Non-Perturbative Effects on Heavy Quark Radiative Energy Loss?

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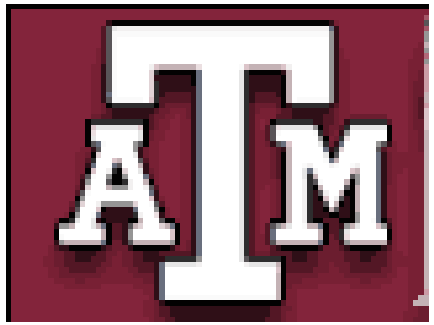
College Station

UCLA Santa Fe Jets and Heavy Flavor Workshop

UCLA, January 28-30, 2019



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Outline

1) Background and Motivation

2) Many-Body Approach to Radiative Process

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

4) Conclusion

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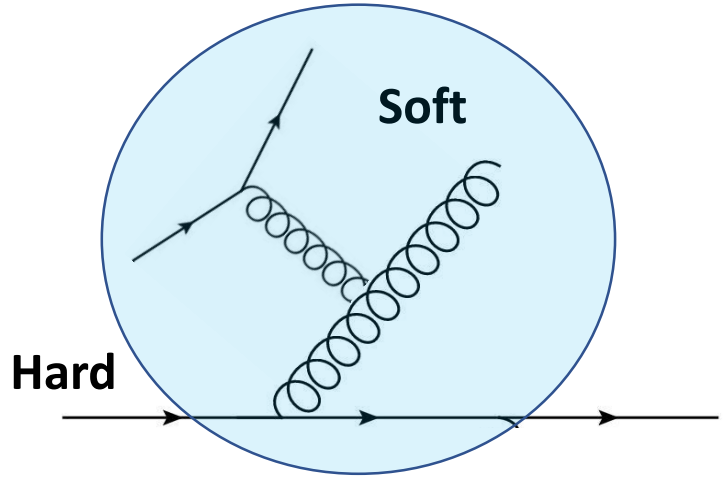
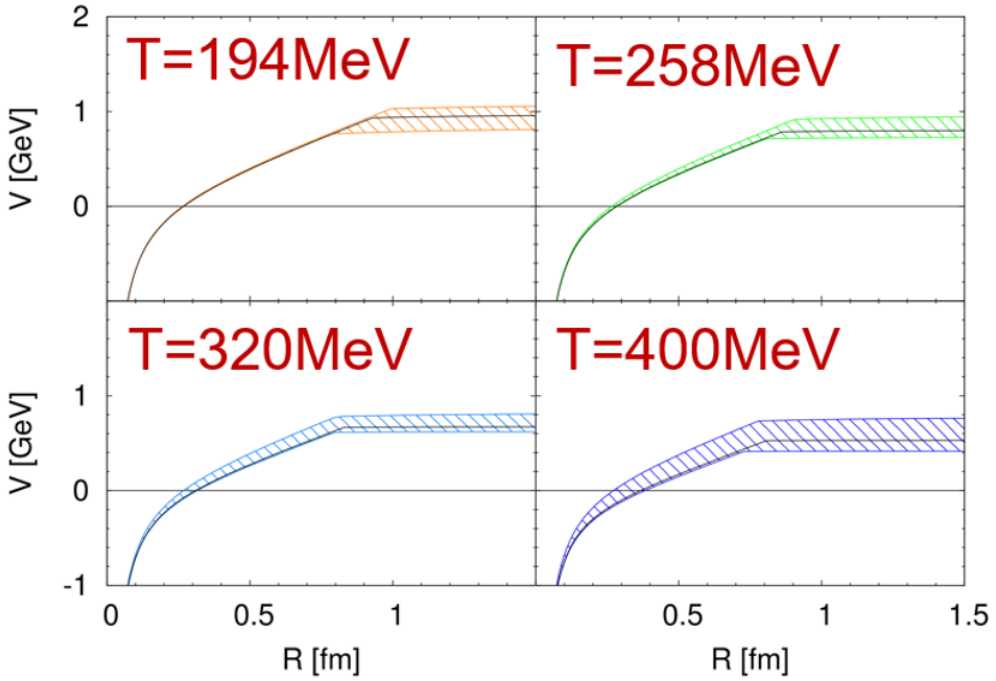
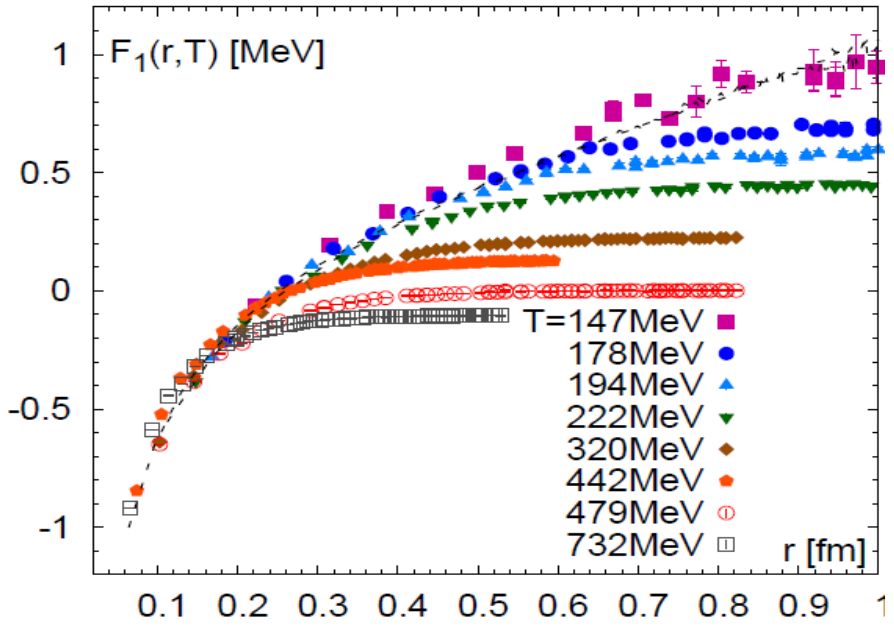
Non-Perturbative Effects for High Energy Partons?

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







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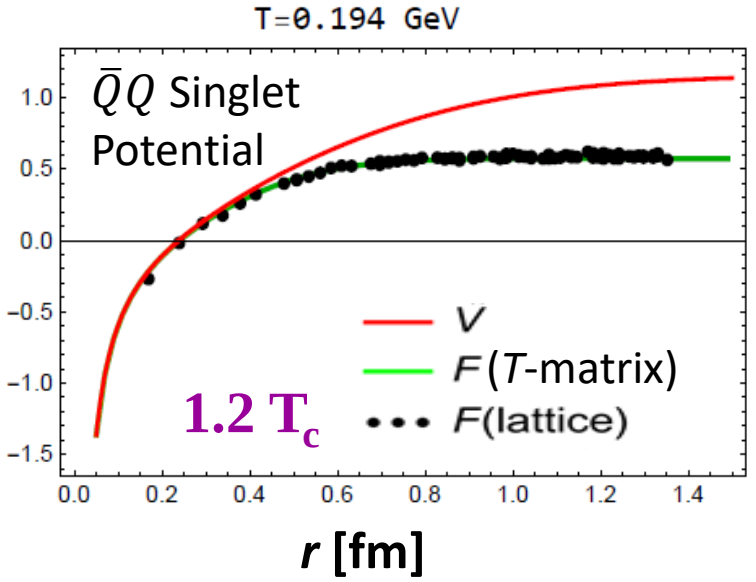
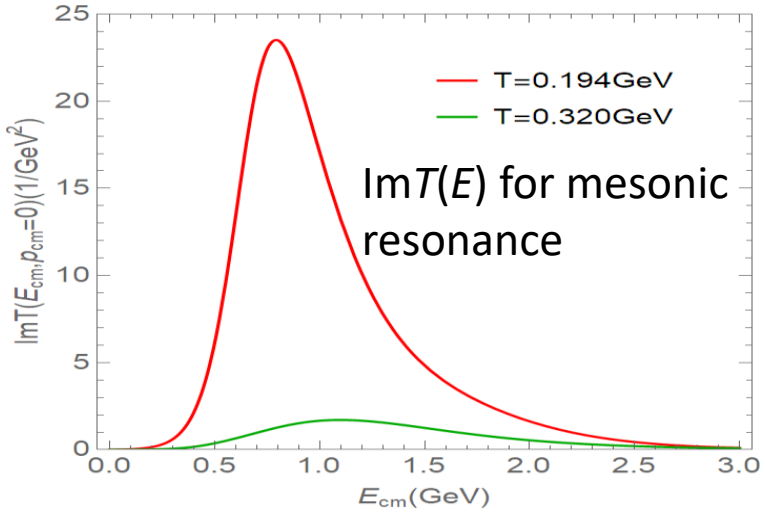
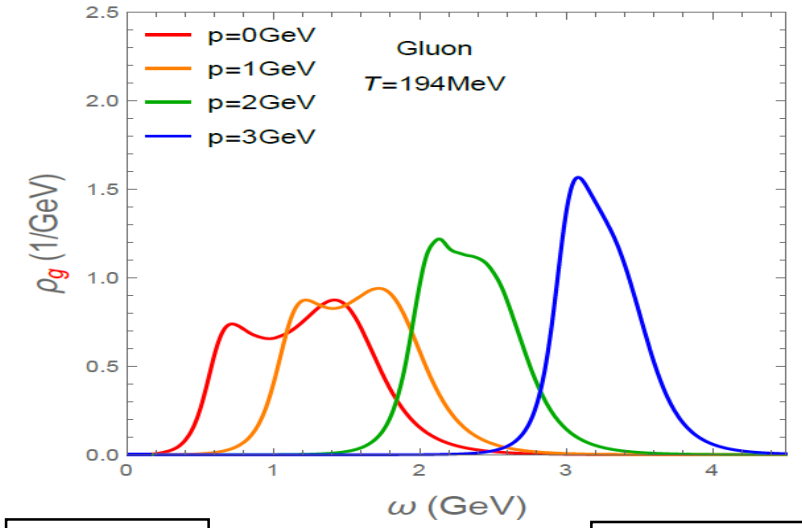
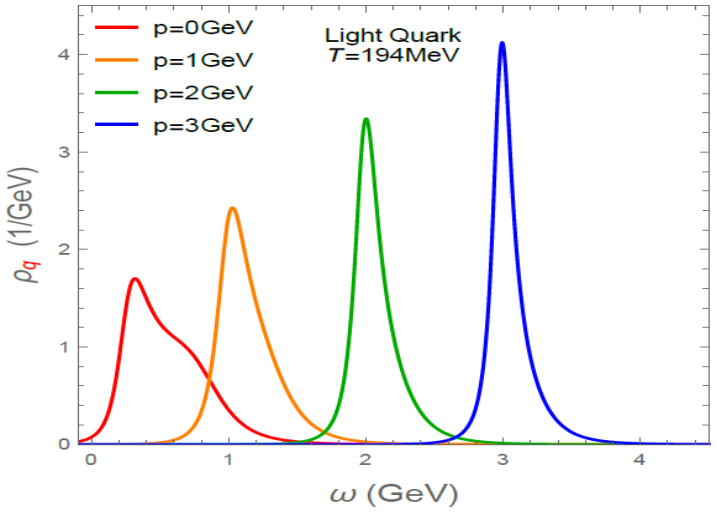
Non-Perturbative Effects in Strongly Coupled QGP

