Heavy flavor suppression in relativistic heavy-ion collisions

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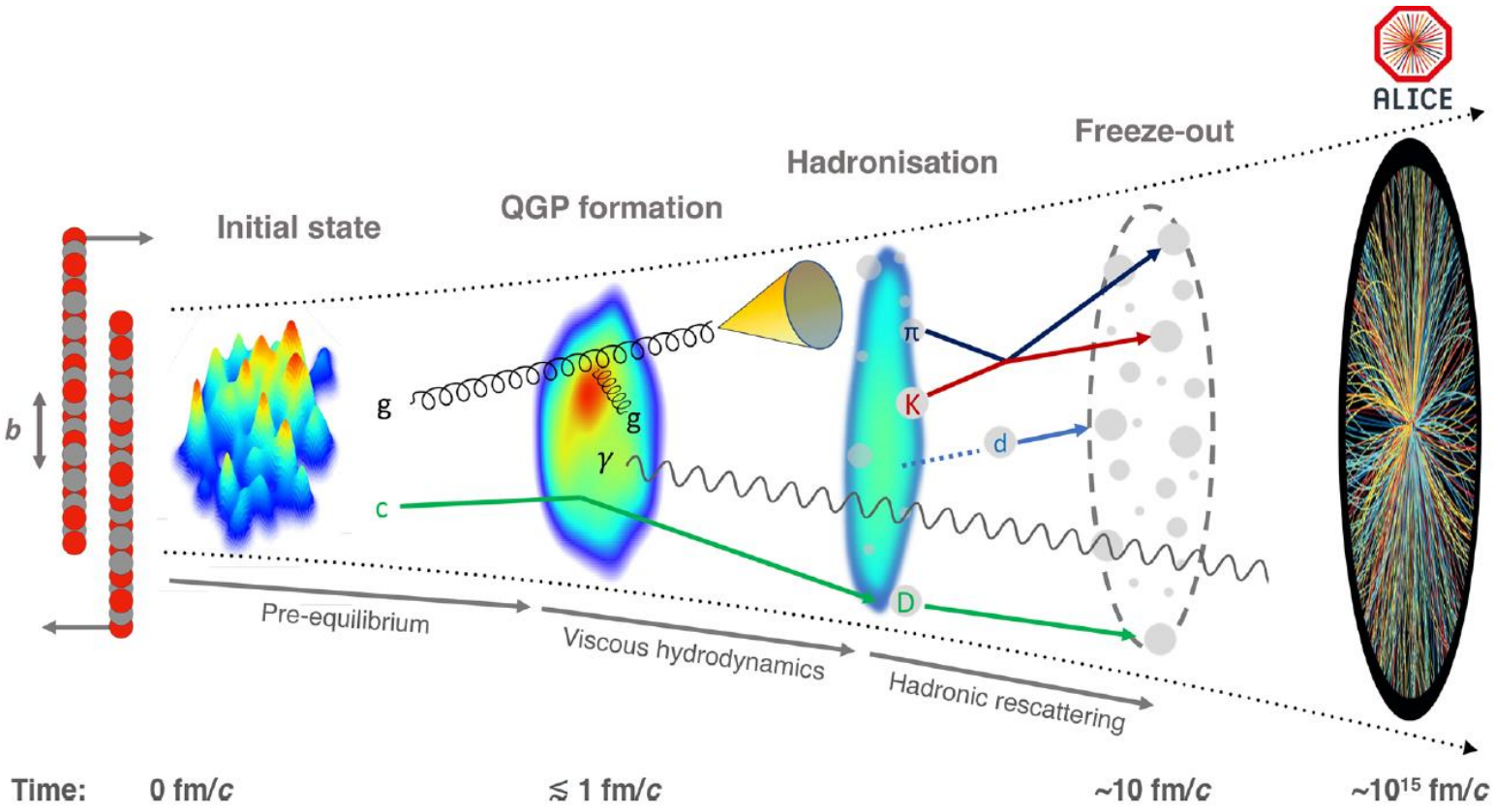
Relativistic heavy-ion collisions

