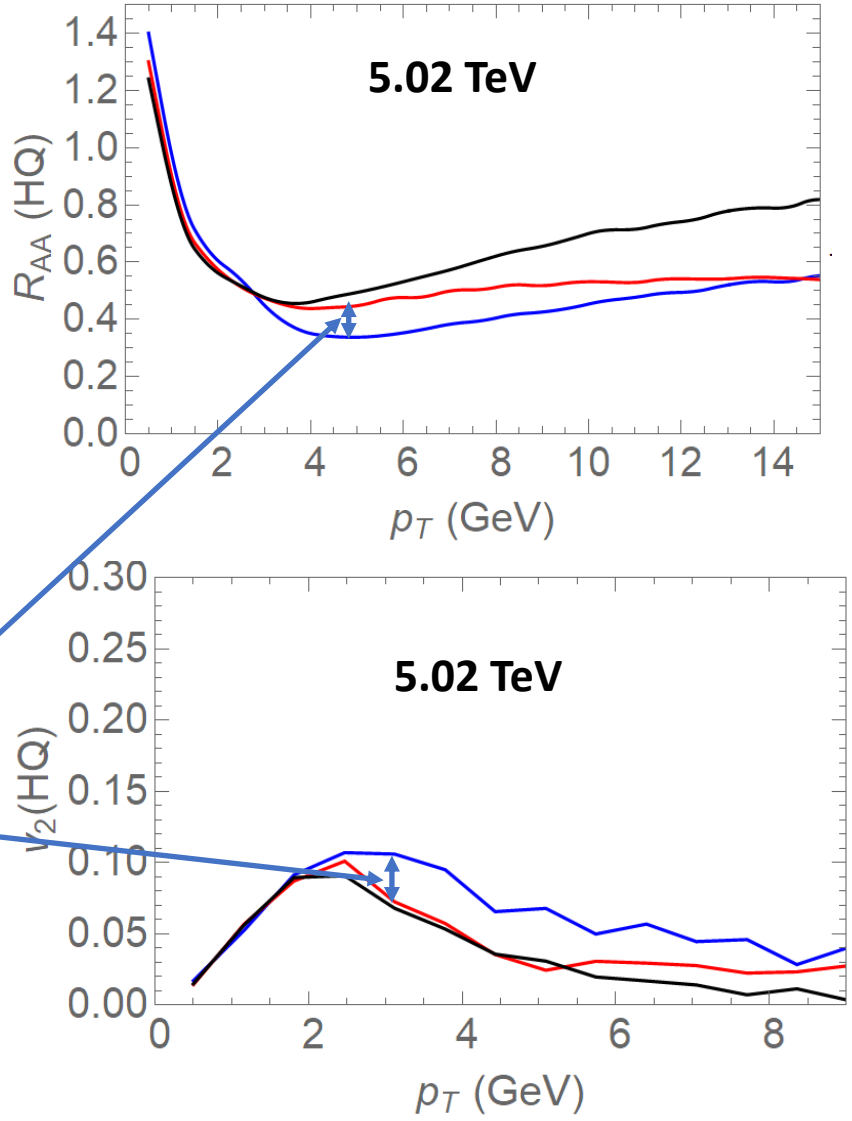
T-matrix elastic+ radiation in this work

T-matrix elastic + High Twist radiation using NP $\hat{q}$ (>5 $\times$ $\hat{q}_{\mathrm{pQCD}}$ at small T, p) from T-matrix

Hybrid, High Twist + NP interactions

Code used in Cao, Sun, Li, Liu, Xing, Qin PLB, 2020

- Radiation is important for R_{AA} and v_2 at low energy~5 GeV, where NP effects are unavoidable
- **Gluon** (radiative) **Mass** (Large(~1GeV)/small) leads to a difference between red and blue
- Could we use these to understand/constrain the NP gluon masses experimentally?



Conclusion

- Developed many-body approach to study the non-perturbative effects for radiative energy loss
- Non-perturbative effects on radiation are important for R_{AA} and v_2 at small/intermediate p_T (5-10 GeV)
- Adding confining force is probably enough for lots of phase space; resummation and off-shell medium effects are important in low p and low T
- Non-perturbative masses are also important uncertainties for radiative process