Heavy-quark suppression and anisotropic flow at intermediate momentum

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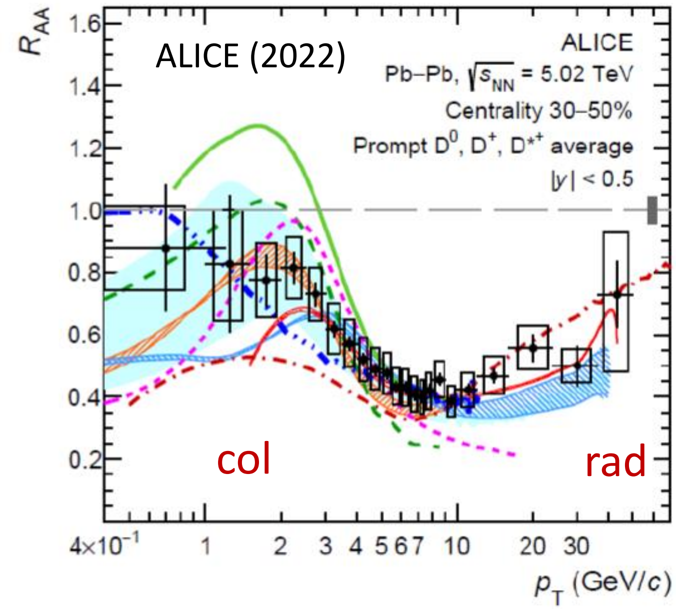
Phys. Rev. C 109 (2024) 024913
Phys. Rev. C 111 (2025) 044910

INPC 2025
May 25-30, 2025
DCC, Daejeon, Korea

Heavy quarks



- Important hard probes
- Large differences between transport models: describe experimental data with adjustment of model parameters
- Heavy quark energy loss
- Collisional/radiative dominant at low/high p_T
- At intermediate momentum, significant uncertainties: transition between collisional and radiative energy loss

Outline

- Boltzmann equation at Intermediate momentum:

$$\left(\frac{\partial}{\partial t} + \boldsymbol{v} \cdot \frac{\partial}{\partial \boldsymbol{x}}\right) f(\boldsymbol{p}) = C_{\rm col}[f] + C_{\rm rad}[f]$$

- Collisional energy loss in the Fokker-Planck approximation

- Radiative energy loss by gluon-bremsstrahlung from a single scattering:
  radiative correction to the collision kernel for diffusion

- Single transport parameter:
  heavy quark diffusion coefficient constrained by lattice QCD

- Consistently describe two energy losses and study the transition

Collisional energy loss at low p

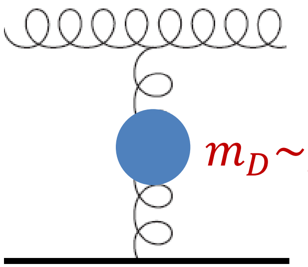
- Elastic scattering
- Brownian motion of heavy quarks

Collisional energy loss

- For soft gluon exchange: Fokker-Planck operator

$$C_{\rm col}[f] = \frac{\partial}{\partial p^i}\underbrace{\left[\eta(\boldsymbol{p})p^i f(\boldsymbol{p})\right]}_{\text{drag}} + \frac{1}{2}\frac{\partial^2}{\partial p^i \partial p^j}\underbrace{\left[\kappa^{ij}(\boldsymbol{p}) f(\boldsymbol{p})\right]}_{\text{diffusion}}$$

Svetitsky (1988)



- Momentum diffusion coefficient: $\kappa^{ij}(\boldsymbol{p}) = \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$

$$\kappa_{L,T}(p) = \int d^3\boldsymbol{q}\,\frac{d\Gamma(\boldsymbol{q})}{d^3\boldsymbol{q}}\,q_{L,T}^2 \qquad\qquad \kappa_L(p=0) = \kappa_T(p=0)$$

- Approach the thermal equilibrium $f(p) \propto e^{-E/T}$: $\eta(p) = \dfrac{\kappa_L(p)}{2TE} + O\left(\dfrac{T}{E}\right)$