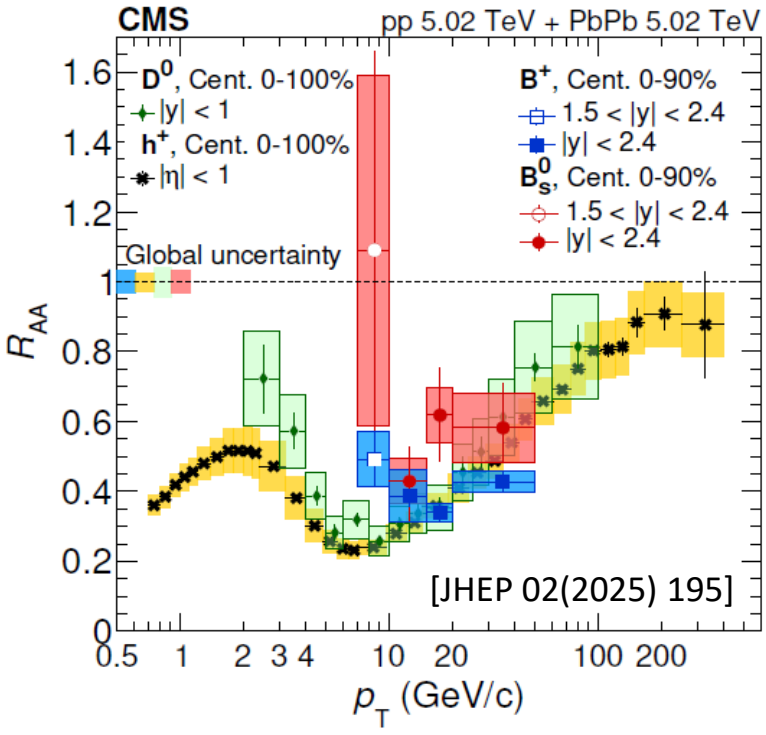


[figure from EPJC 84(2024) 8, 813]

- High temperature and density
- Heavy quarks created in hard processes at the beginning and conserved

Heavy meson suppression

- Various influences through all stages of heavy-ion collisions:
  initial production, medium expansion, HQ interaction in QGP, hadronic effects, etc.
- Heavy-quark energy loss
  - Collisional at low momentum
  - Radiative at high momentum
- Significant uncertainties at intermediate momentum:
  finite mass effect



Transition between collisional and radiative energy loss

Outline

- Heavy quark transport at Intermediate momentum:

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

- Collisional and radiative energy loss with a single transport parameter [heavy quark diffusion coefficient]

- Hadronization: coalescence, fragmentation

- Radiative effects on the suppression factor and anisotropic flow of heavy mesons

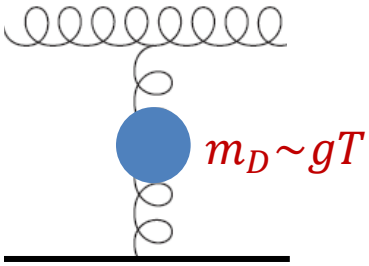
Boltzmann equation

Collisional energy loss

- Heavy quark($\mathrm{m} \gg T$): elastic scattering at low momentum Svetitsky (1988)