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



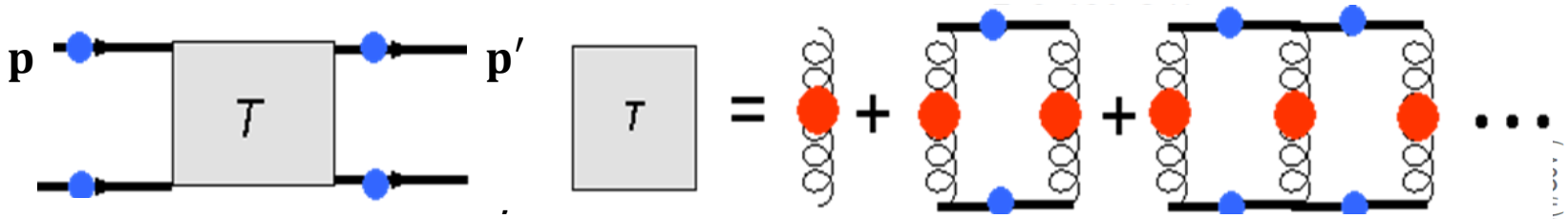




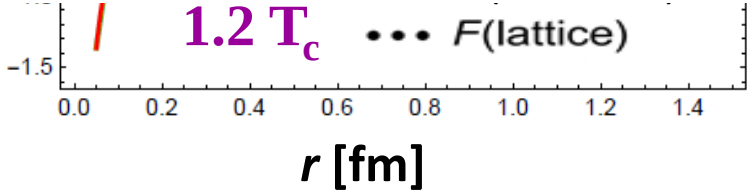


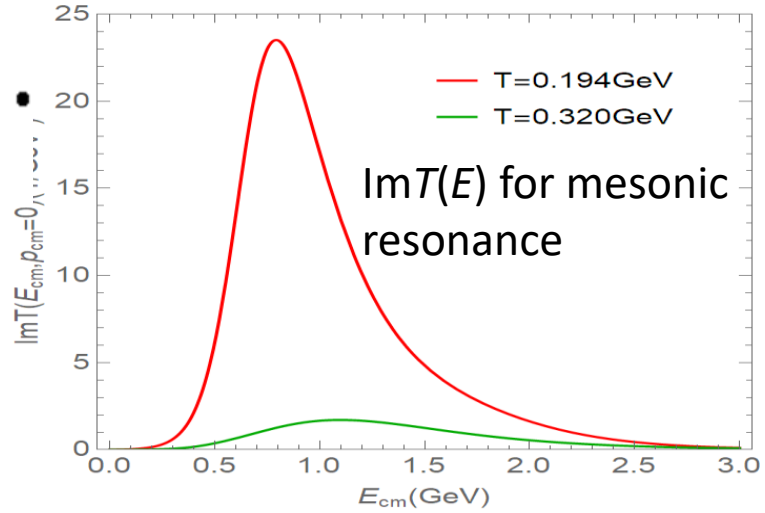
Liquid ⇒ Quasiparticle

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 confining force
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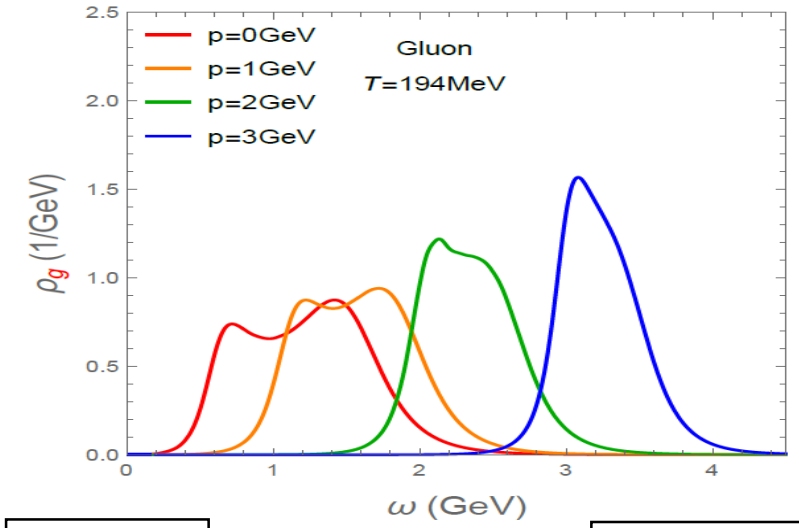
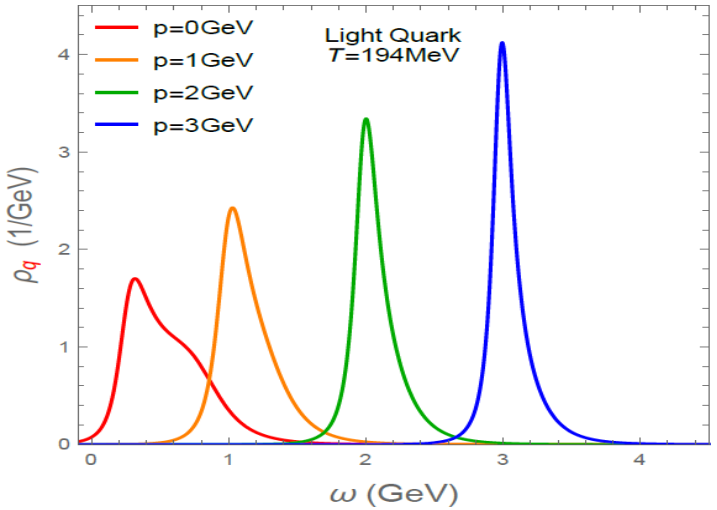


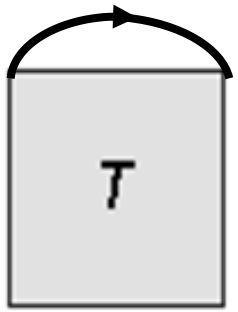


Liquid ⇒ Quasiparticle

Non-Perturbative Effects in Strongly Coupled QGP

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

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



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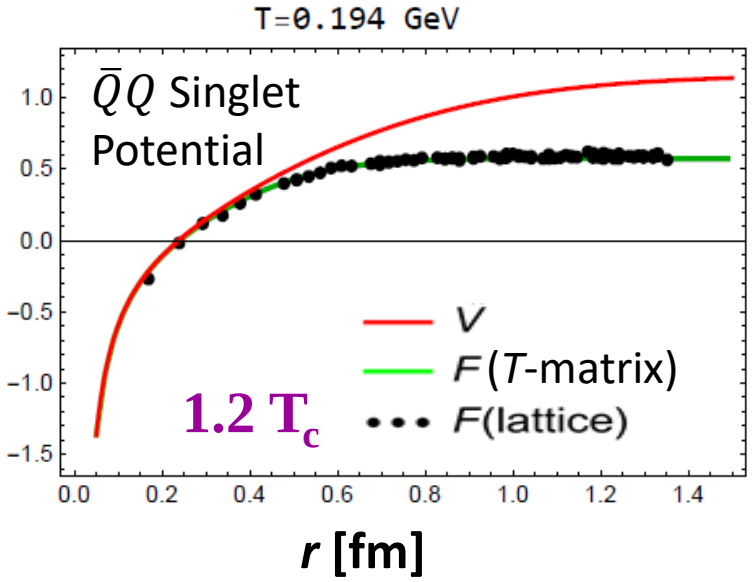

