$\hat{q}$ analysis in a hybrid Boltzmann-Langevin approach with an improved LPM treatment

Weiyao Ke
Collaborators: Yingru Xu, and Steffen Bass

Duke University

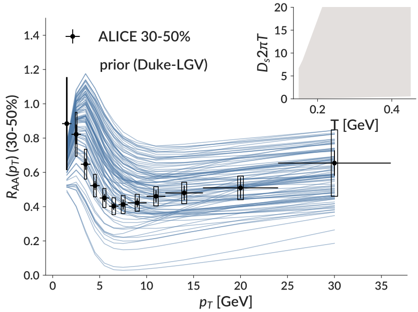
October 2, 2018

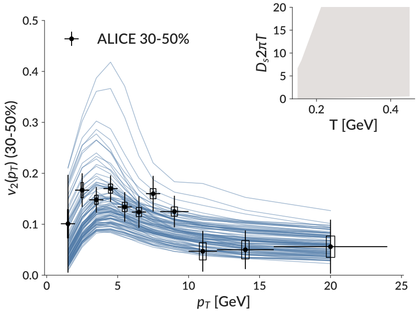
This work is supported by OpenScienceGrid, U.S. Department of Energy Grant no. DE-FG02-05ER41367, National Science Foundation Grant no. OAC-1550225.

Recent efforts to extract heavy quark $\hat{q}$

Extraction of $\hat{q}$ from systematic model-to-data comparison

- Radiation-improved Langevin Eq. (Cao et al PRC 92 024907), coupled to a tuned 2+1D viscous hydro evolution (Bernhard arXiv 1804.06469).
- Input: functional forms of $\hat{q}(E, T)$.
- Compare to R_{AA} and v_2 measurements at the LHC.



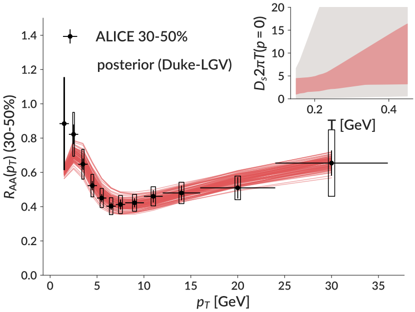


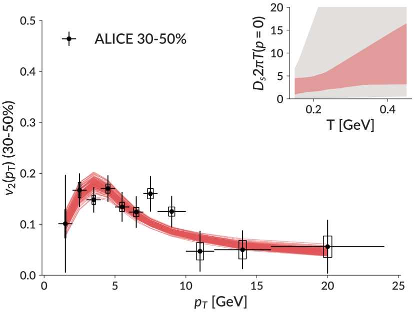
Xu et al, PRC 97 014907 and work in progress, ALICE PRL 120 102301,

Recent efforts to extract heavy quark $\hat{q}$

Extraction of $\hat{q}$ from systematic model-to-data comparison

- Radiation-improved Langevin Eq. (Cao et al PRC 92 024907), coupled to a tuned 2+1D viscous hydro evolution (Bernhard arXiv 1804.06469).
- Input: functional forms of $\hat{q}(E, T)$.
- Compare to R_{AA} and v_2 measurements at the LHC.



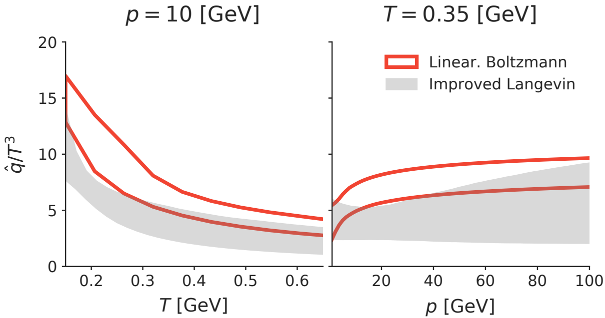


Xu et al, PRC 97 014907 and work in progress, ALICE PRL 120 102301,

Recent efforts to extract heavy quark $\hat{q}$

Issue 1: different approaches lead to different results

- Compare improved Langevin Eq to a recent linearized Boltzmann Eq. (Ke et al, arXiv:1806.08848).
- Use same medium evolution. Compare to the same set of observables.
- However, different 95% credible region of $\hat{q}$.
- Motivate a model that is more inclusive on assumptions.