- Collisional energy loss by $\kappa_{L,T}(p=0)$ and their momentum dependence

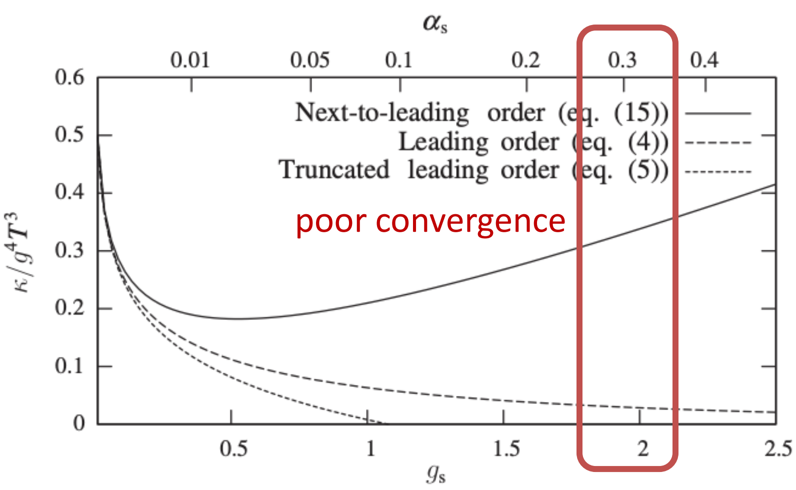
Heavy quark diffusion coefficient

At weak coupling

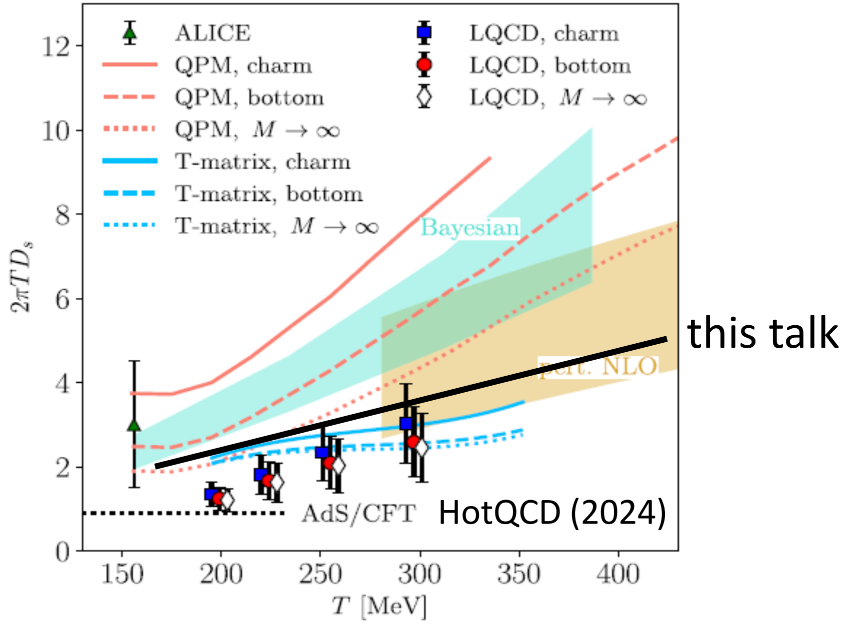
- LO: $\kappa_{LO} \sim \alpha_s^2 T^3$
- NLO: $\kappa_{NLO} \sim g\alpha_s^2 T^3$

Bose−enhancement with soft($k\sim gT$) gluons

$$\alpha_s n_B(k) \sim \alpha_s \frac{1}{e^{k/T}-1} \sim \frac{g^2}{4\pi}\frac{T}{k} \sim g$$



Caron-Huot, Moore (2008)

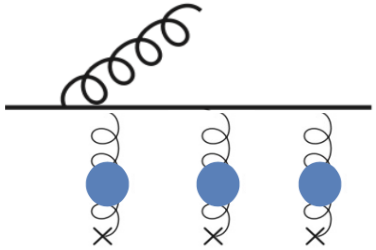


HotQCD (2024)

- Nonperturbative lattice QCD for spatial diffusion: $D_s = \dfrac{2T^2}{\kappa}$
- Temperature dependence by running coupling