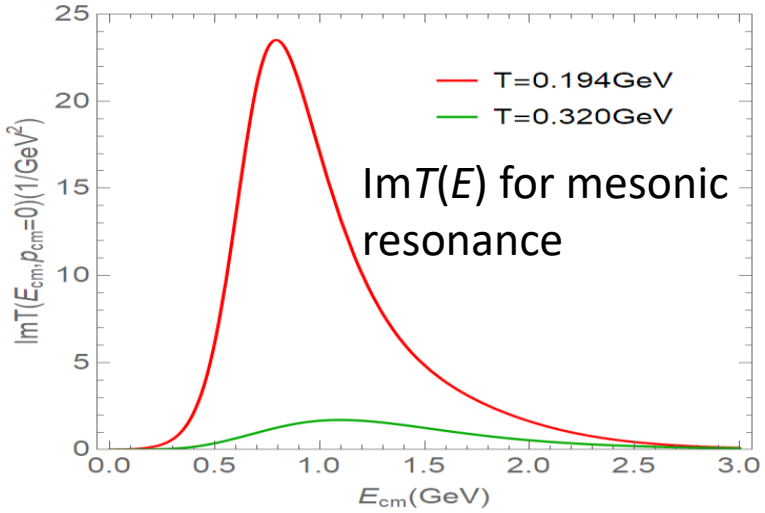

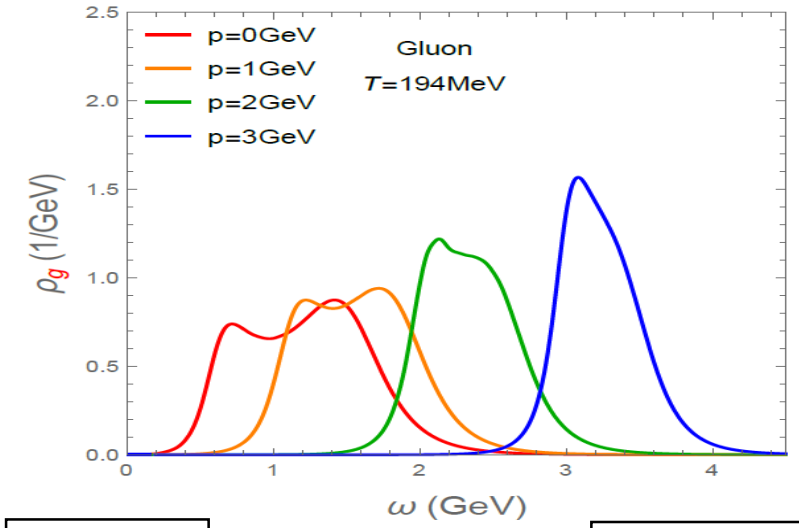

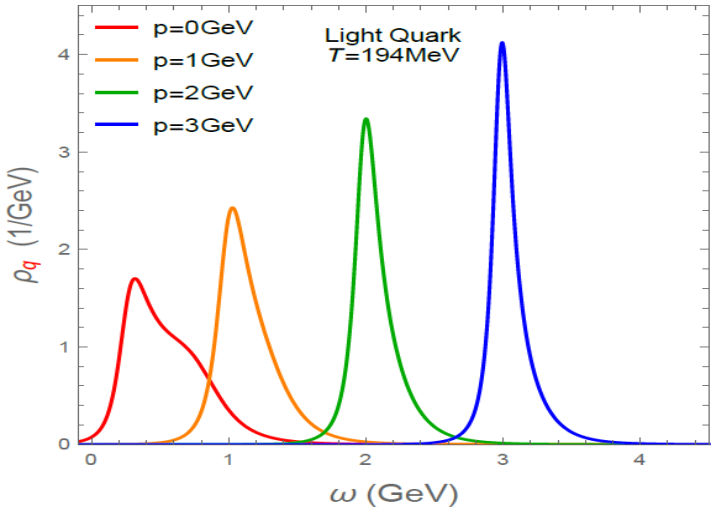

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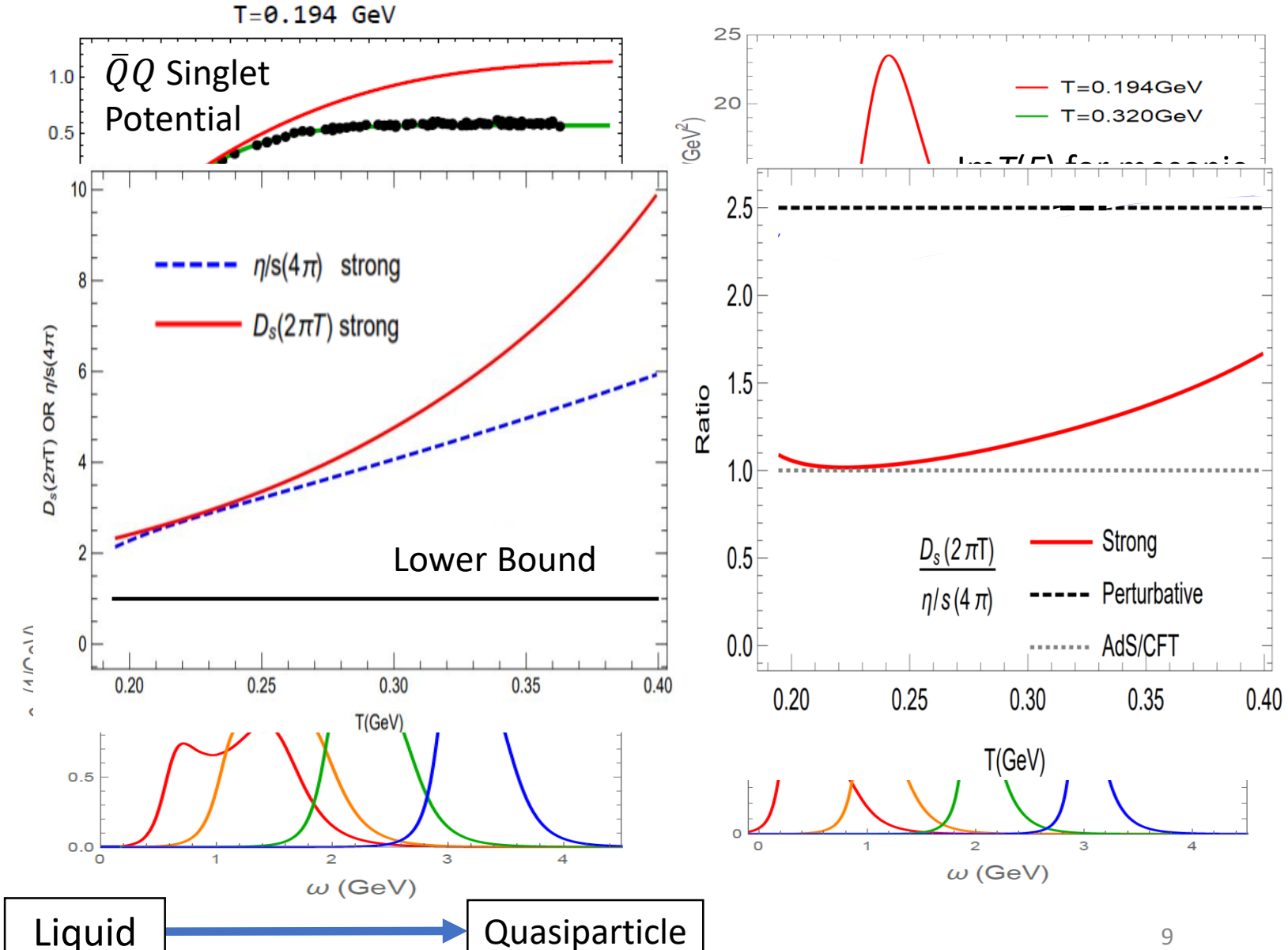
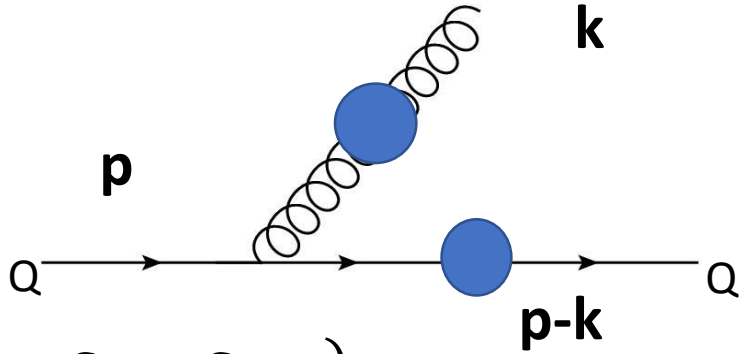


T-matrix Approach for Energy Loss

- Leading skeleton order radiation:



- Main idea:

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

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

- Momentum transition rate:

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

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

- Spectral functions

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

Encode Medium Effects

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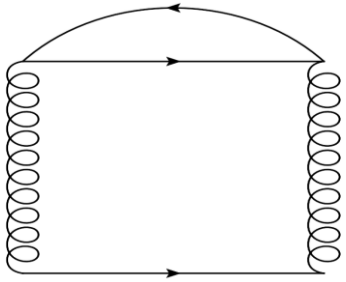
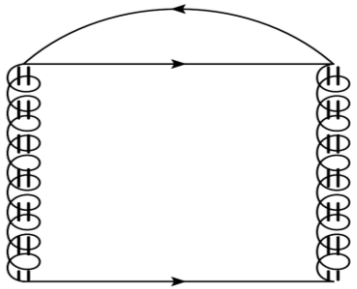
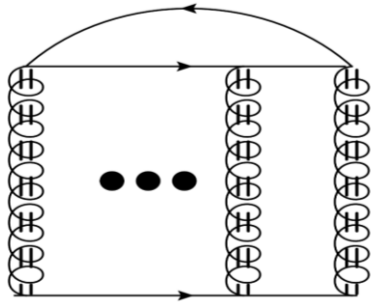
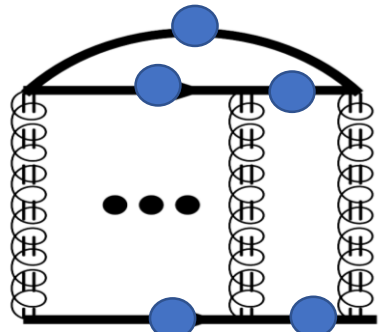
Four Cases with Different NP Effects

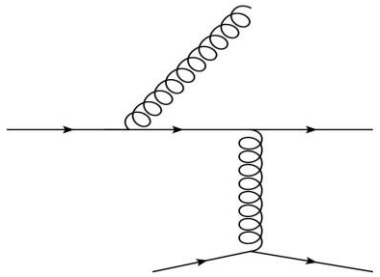
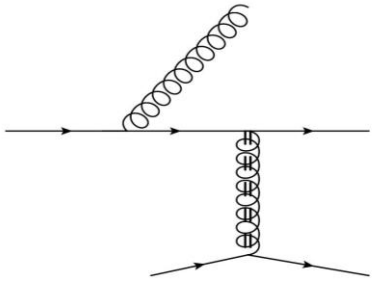
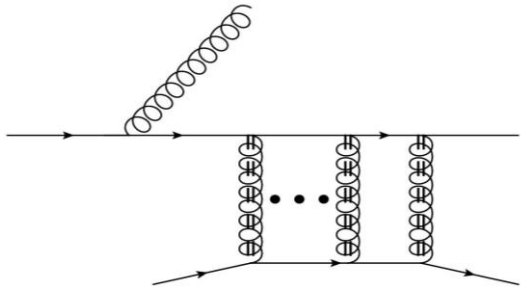
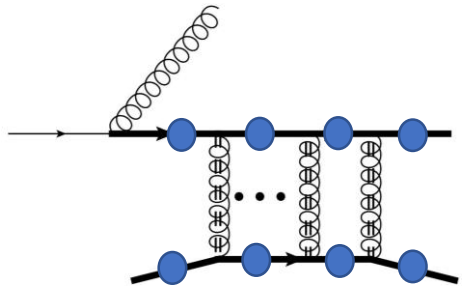
- Remnant confining force
- Ladder resummation
- Non-quasi particle medium

Four Cases with Different NP Effects

- Self-energy Σ_Q for different cases (same diagram set for gluon)

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

Close to pQCD

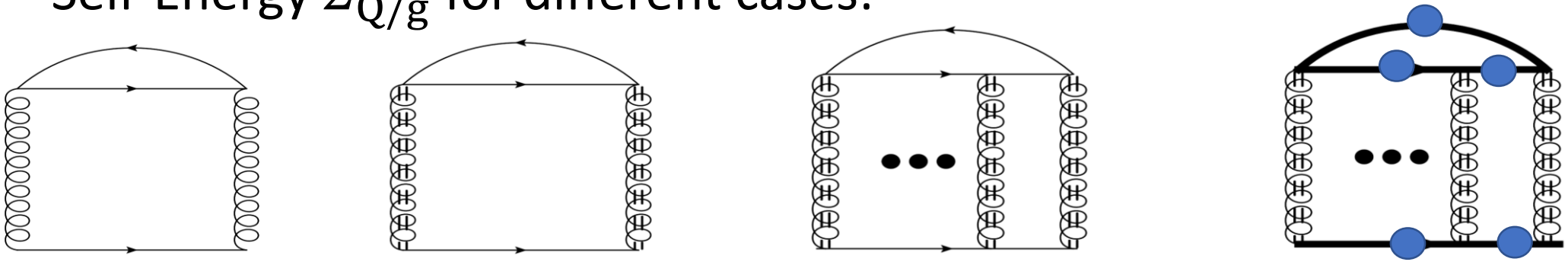
Add confining Interaction

Add the t-Channel resummation

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

Four Different Cases with Different NP Effects

- Self-Energy $\Sigma_{\mathrm{Q/g}}$ for different cases:



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2nd-order	2nd-order	All order	All order
quasi-particle	quasi-particle	quasi-particle	off-shell spectra