Recent efforts to extract heavy quark $\hat{q}$

Issue 2: how to implement a kinetic theory with coherence effect?

- Landau-Pomeranchuk-Migdal effect suppresses incoherent radiation.
  - Qualitative features of coherence ✓
  - Quantitative agreement with theory ?
- This affects the interpretation of theory-to-data comparison.
- Need an improved implementation of the LPM effect.

Roadmap of this presentation

Interpolate diffusion approximation to the scattering picture

- Absorb small $\hat{t}$ processes of the rate equation into a diffusion equation Ghiglieri et al, JHEP 03 (2016) 095 $\rightarrow$ introduce a separation scale $\hat{t}_{\rm cut}$. First implementation for light sector (Dai, today Parallel 1, 17:45).
- Elastic processes $\propto 1/\hat{t}^2$
Inelastic processes $\Big\}$ Rate equation. Sensitive to $\hat{t}$ cut-off.
- Small-$|t|$ interactions are frequent and soft $\approx$ a diffusion process.

Roadmap of this presentation

Interpolate diffusion approximation to the scattering picture

- Absorb small $\hat{t}$ processes of the rate equation into a diffusion equation Ghiglieri et al, JHEP 03 (2016) 095 $\rightarrow$ introduce a separation scale $\hat{t}_{\rm cut}$. First implementation for light sector (Dai, today Parallel 1, 17:45).
- Elastic processes $\propto 1/\hat{t}^2$ Inelastic processes } Rate equation. Sensitive to $\hat{t}$ cut-off.
- Small-$|t|$ interactions are frequent and soft $\approx$ a diffusion process.

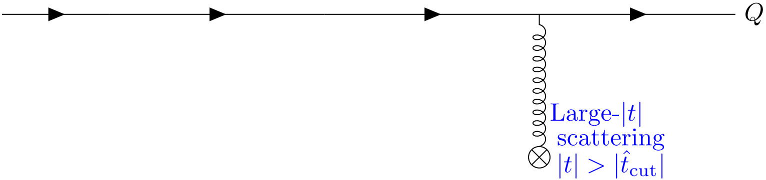
Implement and validate an improved treatment of LPM effect.

- Fine tune MC to match theory calculation ($dI/d\omega$) in special cases.
- Achieve less ambiguous statement when compare to data.

Build the model: start with a light quark

- Large momentum-transfer elastic scattering solved by a rate equation.
- Restrict momenta transfer to $|t| > |\hat{t}_{\rm cut}|$.

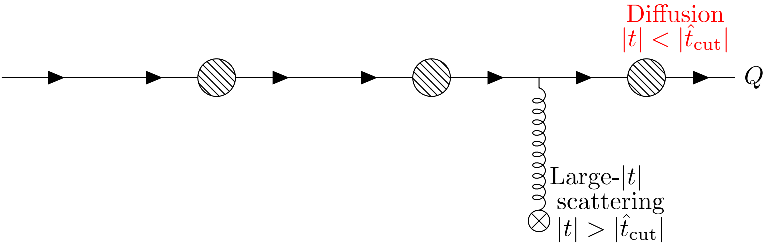
$$df_Q/dt = \mathcal{C}_{>}^{2\leftrightarrow 2}$$



Build the model: start with a light quark

- Small momentum-transfer processes solved by a Langevin equation.
- Transport coefficient $\hat{q}_< = \alpha_s C_F T m_D^2 \ln(1 + |\hat{t}_{\rm cut}|/m_D^2)$.

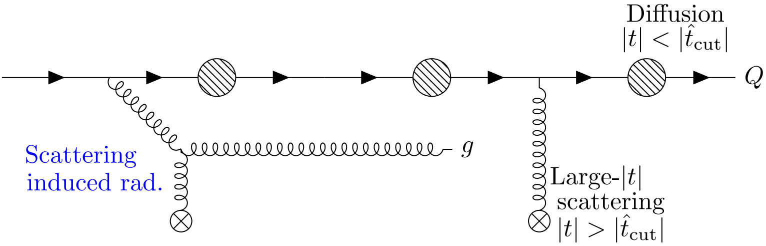
$$df_Q/dt = \mathcal{C}_>^{2\leftrightarrow 2} + \partial_p \left(Ap + \partial_p B\right)_< f_Q$$



Build the model: start with a light quark

- Improved Gunion-Bertsch matrix-element Fochler et al, PRD 88 014018
- Again, require $|t| > |\hat{t}_{\rm cut}|$.