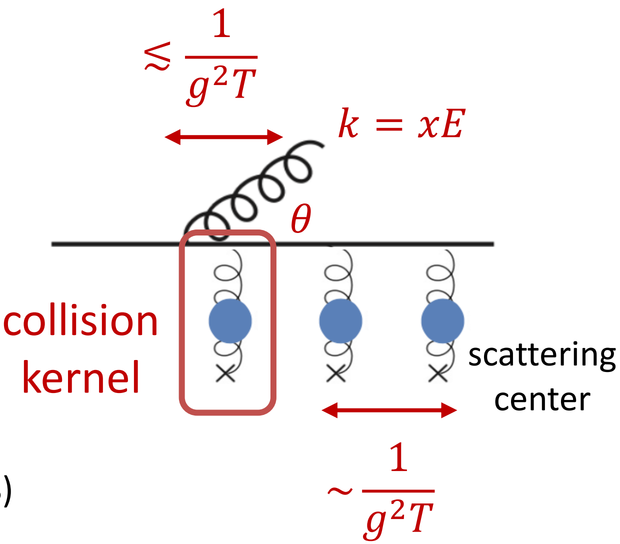
Radiative energy loss at high p

- Medium-induced gluon emission
- Soft gluon exchange, collinear emission



Arnold, Moore, Yaffe (2001,2002)

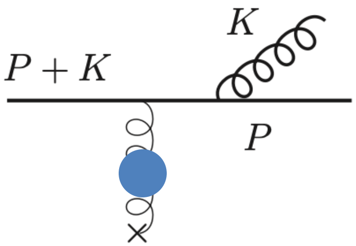
Medium-induced gluon emission



- Semi-collinear emission from a single scattering
- Formation time: $t_f \sim \frac{k}{\underbrace{m^2x^2+k_T^2}} \lesssim mfp$
- Dead-cone for $\theta \sim \frac{k_T}{k} < \frac{m}{E}$ Dokshitzer, Kharzeev (1998)
- Smooth transition between low and high-p regimes
- With diffusion kernel: gluon emission rate with diffusion coefficient:

$$\frac{d\Gamma}{dk} = \frac{g^2C_F\boxed{\kappa_T}}{\pi k}[1+n_B(k)][1-n_F(E_{p-k})][(1-x)^2+1]\int \frac{d^2\boldsymbol{p}_T}{(2\pi)^2}\frac{1}{(\boldsymbol{p}_T^2+m^2x^2+m_g^2)^2}$$

Radiative energy loss



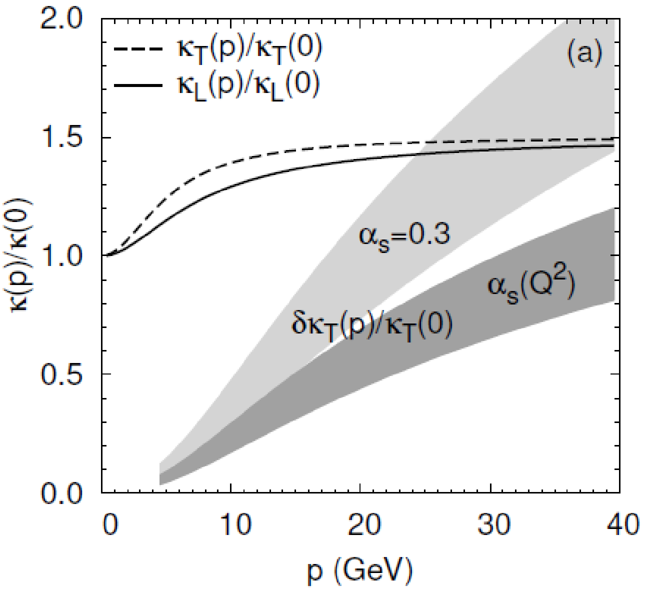
- Eikonal approximation: $\boldsymbol{p}+\boldsymbol{k}=(p+k)\hat{\boldsymbol{p}}$

$$C_{\rm rad}[f]=\underbrace{\int dk}_{\text{if } k<0\text{, gluon absorption for detailed balance}}\left[f((p+k)\hat{\boldsymbol{p}})\frac{d\Gamma(E_{(p+k)\hat{\boldsymbol{p}}},k)}{dk}-f(\boldsymbol{p})\frac{d\Gamma(E_{\boldsymbol{p}},k)}{dk}\right]+\underbrace{\frac{1}{2}\nabla^2_{\boldsymbol{p}_T}[\delta\kappa_T(p)f(\boldsymbol{p})]}_{\text{radiative correction}}$$

- Radiative correction:

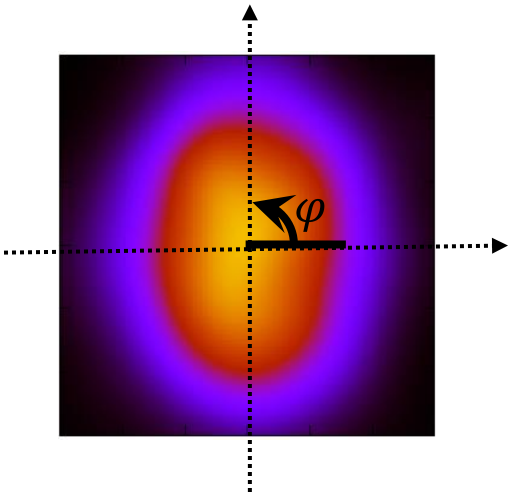
$$\delta\kappa_T=\int\frac{d^2\boldsymbol{k}_T}{(2\pi)^2}\boldsymbol{k}_T^2\,\underbrace{\delta C(\boldsymbol{k}_T)}_{\propto\,\kappa_T}\,[1+n_B(k)]$$

- Radiative energy loss with κ_T

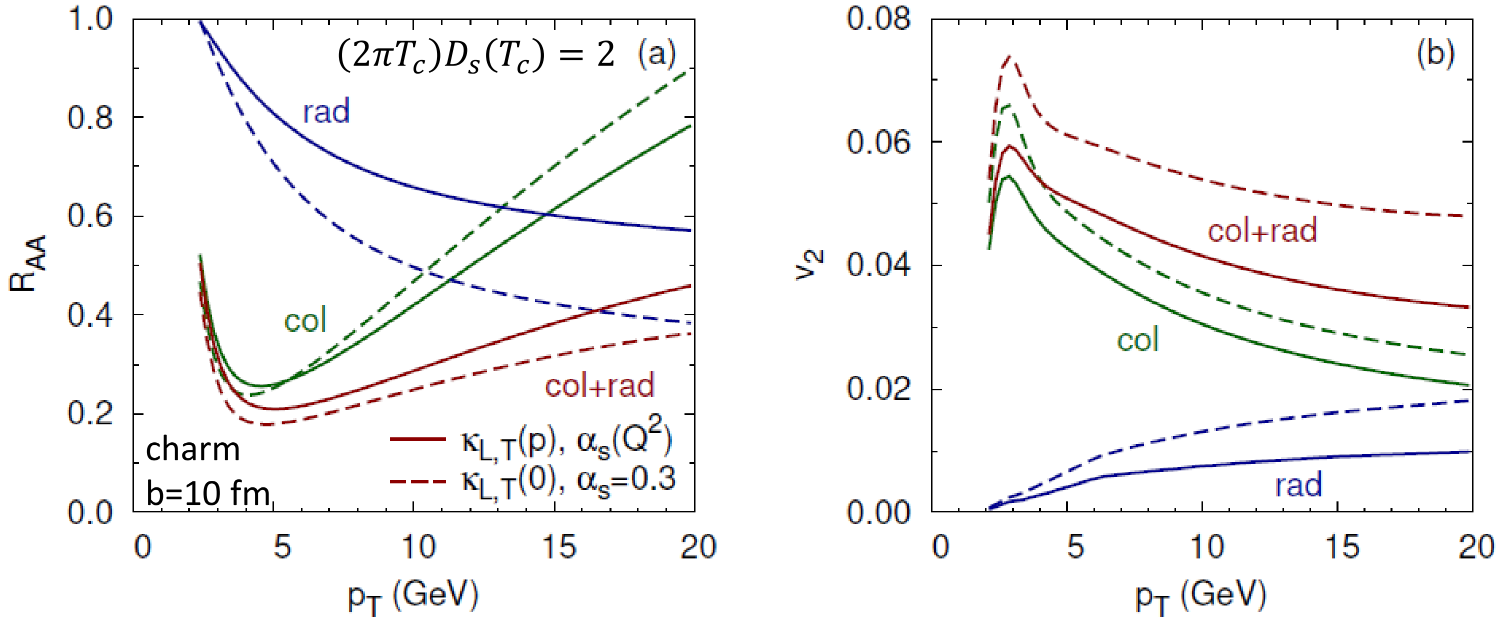


Numerical study

- Hydrodynamics with initial Glauber
- Nuclear modification factor
- Elliptic flow: asymmetric energy loss