- Medium color charge density: readjusted by fit to lattice EoS

Spectral Functions at **Low** Momentum

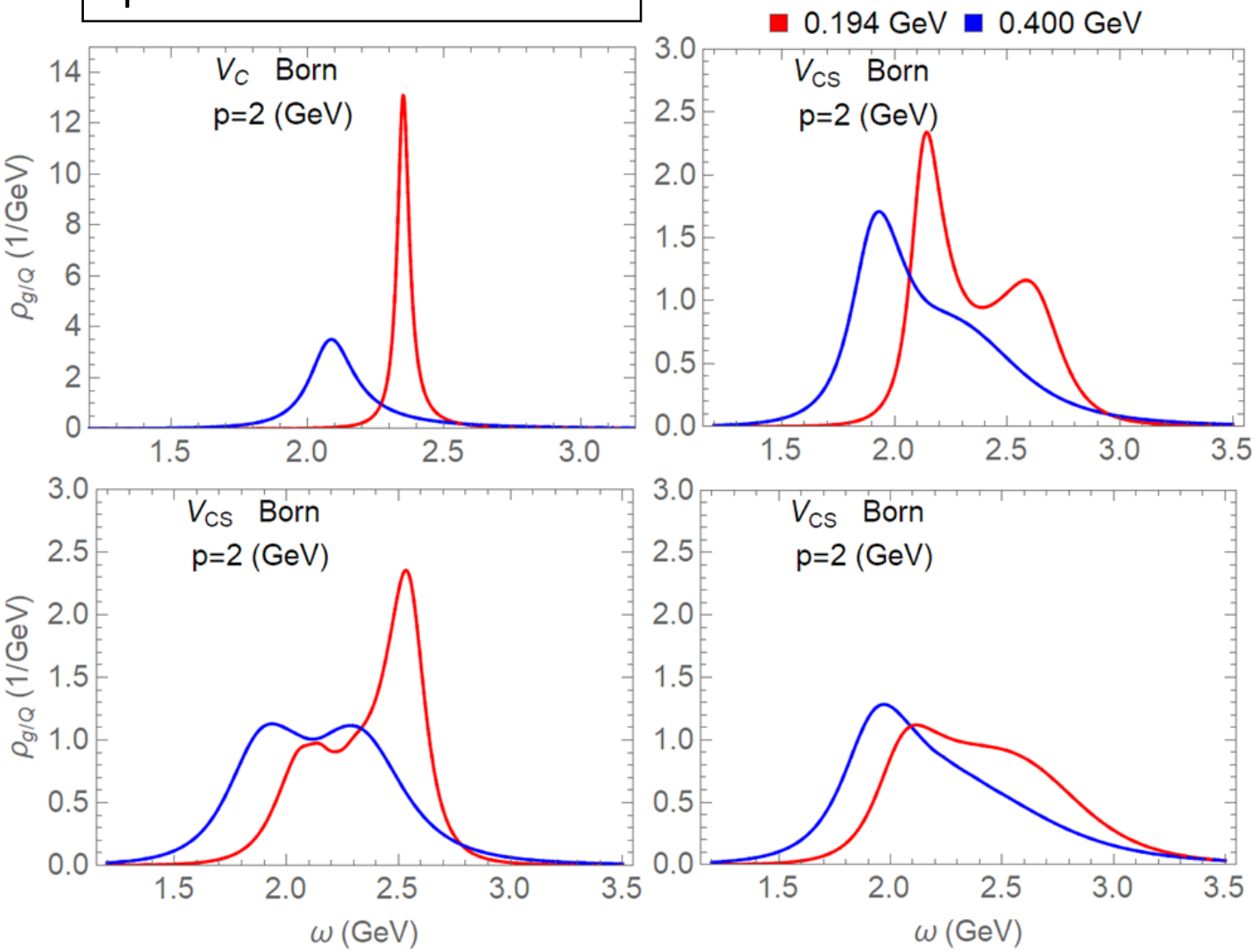
- Broad parton spectral function with NP effects
- Low temperature:

More NP effects

More space like phase space

- High temperature: NP effects suppressed, confining interaction still relevant

Spectral Function of Gluon



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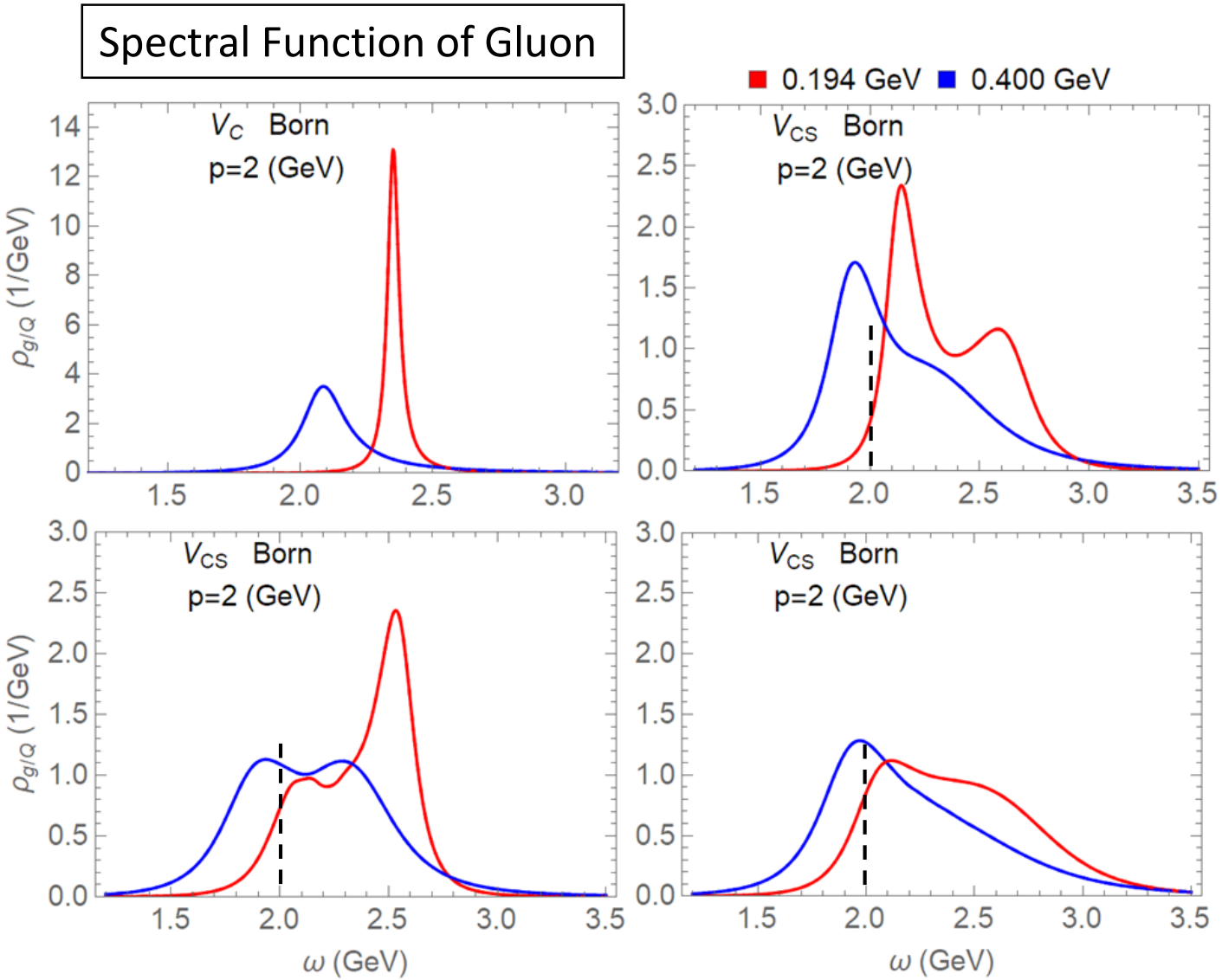
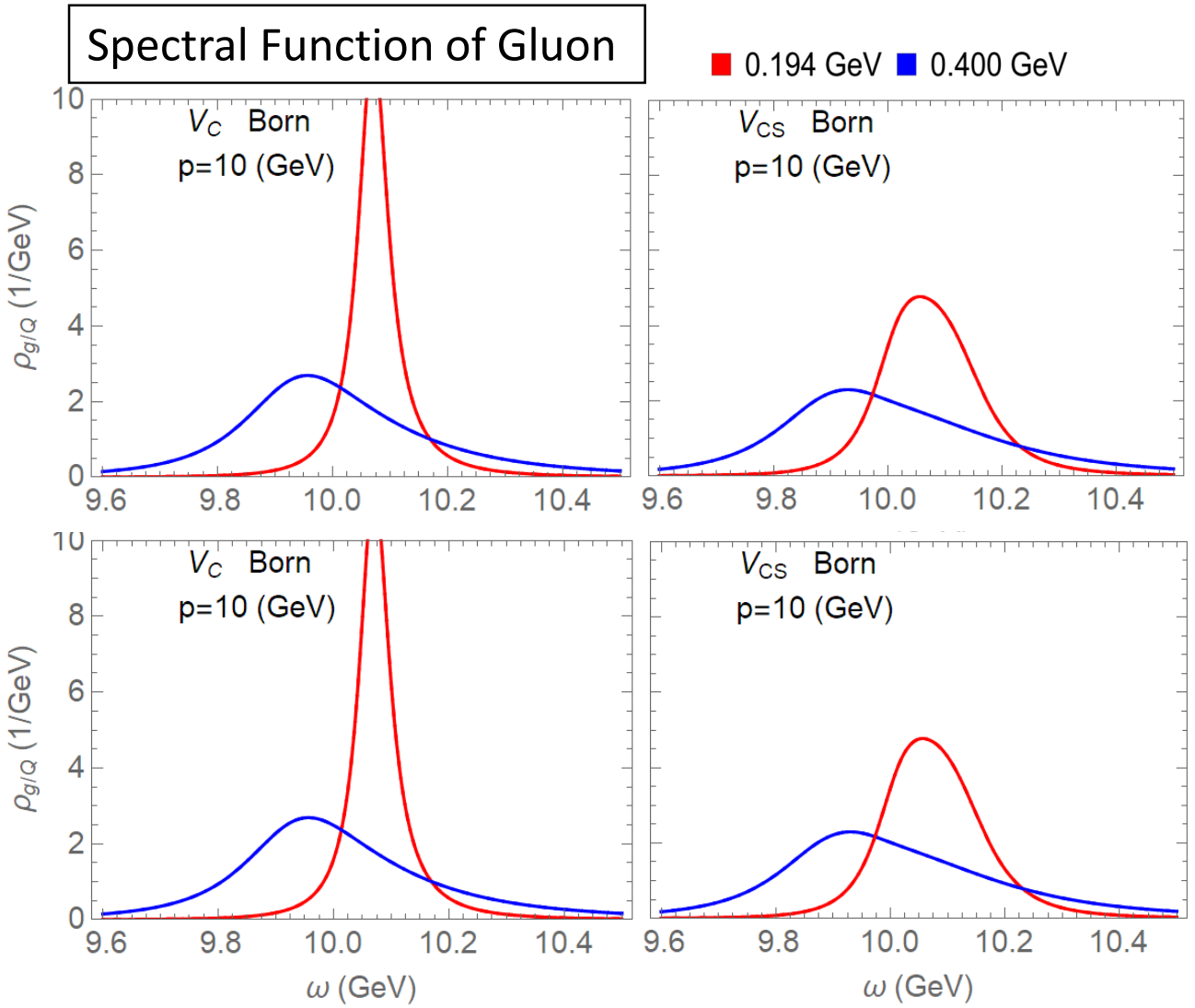