- For soft gluon exchange: Fokker-Planck approximation

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



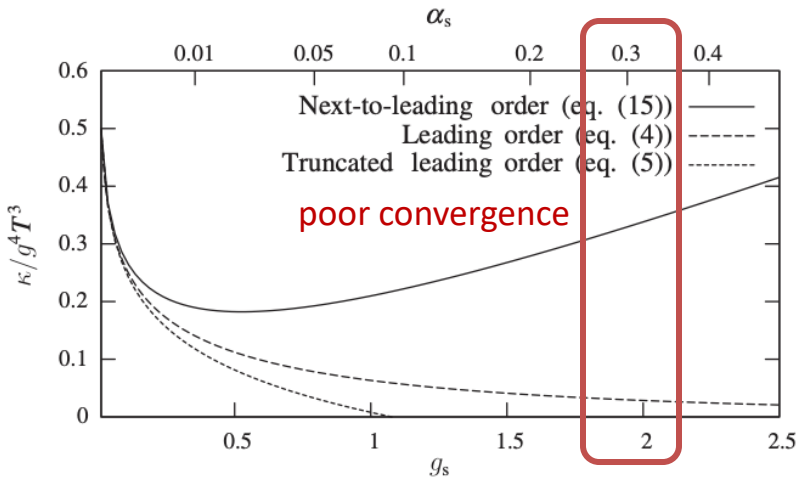
- Momentum diffusion coefficient: $\kappa_{L,T}(p) = \int \frac{d^3\boldsymbol{q}}{(2\pi)^3} C(\boldsymbol{q})\, q_{L,T}^2$

$$C(\boldsymbol{q}) = \frac{\pi}{2} g^2 C_F m_D^2 \int d\omega\, \delta(\omega - \boldsymbol{q}\cdot\boldsymbol{v}) \frac{T}{q}\underbrace{\left[\frac{2}{|\boldsymbol{q}^2 + \Pi_L(Q)|^2} + \frac{(q^2-\omega^2)(q^2v^2-\omega^2)}{q^4|\boldsymbol{q}^2 - \omega^2 + \Pi_T(Q)|^2}\right]}_{\text{Hard-Thermal-Loop resummations}}$$

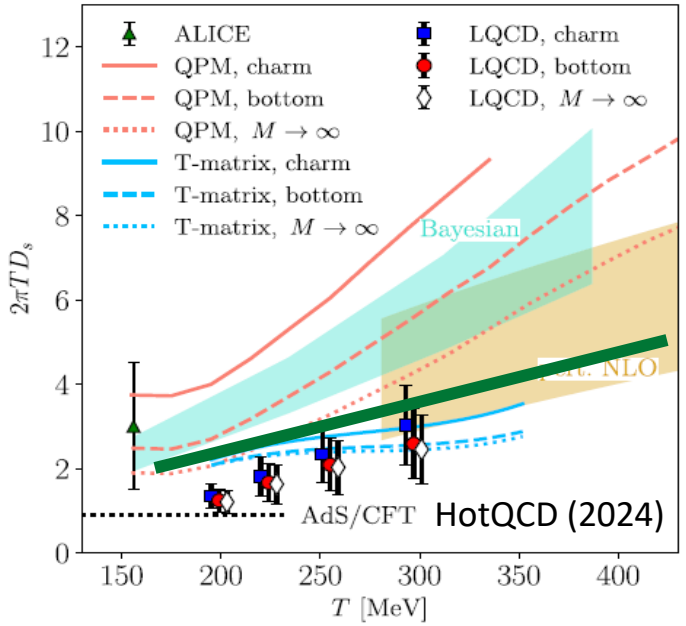
- Thermal equilibrium $\left[f(p) \propto e^{-E/T}\right]$ in $t \to \infty$: $\eta(p) \approx \frac{\kappa_L(p)}{2TE}$

Heavy quark diffusion coefficient

- Weak coupling expansion: $\kappa_{LO} \sim \alpha_s^2 T^3, \quad \kappa_{NLO} \sim g\alpha_s^2 T^3$



Caron-Huot, Moore (2008)



HotQCD (2024)

this talk

- Nonperturbative lattice QCD for spatial diffusion: $D_s = \frac{2T^2}{\kappa}$
- Temperature dependence by running coupling: $\kappa \propto \alpha_s(ET)\,\alpha_s(m_D^2)$