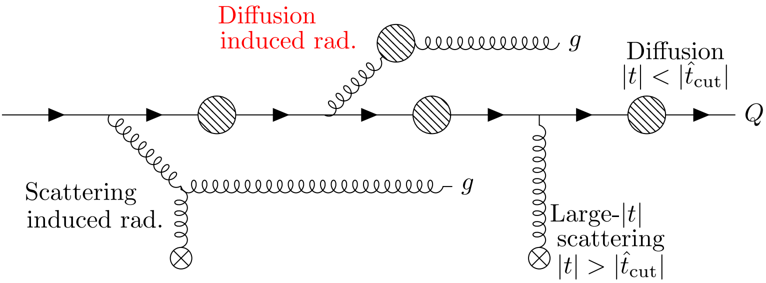
$$df_Q/dt \quad = \quad \mathcal{C}_{>}^{2\leftrightarrow 2} + \partial_p\left(Ap + \partial_p B\right)_{<} f_Q + \mathcal{C}_{>}^{2\to 3}$$



Build the model: start with a light quark

- Take small momenta transfer limit of Gunion Bertsch matrix-element.
- Diffusion induced radiation $d\Gamma/dxdk_\perp^2 \sim \alpha_s \hat{q}_{g,<}/(\pi x k_\perp^4)$

$$df_Q/dt = \mathcal{C}_>^{2\leftrightarrow 2} + \partial_p (Ap + \partial_p B)_< f_Q + \mathcal{C}_>^{2\to 3} + C_<^{1\to 2}$$

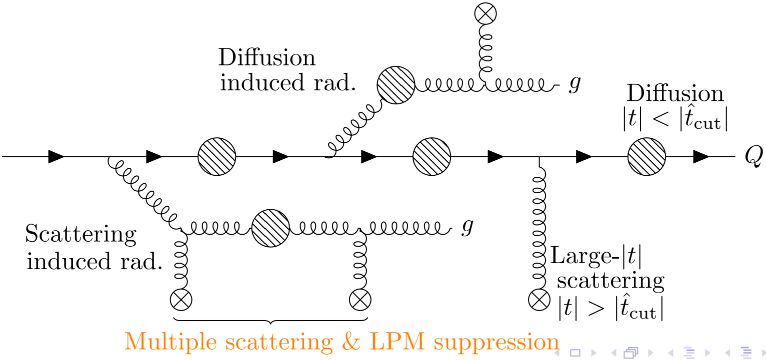


Build the model: start with a light quark

- Allow gluon elastic processes until it is "fully formed" when $\tau_f < \Delta t$
  Zapp et al, JHEP 07 (2011) 118.

$$df_g/dt \quad = \quad \mathcal{C}_{>}^{2\leftrightarrow 2} + \partial_p\left(A_g p + \partial_p B_g\right)_{<} f_g$$

- Gluon formation time $\tau_f \sim 2k/k_\perp^2$ changes as a function of Δt.

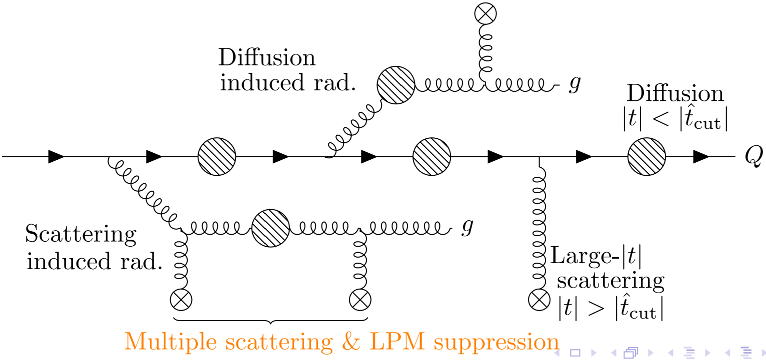


Build the model: start with a light quark

- LPM effect: accept incoherent radiation with probability $p \sim m_D^2/\hat{q}\tau_f$.