Heavy quark R_{AA} and v_2

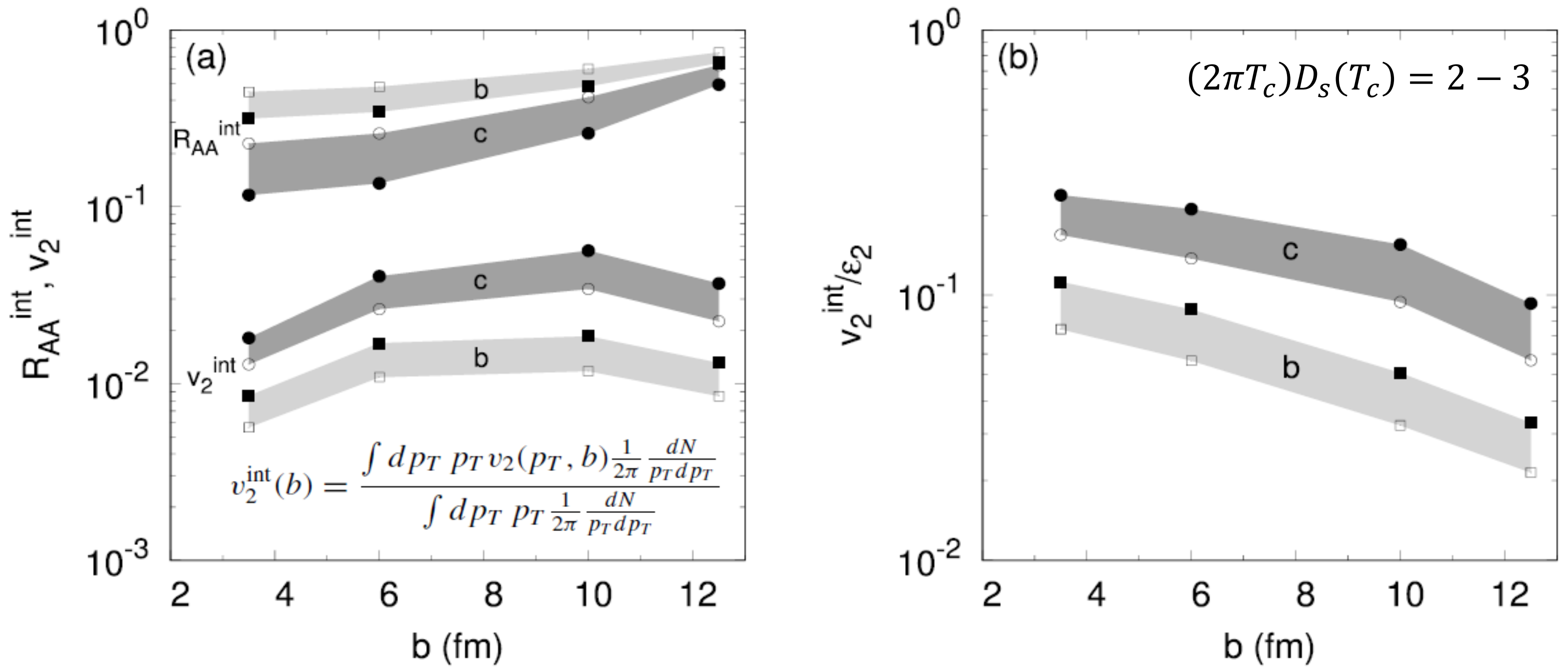


- $\kappa_{L,T}(p)$ increase with p at leading-log   Moore, Teaney (2005)
- Temperature dependence by running coupling: $\kappa_{L,T} \propto \alpha_s(ET)\,\alpha_s(m_D^2)$

  Peigne, Peshier (2008)

- Collisional/radiative energy loss dominant at low/high momentum: qualitatively different
- p, T-dependent $\kappa_{L,T}$: transition at higher momentum

b, m-dependence



- R_{AA}: larger energy loss in more central collisions
- v_2: energy loss $\longleftrightarrow$ geometric deformation
- $m_b \approx 3\, m_c$: $R_{AA}^b > R_{AA}^c$, $v_2^b < v_2^c$

Summary

- Heavy quark transport at intermediate momentum
- Boltzmann equation with a single transport parameter:
  heavy quark diffusion coefficient constrained by nonperturbative lattice QCD
- Collisional/radiative energy loss dominant at low/high momentum:
  qualitatively different momentum dependence
- Transition between collisional and radiative effect
- Significance of radiative effect depends on $\kappa_{L,T}(p,T)$

Thank you for your attention!