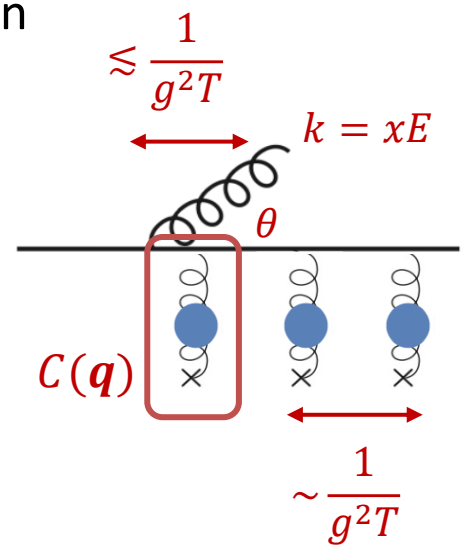
Peigne, Peshier (2008)

Medium-induced gluon emission

- Radiative energy loss at high momentum

Arnold, Moore, Yaffe (2001,2002)

- Ultrarelativistic: soft gluon exchange, collinear emission
- Formation time for heavy quark: $t_f \sim \frac{k}{m^2x^2+k_T^2} \lesssim mfp$

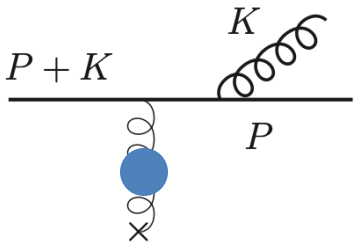


- Semi-collinear emission from a single scattering
- Dead-cone for $\theta \sim \frac{k_T}{k} < \frac{m}{E}$ Dokshitzer, Kharzeev (1998)
- Using diffusion kernel, gluon($k \sim T$) emission rate by diffusion coefficient:

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

Radiative energy loss

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



$$C_{\rm rad}[f]=\int dk\left[f((p+k)\hat{\boldsymbol{p}})\frac{d\Gamma(E_{(p+k)\hat{\boldsymbol{p}}},k)}{dk}-f(\boldsymbol{p})\frac{d\Gamma(E_{\boldsymbol{p}},k)}{dk}\right]+\frac{1}{2}\nabla^2_{\boldsymbol{p}_T}[\delta\kappa_T(p)f(\boldsymbol{p})]$$

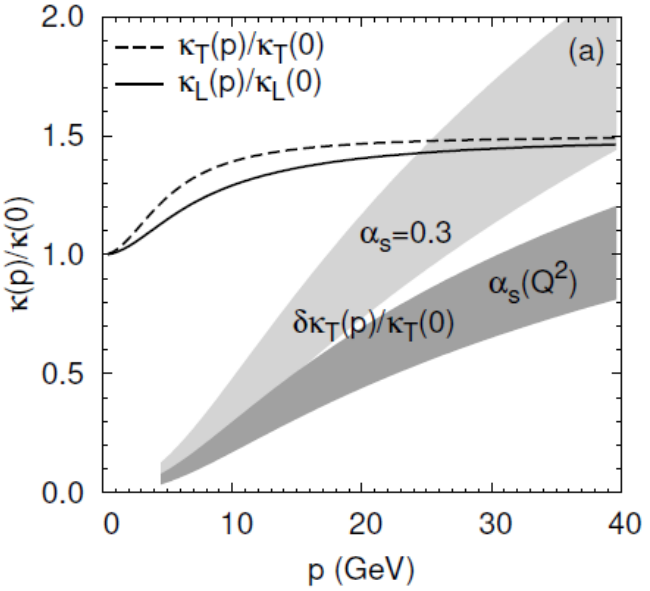
if $k<0$, gluon absorption for detailed balance — radiative correction

- Radiative correction:

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

$\delta C(\boldsymbol{k}_T) \propto \kappa_T$

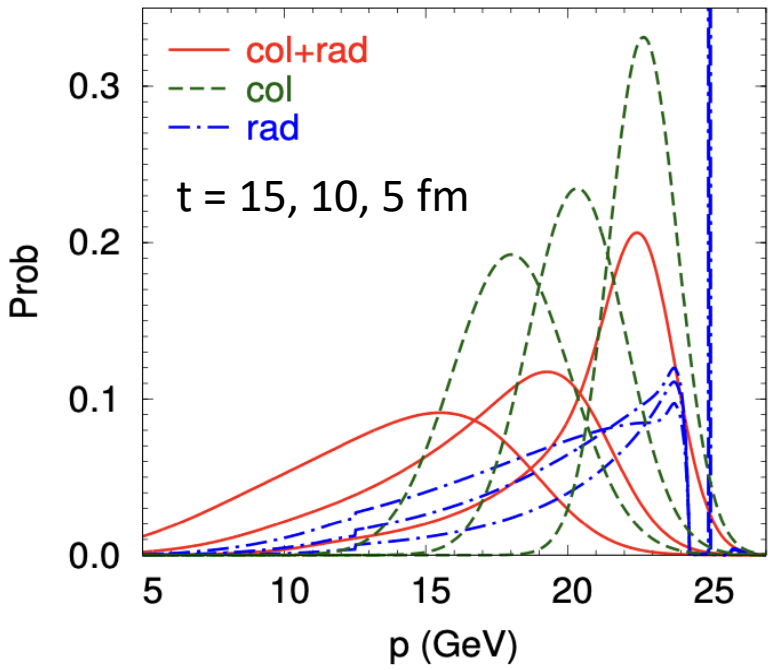
$$\sim g^2\kappa_T\ln\frac{E}{m}\ln\frac{p}{T}$$ [quantum correction to $\hat{q}$]



- Radiative energy loss by κ_T
- Boltzmann equation with only κ_T [which can be constrained by lattice QCD]

Numerical study

Heavy quark distribution



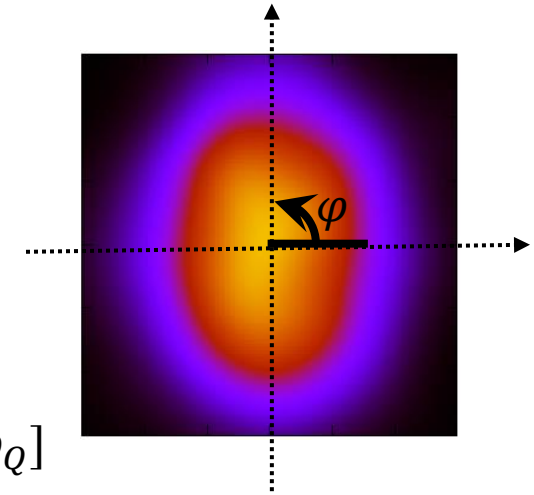
- b evolution with initial δ-function in a static medium
- Collisional energy loss: Gaussian fluctuations
- Radiative energy loss: non-Gaussian distributions
- Qualitatively distinguishable medium modifications by two energy losses

Observables

- Nuclear modification factor: $R_{AA} = \dfrac{\frac{dN_{AA}}{dp_T}}{N_{coll}\frac{dN_{pp}}{dp_T}}$
- Collective flow by Fourier components of the azimuthal angle distribution:

$$\frac{dN}{d^2\boldsymbol{p}_T} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left[1 + 2\sum_n v_n(p_T)\cos n\phi\right]$$

- Hydrodynamic simulation: anisotropic temperature and flow velocity
- Elliptic flow by asymmetric energy loss