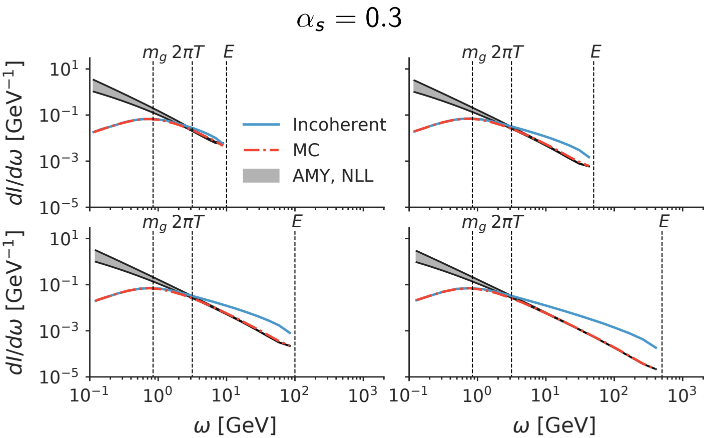
$$df_g/dt = \mathcal{C}_{>}^{2\leftrightarrow 2} + \partial_p \left(A_g p + \partial_p B_g\right)_{<} f_g$$

$$df_Q/dt = \mathcal{C}_{>}^{2\leftrightarrow 2} + \partial_p \left(Ap + \partial_p B\right)_{<} f_Q \quad \underbrace{+\mathcal{C}_{>}^{2\leftrightarrow 3} + C_{<}^{1\leftrightarrow 2}}_{\text{Accept with } p \sim m_D^2/\hat{q}\tau_f}$$



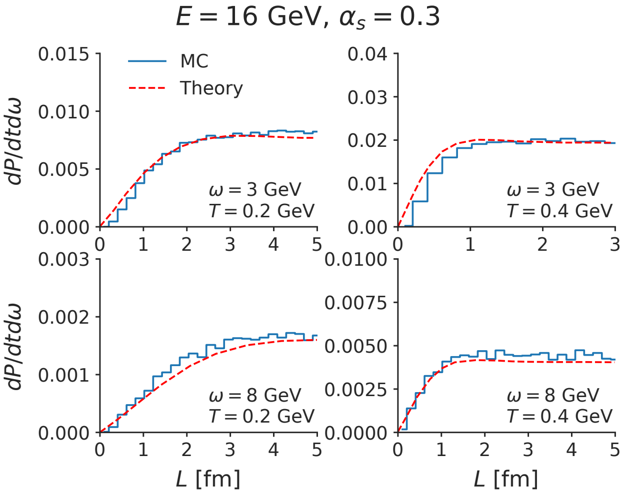
Validate the LPM treatment: infinite medium limit

- Theoretical spectra $dI/d\omega$ from AMY, NLL Arnold and Dogan, PRD 78 065008.
- $\omega < 2\pi T$, goes back to incoherent simulation (blue lines)
- $\omega > 2\pi T$, agree with theoretical results within $\pm 15\%$



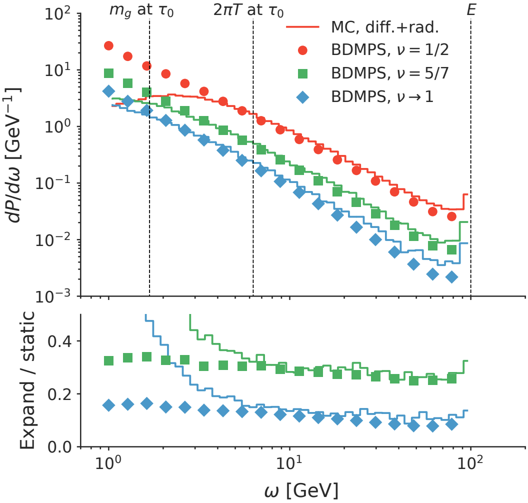
Validate the LPM treatment: finite medium

- Path-length (L) dependent $dI/d\omega$ Caron-Huot and Gale, PRC 82 064902.
- Achieve similar level of accuracy as the previous case.



