Hard Scatterings and Stochastic Reformulation of Parton Energy Loss

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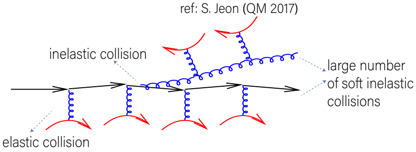
Weakly-Coupled Effective Kinetic Approach

- Perturbative parton-medium interaction
- HTL resummed diagrams
- Dynamics of quasiparticles are described by transport equations
- Energy gain and loss are naturally included

Leading-order realizations (e.g. MARTINI):

$$(\partial_t + \boldsymbol{v} \cdot \nabla_{\boldsymbol{x}}) f^a(\boldsymbol{p}, \boldsymbol{x}, t) = -\mathcal{C}_a^{2\leftrightarrow 2}[f] - \mathcal{C}_a^{1\leftrightarrow 2}[f]$$

Energy Loss Reformulation



Interactions with the medium:

- Large number of soft interactions
- Rare hard scatterings

Parton energy loss reformulated as **hard interactions + diffusion process**[1]

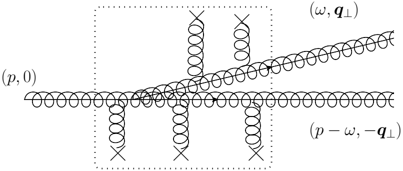
Benefits of Reformulated Transport Model

- Systematically factorized soft and hard parton-plasma interactions
- Efficient and flexible stochastic description of soft interactions
- Simplified next-to-leading order calculation

[1] J. Ghiglieri, G. Moore, D. Teaney, JHEP03 (2016) 095

Hard Interactions - Large-ω **Inelastic** Interactions

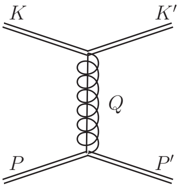
Multiple soft interactions with the plasma induce the radiation of a parton of energy ω.



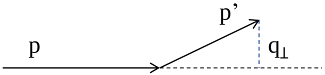
Large-ω interactions

- $\omega > \mu_\omega$, $\mu_\omega \lesssim T$
- Described with emission rates (obtained from AMY integral equations)
- Leading order calculation

Hard Interactions - Large-$q_\perp$ **Elastic** Interactions



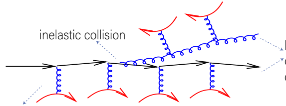
The transverse momentum transfer in elastic interaction is denoted as $q_\perp$.



Large-$q_\perp$ interactions

- $q_\perp > \mu_{q_\perp}$, $T \gg \mu_{q_\perp} \gg gT$
- Calculated using leading order pQCD matrix elements
- Vacuum matrix elements: plasma effect only significant at small $q_\perp$
- Keep zero-th order term of T/p

Identity Preserving Soft Interactions - Diffusion



Number and identity preserving soft collisions are described stochastically with drag and diffusion.

$$\mathcal{C}^{diff}[f] = -\frac{\partial}{\partial p^i}\left[\eta_D(p)p^i f(\boldsymbol{p})\right] - \frac{1}{2}\frac{\partial^2}{\partial p^i \partial p^j}\left[\left(\hat{p}^i\hat{p}^j\hat{q}_L(p) + \frac{1}{2}\left(\delta^{ij} - \hat{p}^i\hat{p}^j\right)\hat{q}(p)\right)f(\boldsymbol{p})\right]$$

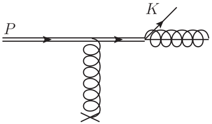
- Both elastic and inelastic soft interactions included
- Treated with Langevin model
- Coupling constant order: $\hat{q}$, $\hat{q}_L^{elas} \sim \mathcal{O}(g^2)$, $\hat{q}_L^{inel} \sim \mathcal{O}(g^4)$
- T/p order: $\hat{q}$, $\hat{q}_L^{elas}$, $\hat{q}_L^{inel} \sim \mathcal{O}(1)$, $\eta_D \sim \mathcal{O}(T/p)$

Identity Non-preserving Soft Interactions - Conversion

Conversion processes: change identity by conversion rate

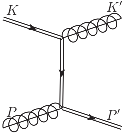
Inelastic conversion processes

$q \leftrightarrow gq$, $g \leftrightarrow q\bar{q}$
Conversion rate $\sim \mathcal{O}(g^4)$
Suppressed by T/p