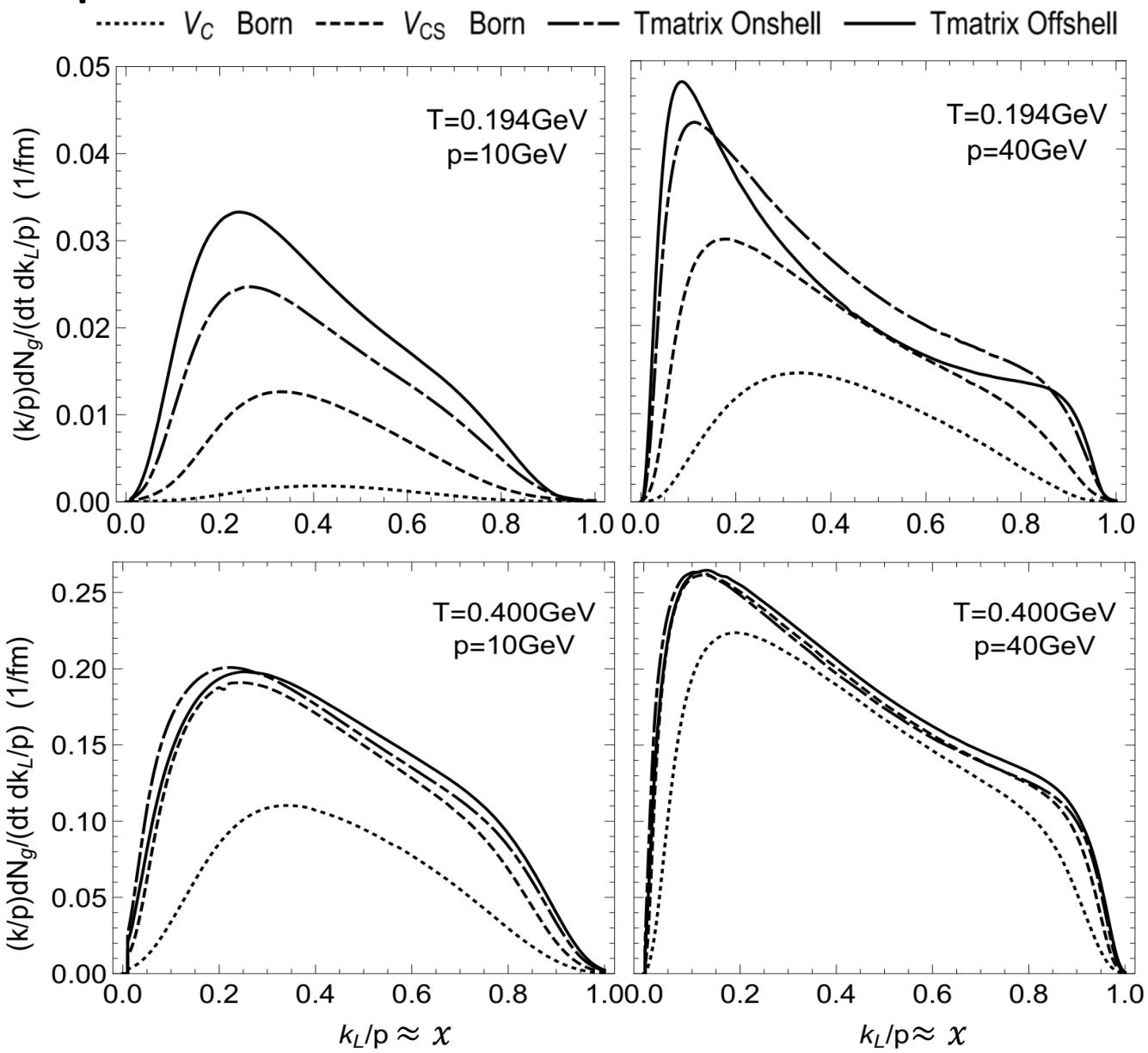
Spectral Functions at **High** Momentum

- Quasi-particle like spectrum
- Low temperature: NP effects suppressed, confining interaction still relevant
- High temperature: NP effects (including Confining effects) suppressed



Radiative Power Spectrum

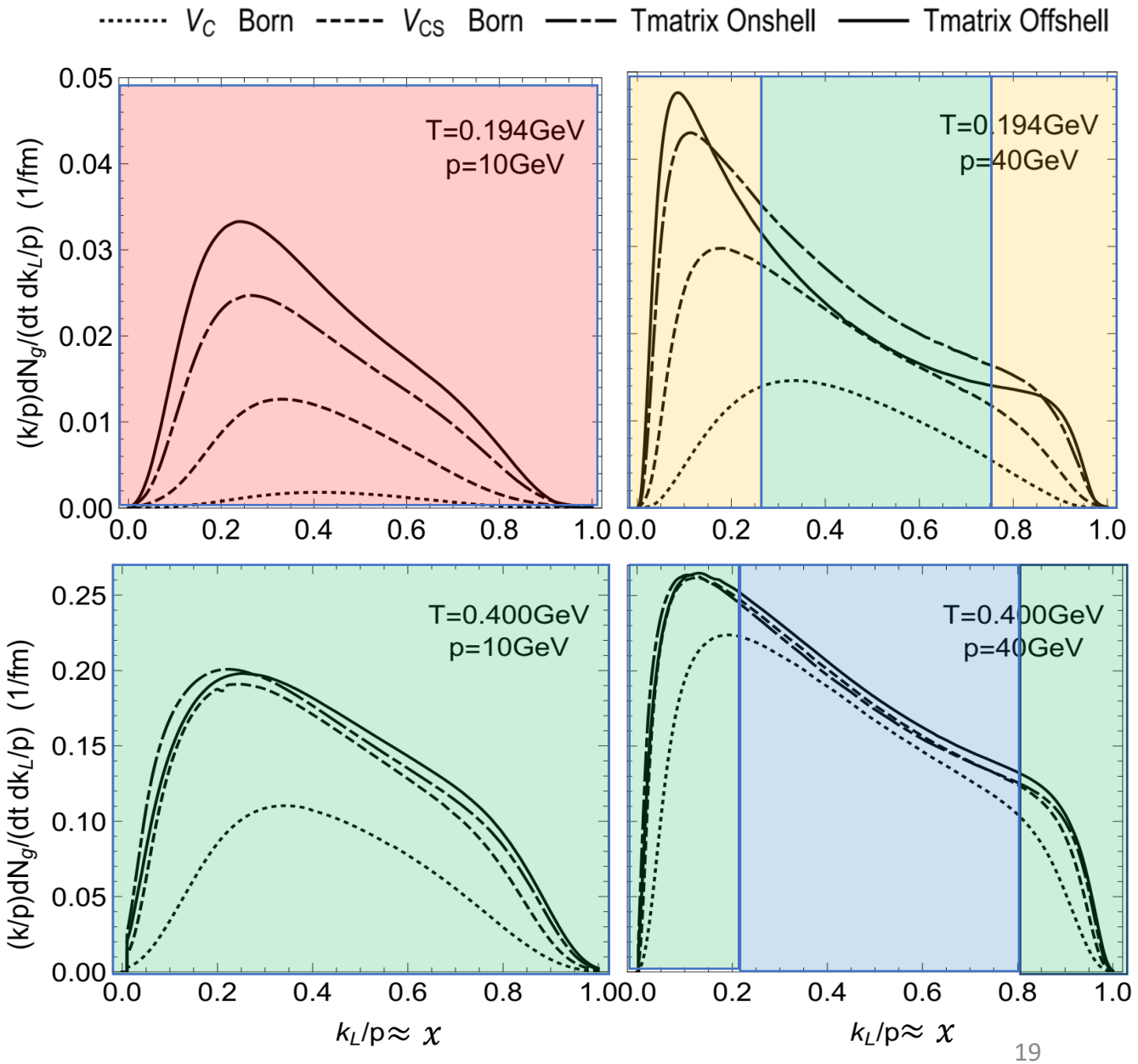
- Power spectrum $\frac{(k/p)dN_g}{dt\ d(k_L/p)} \approx \frac{xdN_g}{dt\ dx}$



Radiative Power Spectrum

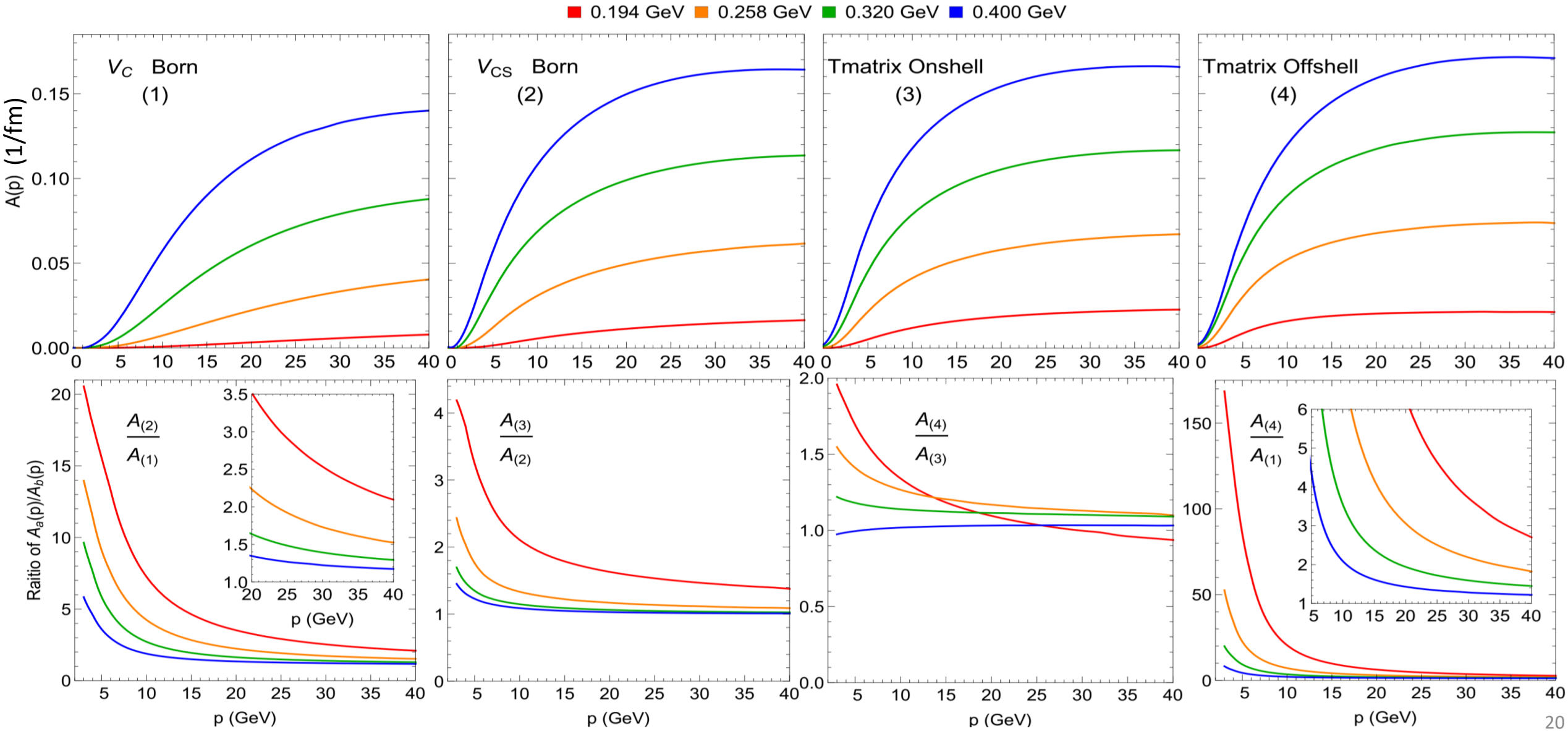
- Power spectrum $\frac{(k/p)dN_g}{dt\ d(k_L/p)} \approx \frac{xdN_g}{dt\ dx}$

- **Red region**: all NP Effects important
- **Yellow region :** quasi-particle applicable but other NP effects important
- **Green region**: quasi-particle+ leading order + confining force
- **Blue region**: quasi-particle+ leading order +Coulomb force; perturbative region