Validate the LPM treatment: expanding medium

- Spectra in an expanding medium Baier et al, PRC 58 1706.
- $(T/T_0)^3 = (\tau_0/\tau)^{2-1/\nu}$. Static: $\nu = 1/2$. Bjorken: $\nu = 1$.



Running coupling and dead-cone effect

Running coupling constant

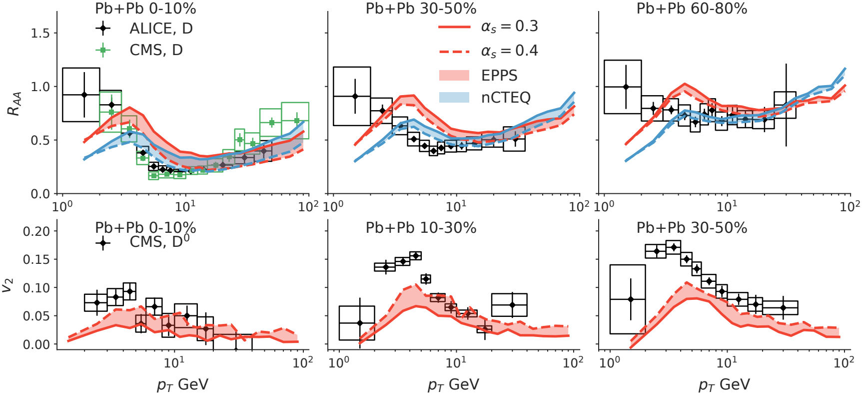
- $\alpha_s^{\mathrm{el}} = \alpha_s(Q^2 = \hat{t})$, $\alpha_s^{\mathrm{rad}} = \alpha_s(Q^2 = k_\perp^2(\Delta t))$.
- The running is cut-off at a medium scale $\mu \sim T$, $\alpha_s = \alpha_s(\max\{Q, \mu\})$

Mass (Dead-cone) effect

- Accept gluon according to $\left(\frac{\theta^2}{\theta^2+\theta_D^2}\right)^n$, $\theta_D = M/E$.
- $\theta = k_\perp/\omega$ evolves with Δt due to gluon reinteraction.

Benchmark result:

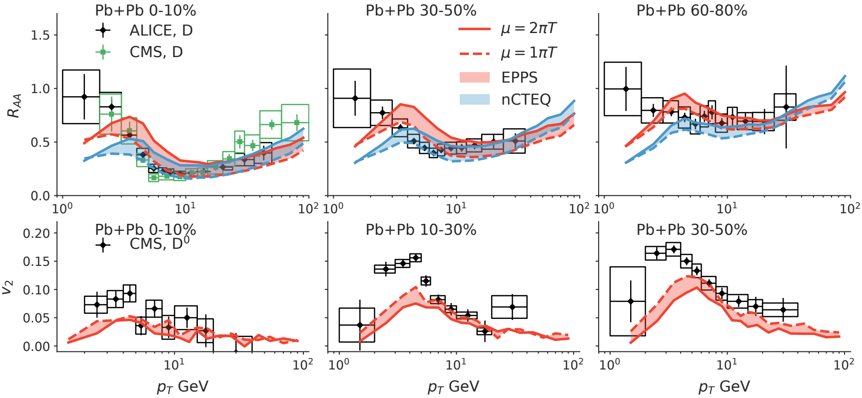
- Fixed coupling calculation $\alpha_s = 0.3, 0.4$; $|\hat{t}_{\rm cut}| = m_D^2$.
- Reasonable description above $p_T = 10$ GeV with large α_s.



ALICE arXiv:1804.09083, CMS PRL 120 202301, PLB 2018 05 074.

Benchmark result:

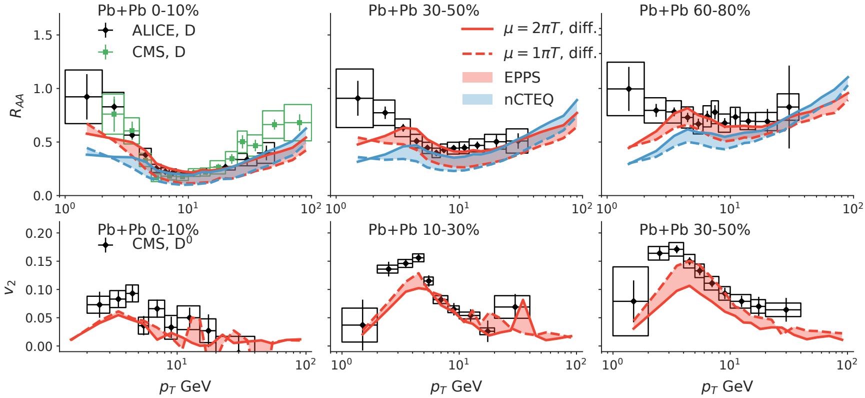
- **Running coupling** $\alpha_s(\max\{Q,\mu\})$, $\pi T < \mu < 2\pi T$, $|\hat{t}_{\rm cut}| = m_D^2$.
- Shape of $R_{\rm AA}$ and v_2 slightly improved.



ALICE arXiv:1804.09083, CMS PRL 120 202301, PLB 2018 05 074.

Benchmark result:

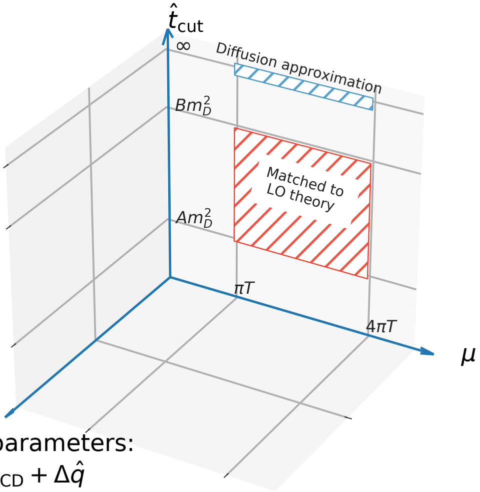
- $|\hat{t}_{\rm cut}| \to \infty$, approximate all interactions by diffusion+radiation.
- Intermediate p_T range suppressed more compared to high p_T.



$$\frac{\hat{q}_g(E,T)}{\alpha_s(\mu) C_A T m_D^2} = \ln\left[\frac{\mu^2}{\Lambda^2}\left(1+\frac{\mu^2}{m_D^2}\right)\right] - \frac{\ln^2\left(\mu^2/\Lambda^2\right)}{\ln\left(6ET/\Lambda^2\right)}$$

ALICE arXiv:1804.09083, CMS PRL 120 202301, PLB 2018 05 074.

Application to future Bayesian analysis

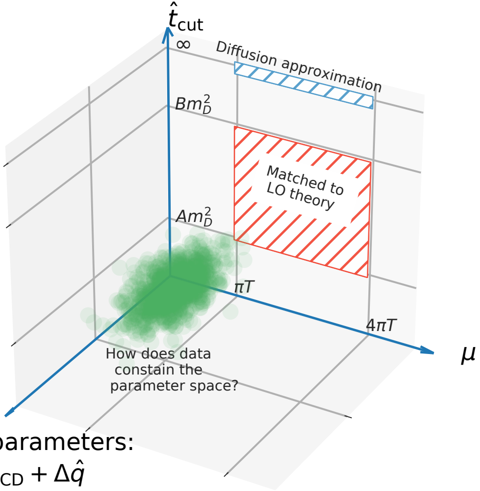


More parameters:
$\hat{q}_{\rm LO,\,pQCD} + \Delta\hat{q}$

$\Delta\hat{q}$ may be

1. Higher order.
2. Non-perturbative.
3. Parametric.

Application to future Bayesian analysis



More parameters:
$\hat{q}_{\text{LO, pQCD}} + \Delta\hat{q}$

$\Delta\hat{q}$ may be

1. Higher order.
2. Non-perturbative.
3. Parametric.

Summary

The development of the Lido model

- Small-$|t|$ processes are absorbed into a diffusion equation.
- Large-$|t|$ processes are solved by a rate equation.

Improving the LPM implementation

- Gluon reinteraction is included.
- Validate in infinite/ finite, static/ expanding medium.