Elastic conversion processes

Soft fermion exchange with the medium
Conversion rate $\sim \mathcal{O}(g^2)$
Suppressed by T/p



Summary of the Treatments to Different Processes

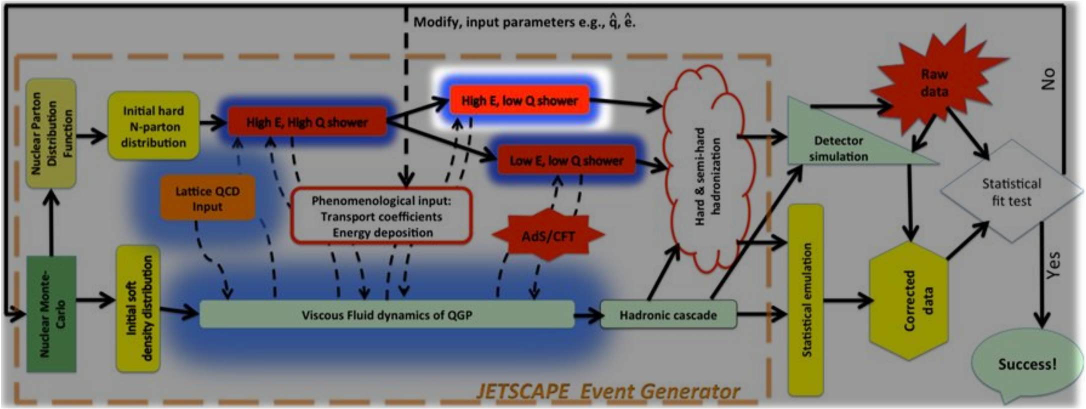
reformulated interactions		identity preserving	identity non-preserving
soft interactions	small-$q_\perp$ elastic	diffusion processes	conversion rate
	small-ω inelastic		
hard interactions	large-$q_\perp$ elastic	vacuum matrix elements	
	large-ω inelastic	AMY integral equations	

$$\mathcal{C}^{2\leftrightarrow 2} + \mathcal{C}^{1\leftrightarrow 2} = \mathcal{C}^{large-q_\perp}(\mu_{q_\perp}) + \mathcal{C}^{large-\omega}(\mu_\omega) + \mathcal{C}_a^{diff}(\mu_{q_\perp}, \mu_\omega) + \mathcal{C}_a^{conv}(\mu_{q_\perp}, \mu_\omega)$$

If the division of the energy loss model is valid, energy loss should be **independent on the cutoffs** (in a reasonable range).

Practical Implementation

Reformulated energy loss model is **added as a separate external module** in a modified version of the public JETSCAPE code.



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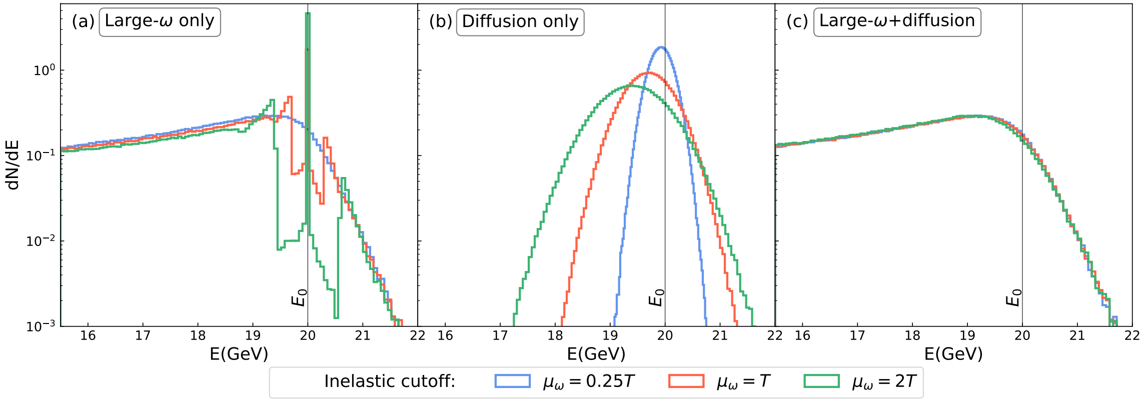
[2] JETSCAPE Collaboration