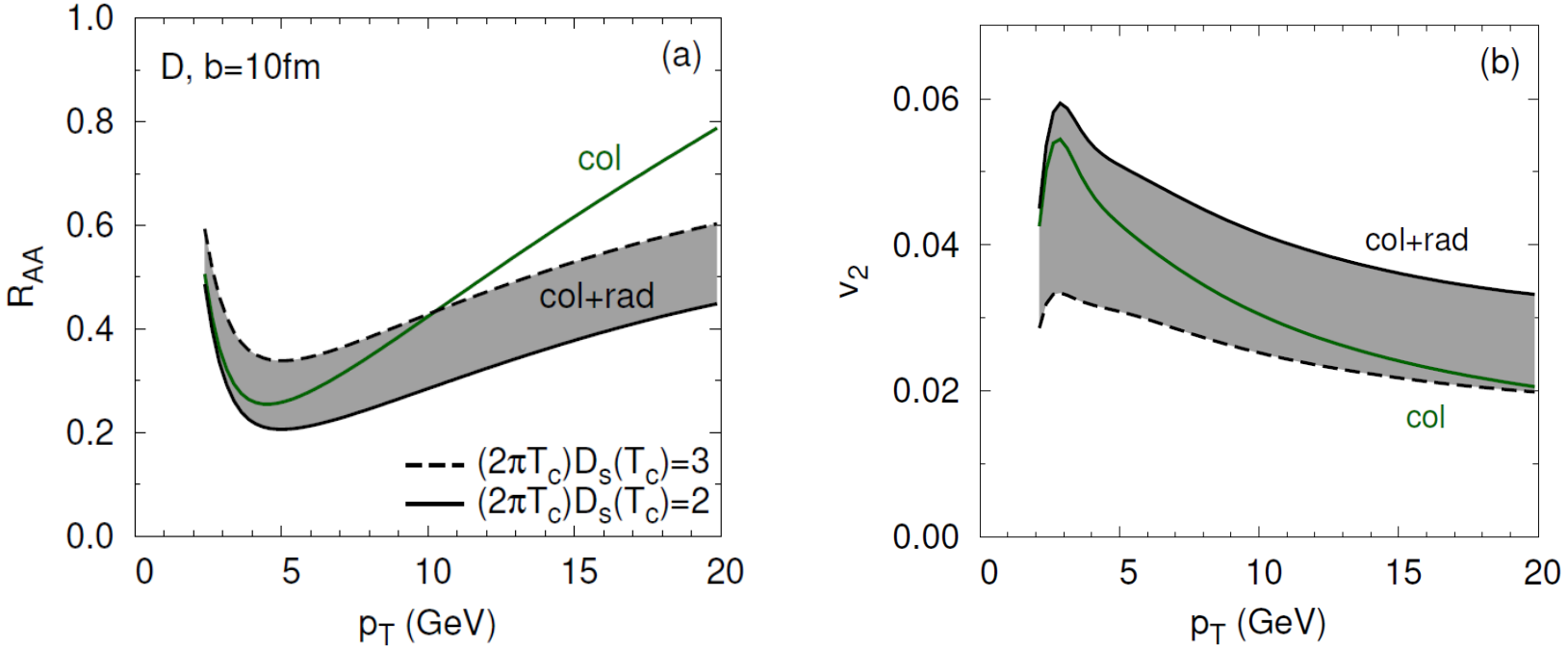


- Coalescence near T_c:

$$\frac{dN}{d^3p} = \int d^3p_Q d^3p_{\bar{q}} \frac{dN_Q}{d^3p_Q}\frac{dN_{\bar{q}}}{d^3p_{\bar{q}}} \underbrace{f_W(p_Q, p_{\bar{q}})}_{\propto e^{-\sigma^2 p_{rel}^2}} \delta(p - p_Q - p_{\bar{q}})$$