Radiative Contribution to Drag Coefficients

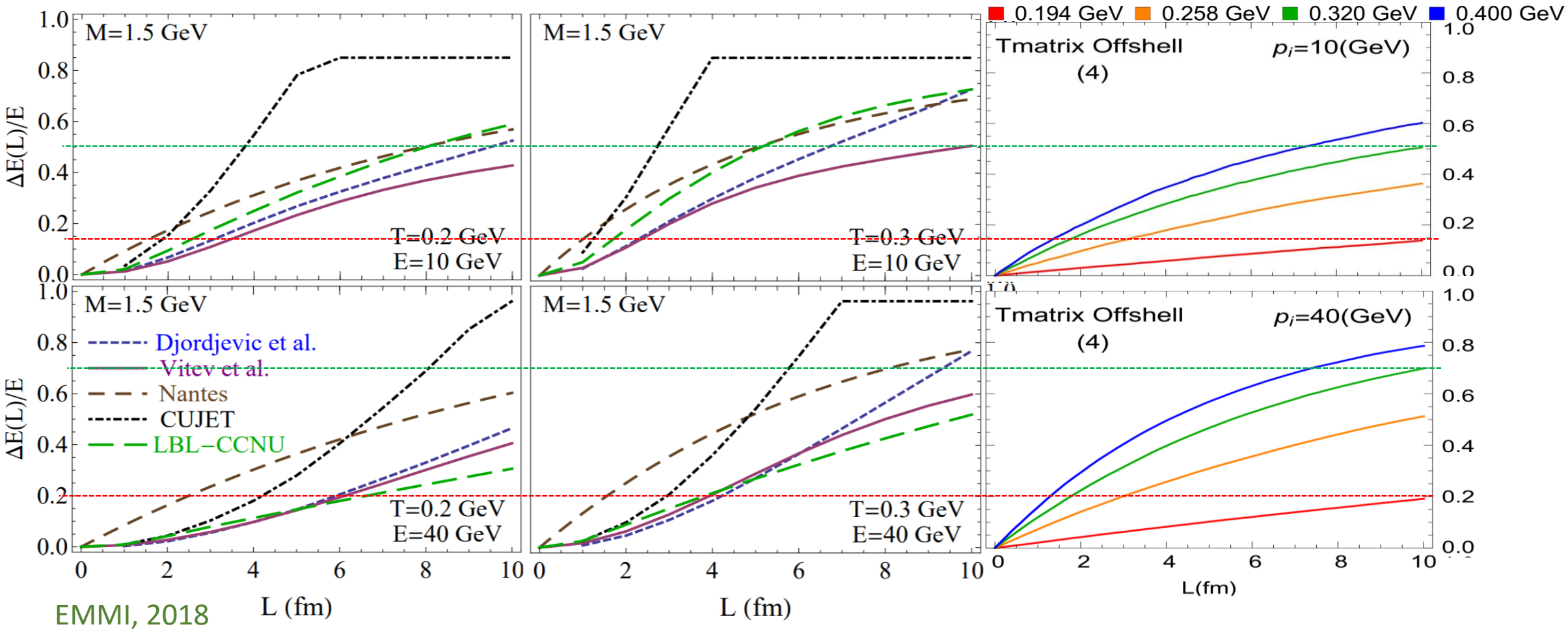
- $\mathrm{A(p)} \approx \left(E^{-1}dE\right)/dt \;\; (1/\mathrm{fm})$ percentage of energy loss per (fm) time



Conclusion

- Developed Many-Body Approach to Study the Non-Perturbative Effects for Radiative Energy Loss:
  - At low T and low *p*: confining force effect (large), resummation effect (moderate), non-quasi-particle effects (significant) are all important
  - As low T and *p* increase: all effects suppressed; non-quasi-particle effects disappear first, then resummation effects disappear.
  - At high T and high *p*: pQCD should work in most of phase space. But for small/large x, effects from the confining force are still visible.

Energy loss of Heavy Quark in Static Medium

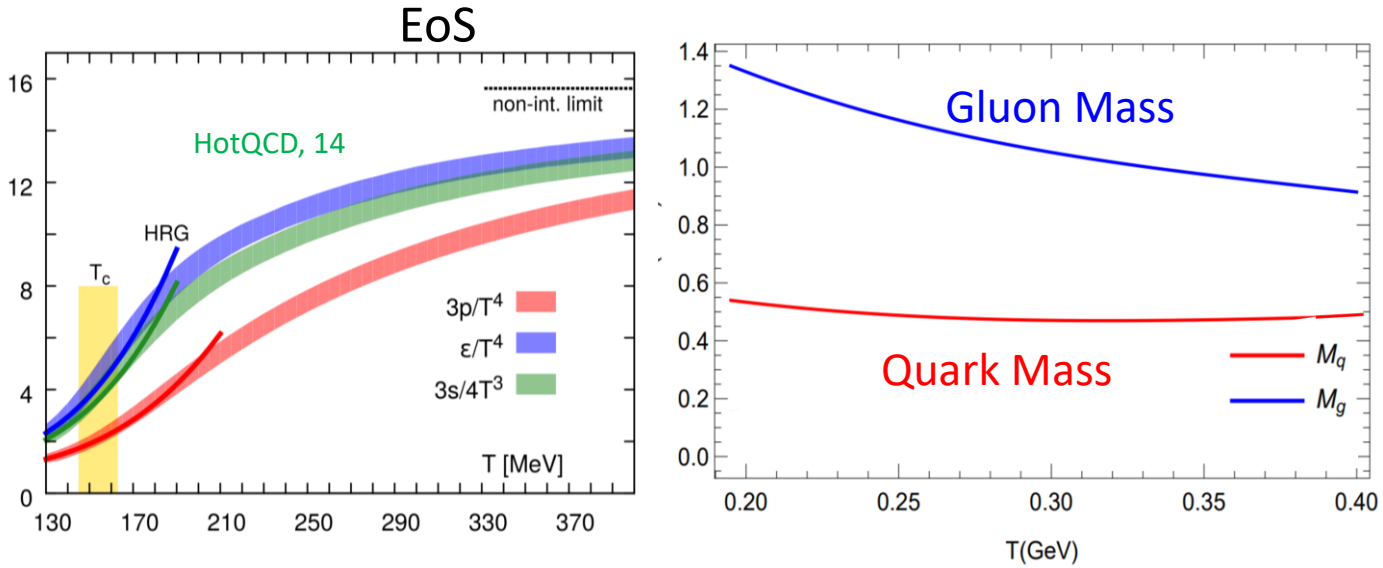


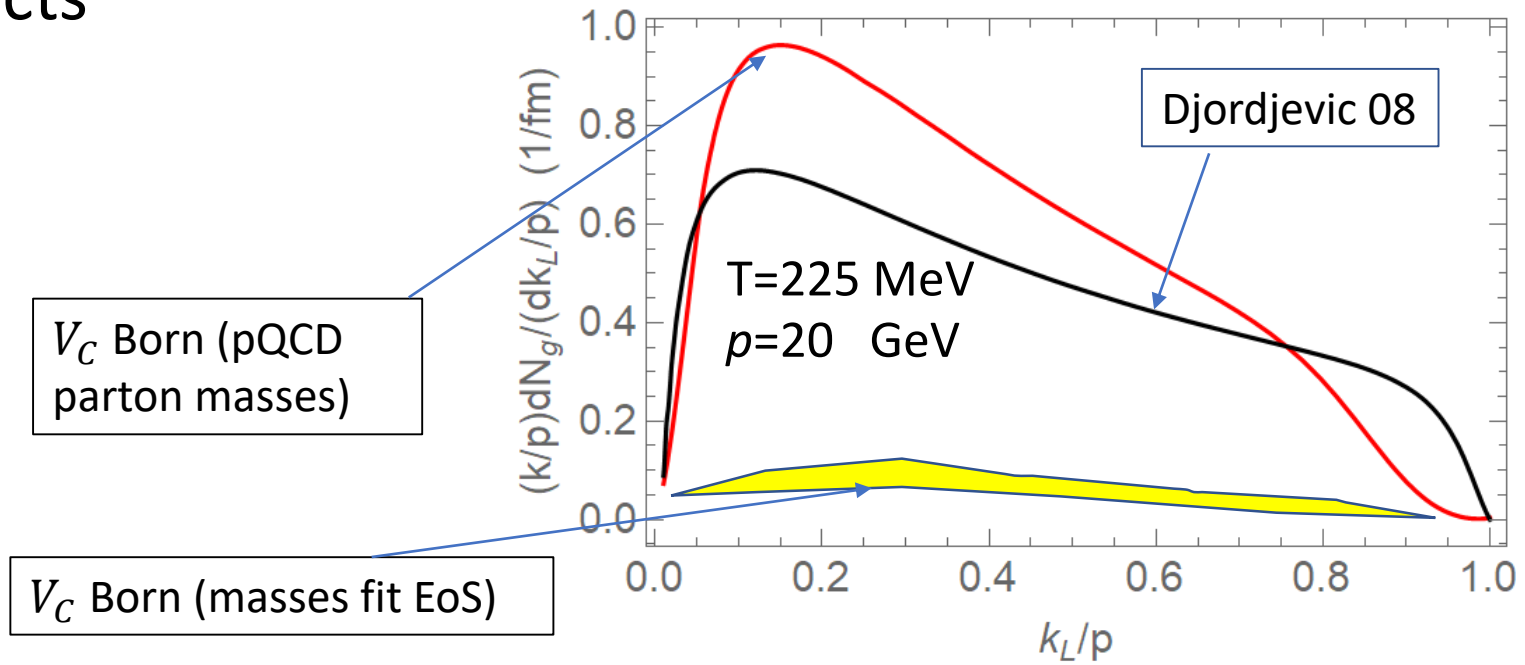
EMMI, 2018

- Significantly smaller at low momentum and low temperature.
- Comparable at high temperature and high momentum.

Difference to pQCD Based Approaches

- Large parton mass, larger than 1GeV for gluons (strongly suppress)
- No LPM effects (enhance)
- No initial Off-Shell effects (suppress)





V_C Born (pQCD parton masses)

V_C Born (masses fit EoS)

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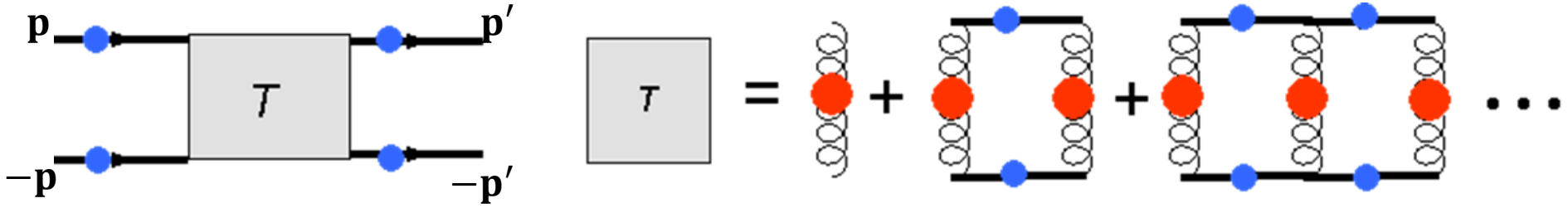
Strategy to Study Non-Perturbative(NP) Effects

- Suitable approach → *T*-matrix approach
- Scenarios containing different NP effects → Remnant confining force, resummation, non quasi-particles effects
- Manifestation of the different scenarios → Spectral functions, power spectrum, drag coefficient, energy loss…