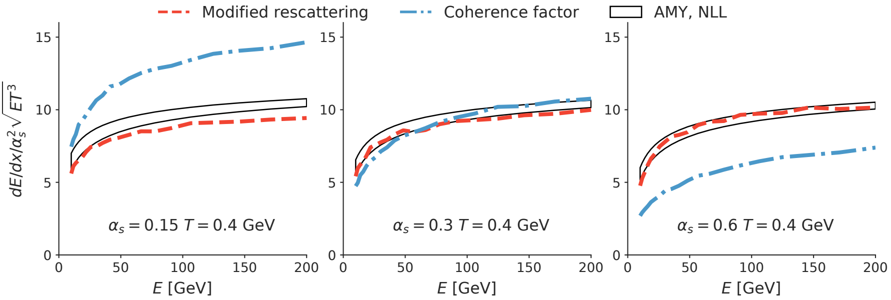
Future plan

- Perform a Bayesian parameter extraction of $\hat{q}$.
- Couple to quarkonium transport (Yao, Wed Session 3, 09:40).
- Integrate the model into the JetScape framework.

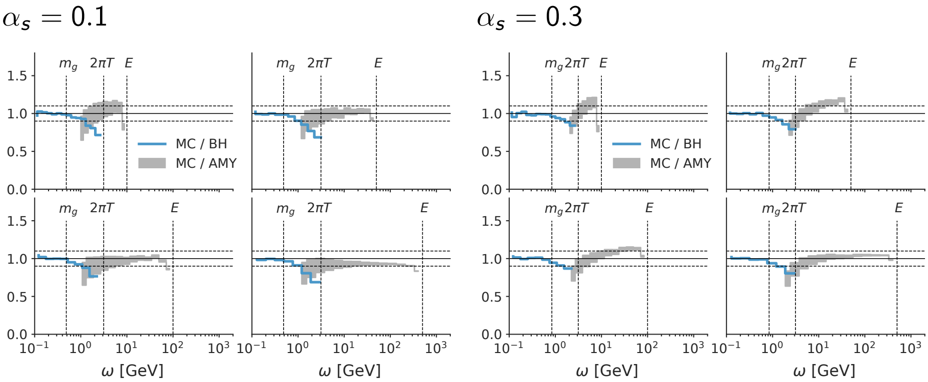
Back-up: compare to the old approach

In our <u>old</u> approach, LPM effect is introduced as a coherence factor in the $2 \to 3$ matrix-element, but exclude multiple scatterings.

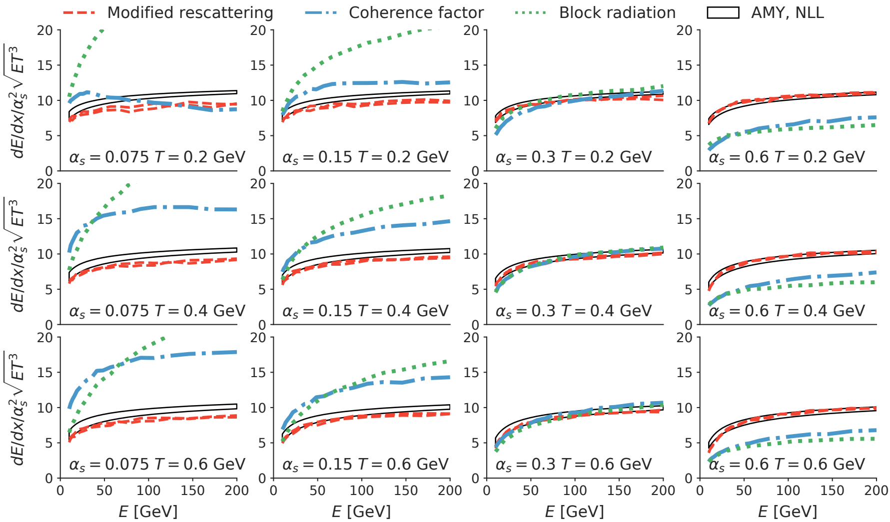
$$\int \frac{d\sigma_{23}}{d\hat{t}dk^3} d\hat{t}\frac{dk^3}{2k} \to \int \frac{d\sigma_{23}}{d\hat{t}dk^3} 2\left[1-\cos\left(\frac{\Delta t}{\tau_f}\right)\right] d\hat{t}\frac{dk^3}{2k}, \tau_f \sim \frac{2k}{k_\perp^2}$$



Back-up: detailed comparison



Back-up: energy loss in an infinite medium



Back-up: mass dependence