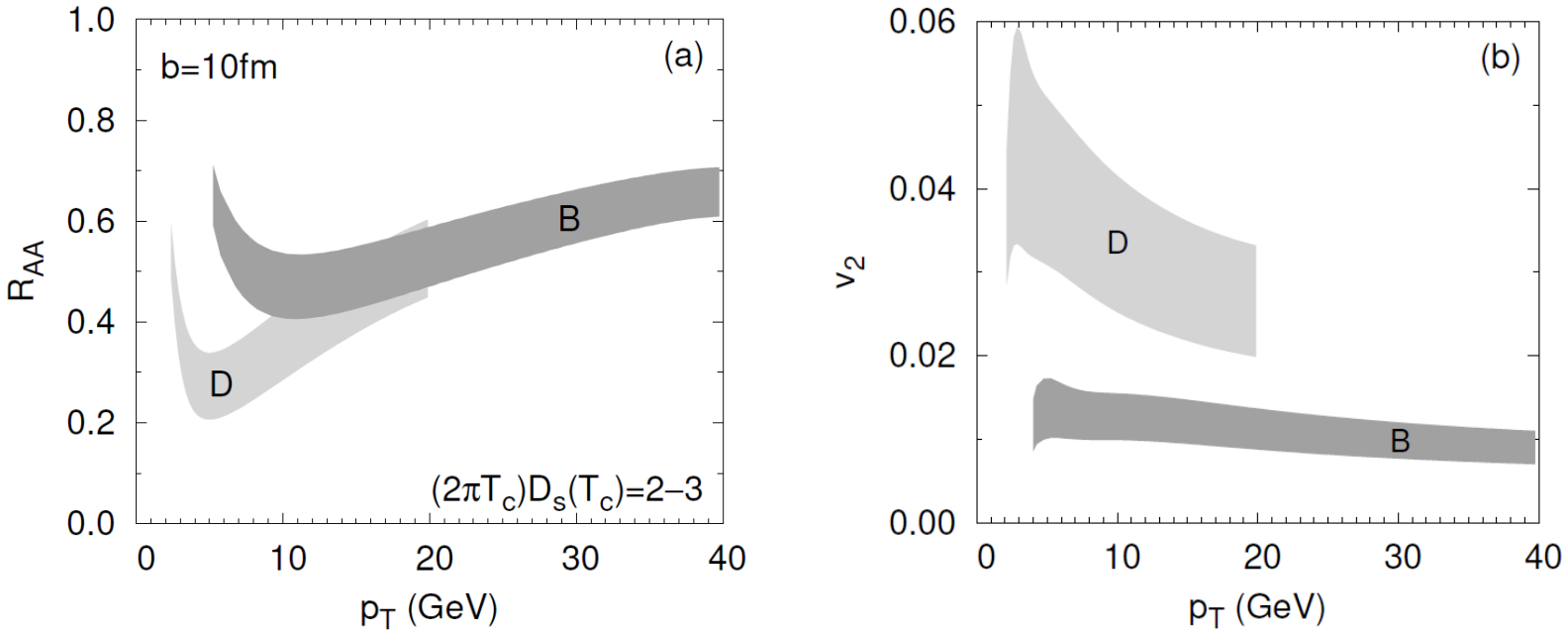
- Fragmentation: $E\frac{d\sigma}{d^3p} = E_Q \frac{d\sigma_Q}{d^3p_Q} \otimes \underbrace{D_{Q\to M}(z)}_{\propto \frac{1}{z\left[1-\frac{1}{z}-\frac{\epsilon}{1-z}\right]^2}} \quad [z = p/p_Q]$

Heavy meson R_{AA} and v_2



- Collisional energy loss is dominant at low momentum
- Radiative effects increase with momentum:
  make R_{AA} and v_2 more independent of p_T
- Transition between two energy losses: qualitatively different p_T-dependence

Mass dependence



- $m_b \approx 3m_c$: less suppression, weaker anisotropy

Summary

- Heavy quark transport at intermediate momentum
- Boltzmann equation with a single transport parameter:
  heavy quark diffusion coefficient constrained by nonperturbative lattice QCD
- Medium modifications by collisional/radiative energy loss are distinguishable because of different momentum dependence
- Momentum-dependent transition between collisional and radiative effects
- As radiative effects increase, R_{AA} and v_2 become more independent of p_T

Thank you for your attention