T-matrix Approach



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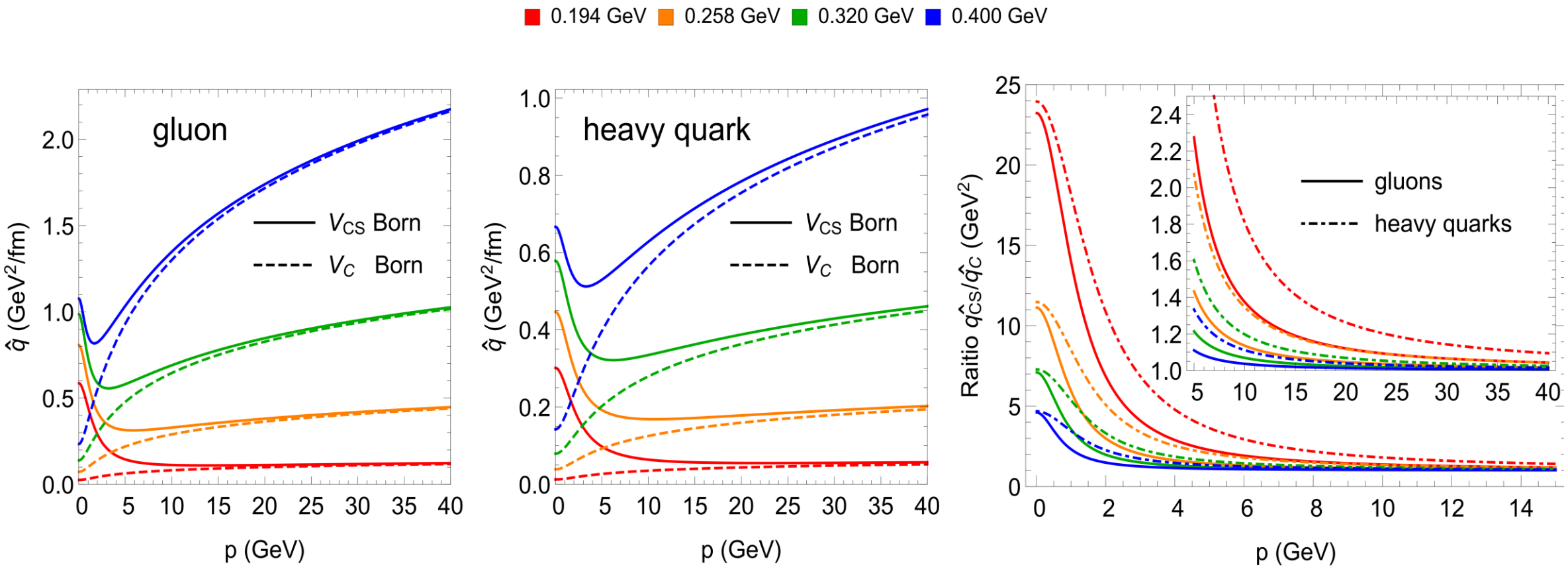
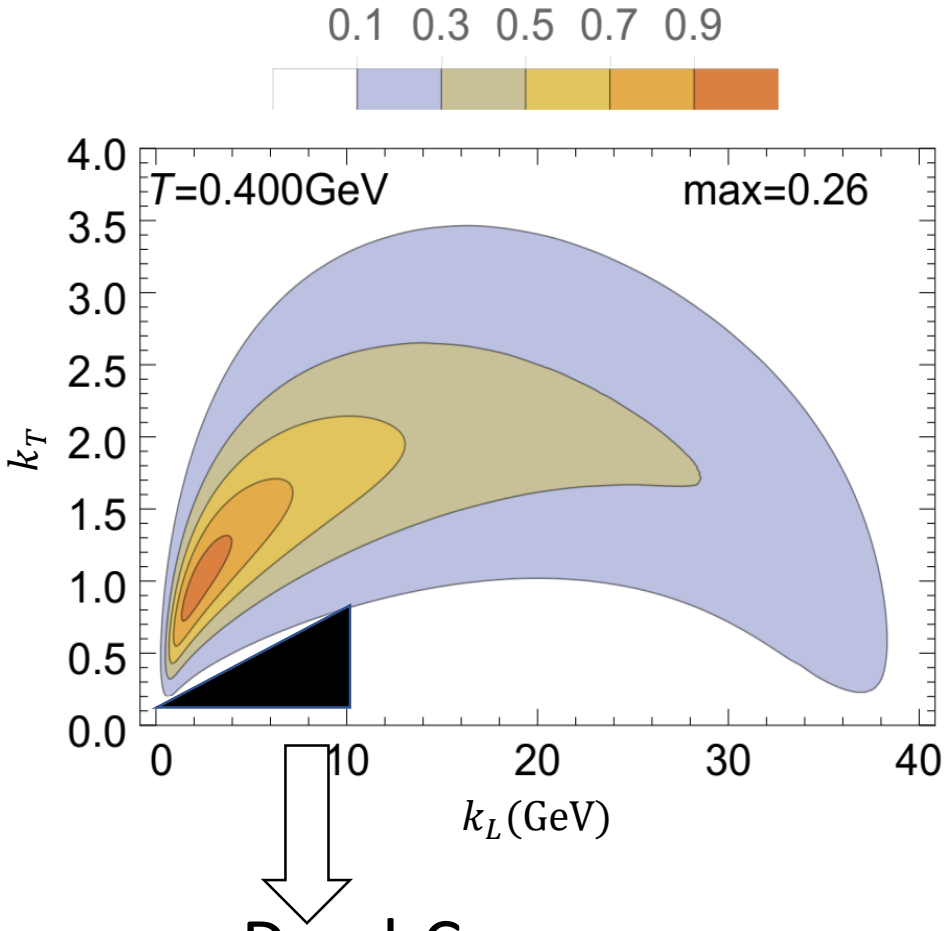
- Incorporates: large confining force, resummation, broad spectral functions
- Inputs: color potential and in-medium masses
- Constrained by lattice: EoS, free energy, quarkonium correlators, $(2\pi T)D_s$
- Predict: shear viscosity, emerging resonances, parton spectral functions

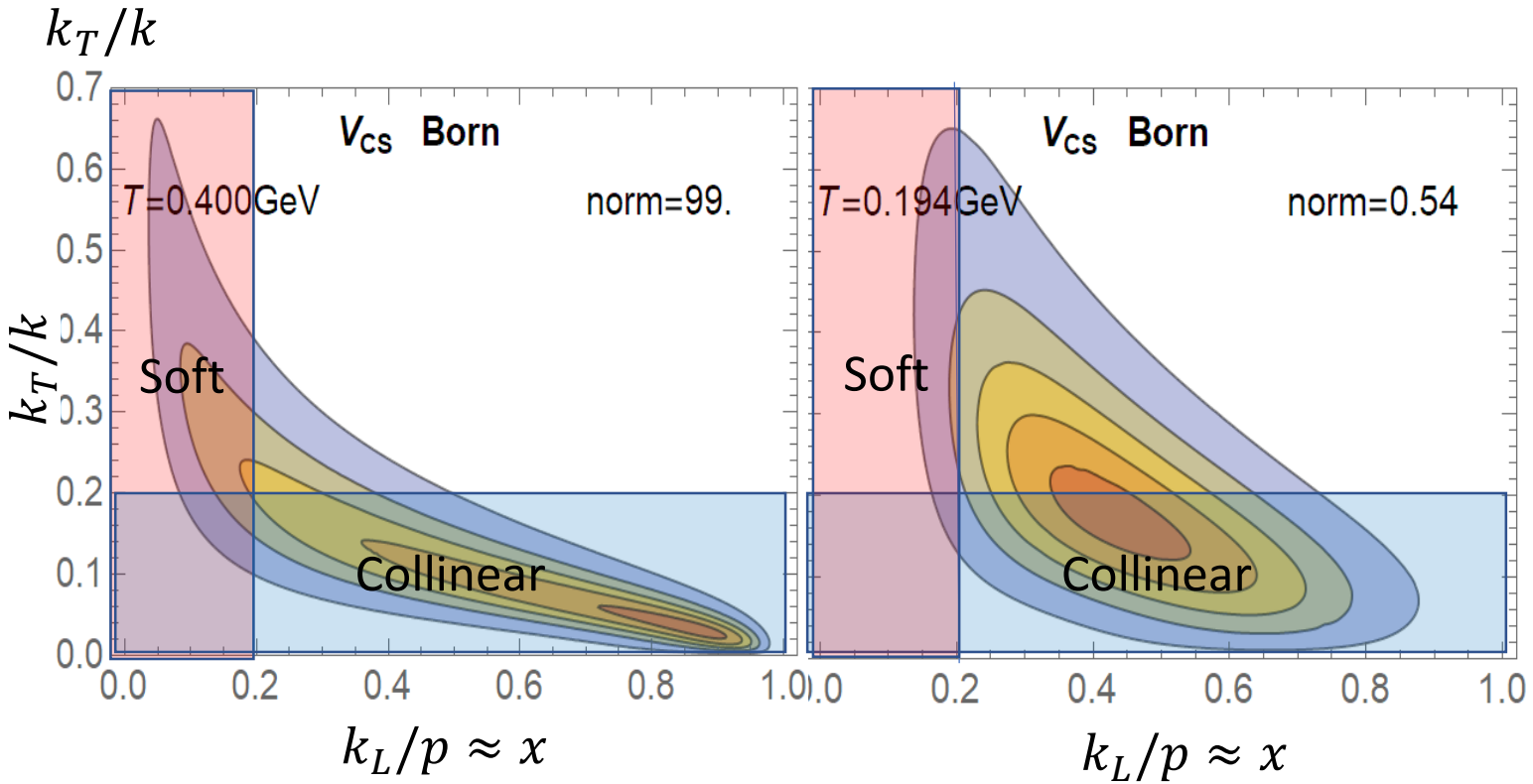
q-hat for two cases



- Strongly enhanced q-hat at low momentum region
- Using momentum dependent q-hat to include the NP effects?

2D power spectrum





- Dead-Cone
- soft or collinear expansion good at high momentum

Non-Perturbative Effects for High Energy Partons?

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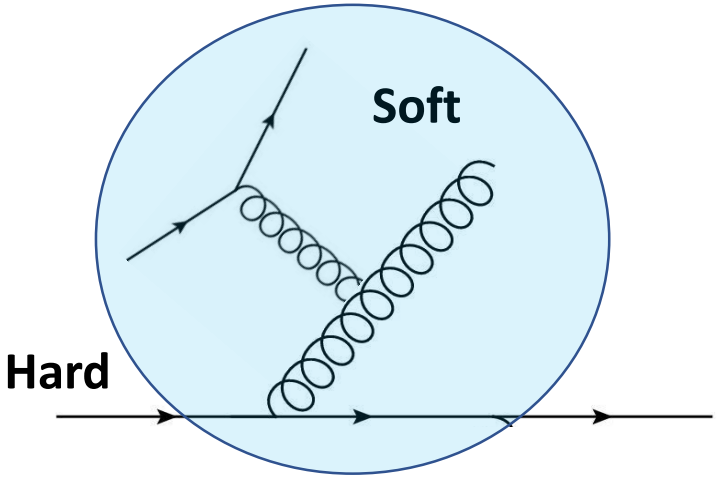
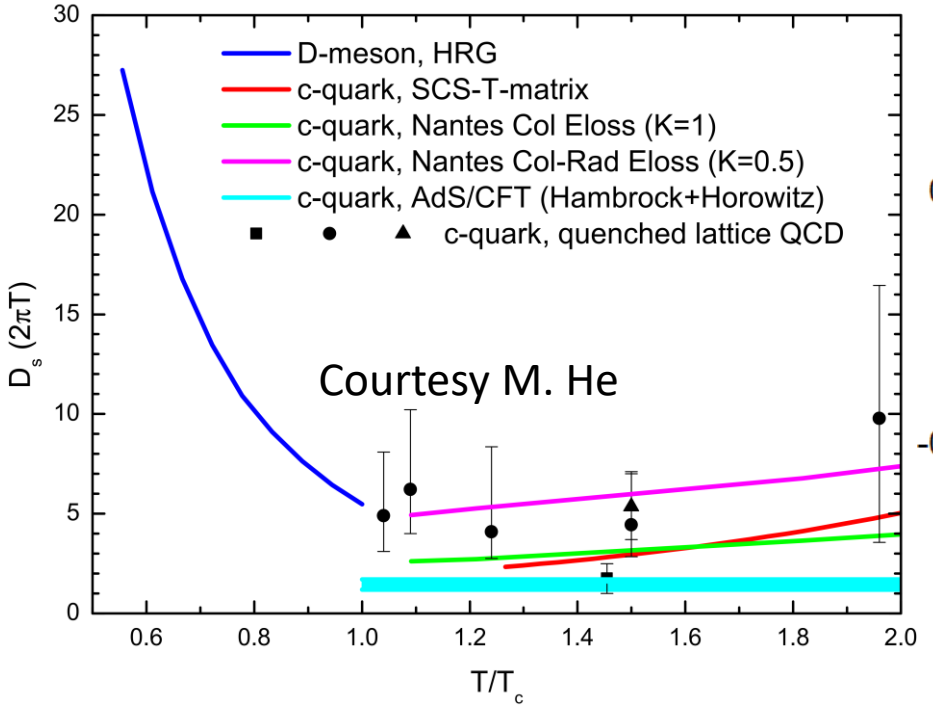
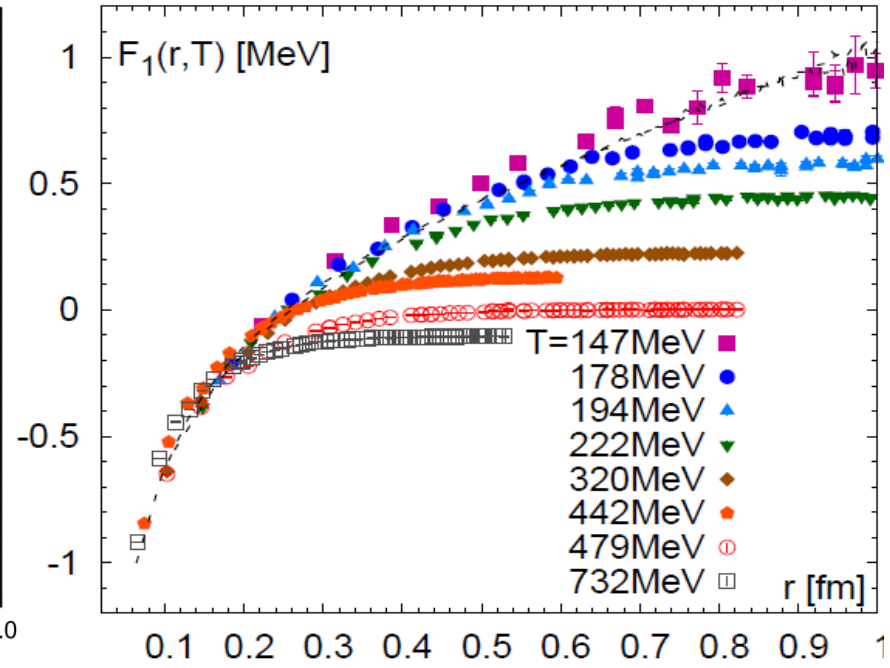
- Gluons emitted at soft scale
- Interactions at soft scale, strong!







Remnant of confining force,

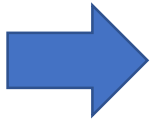
Resummation,

No quasi particles

Four Cases with Different NP Effects

How they affects radiative energy loss?

- Remnant confining force
- Ladder resummation
- Non-quasi particle medium

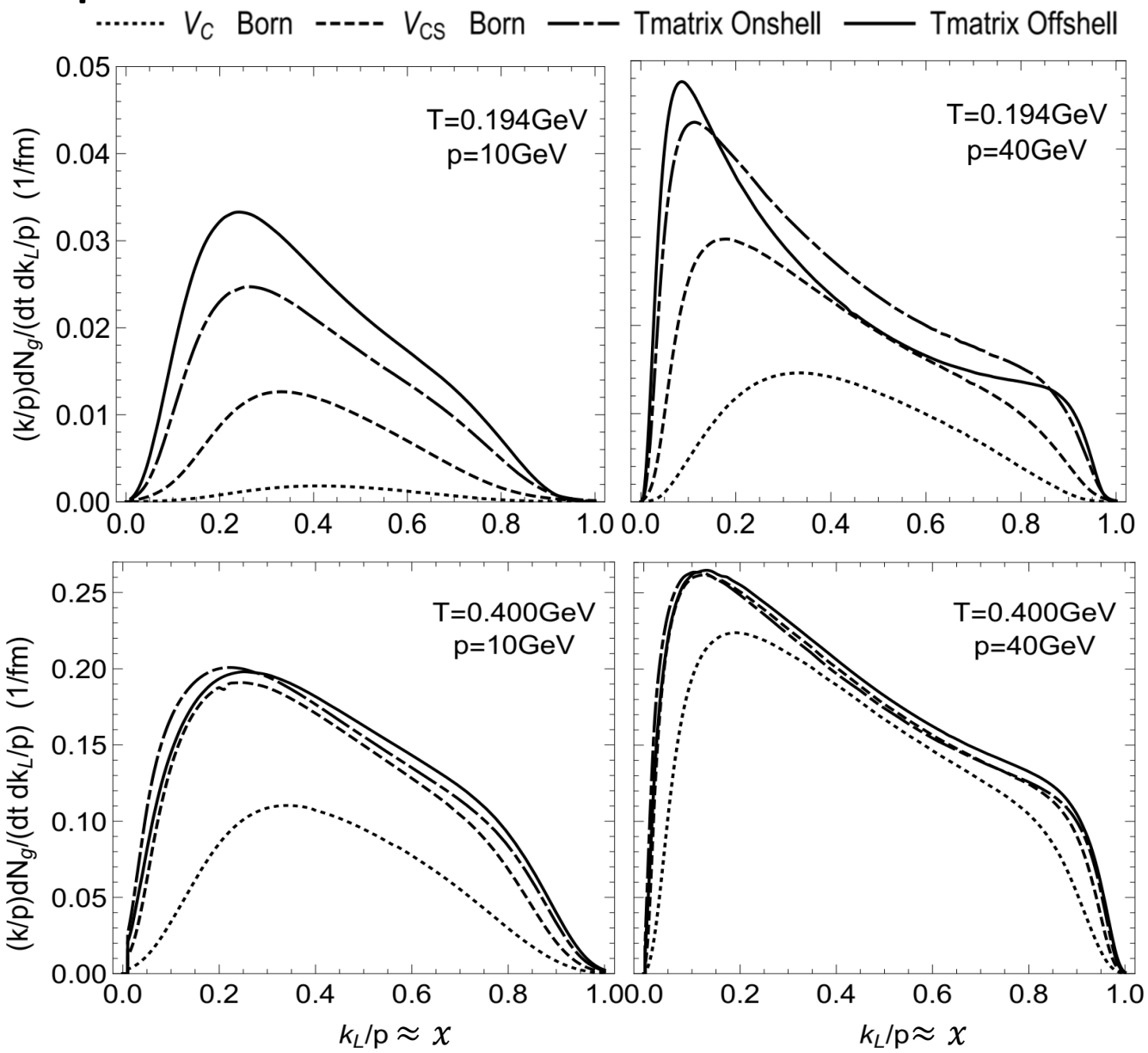


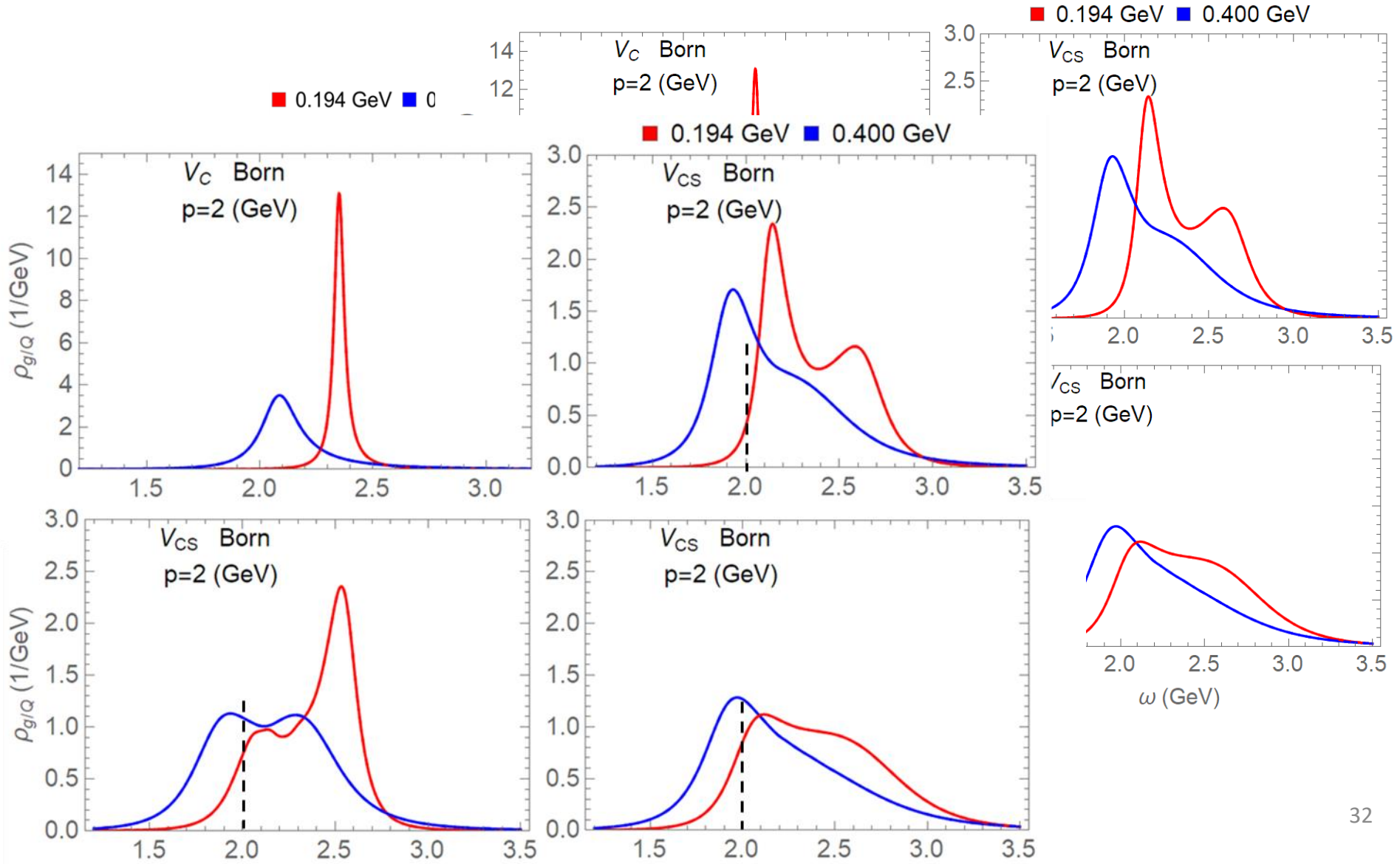
Strategy

- Define four cases containing different NP effects
- Compare their output: spectral functions, power spectrum, drag coefficient, energy loss…

Radiative Power Spectrum

- Power spectrum $\frac{(k/p)dN_g}{dt\ d(k_L/p)} \approx \frac{xdN_g}{dt\ dx}$
- Low *p* low *T*: NP effects at all x
- High *p* low *T*: NP enhancement at small/large x
- High *T* low *p*: confining effects at all x, others not significant
- High *T* low *p*: confining effects at small/large x, others not significant




0.194 GeV
0.400 GeV
V_C Born
p=2 (GeV)
V_{CS} Born
p=2 (GeV)
$\rho_{g/Q}$ (1/GeV)
ω (GeV)