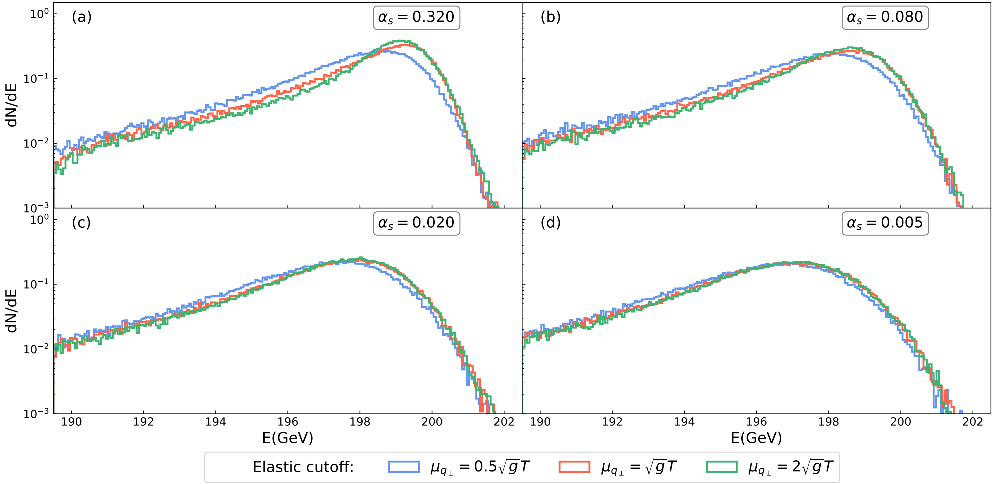
Inelastic Cutoff Independence - Inelastic Interactions Only

20 GeV gluon, $\alpha_s = 0.3$, T = 300 MeV, infinite medium, $\tau = 1\text{fm/c}$

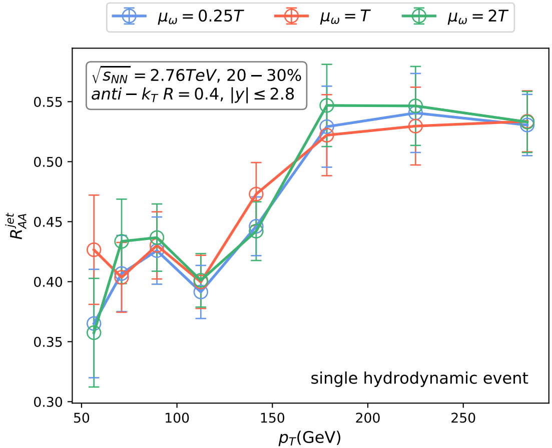


Elastic Cutoff Independence - Elastic Interactions Only

200 GeV gluon, T = 300 MeV, infinite medium, $\alpha_s^2\tau = 0.3^2\text{fm/c}$



Cutoff Independence of Observables - R_{AA}



Nuclear modification factor[3]:

$$R_{AA}^{jet} = \frac{\frac{d^2 N_{jet}}{dp_T dy}\Big|_{AA}}{\langle N_{bin} \rangle \frac{d^2 N_{jet}}{dp_T dy}\Big|_{pp}}$$

- Both elastic and inelastic interactions are included
- **Realistic** hydrodynamic event is used, $\alpha_s = 0.3$
- Different cutoff results are consistent within the statistical errorbars

[3] Assumes jets are produced at the center of the medium.

Conclusion and Outlook

Energy loss model is reformulated as hard collisions+diffusion.

- A systematic factorization in the weakly-coupled limit
- This factorization still holds in phenomenological regime
- The reformulated model is expected to be efficient and flexible.

Future Plan

- Data driven constraints can be applied on drag and diffusion coefficients.
- The reformulated approach can be extended to the next-to-leading order.

Back Up - Drag and Diffusion Coefficients

$$\hat{q} = \frac{g^2 C_R T m_D^2}{4\pi} \ln(1 + (\frac{\mu_{q_\perp}}{m_D})^2)$$

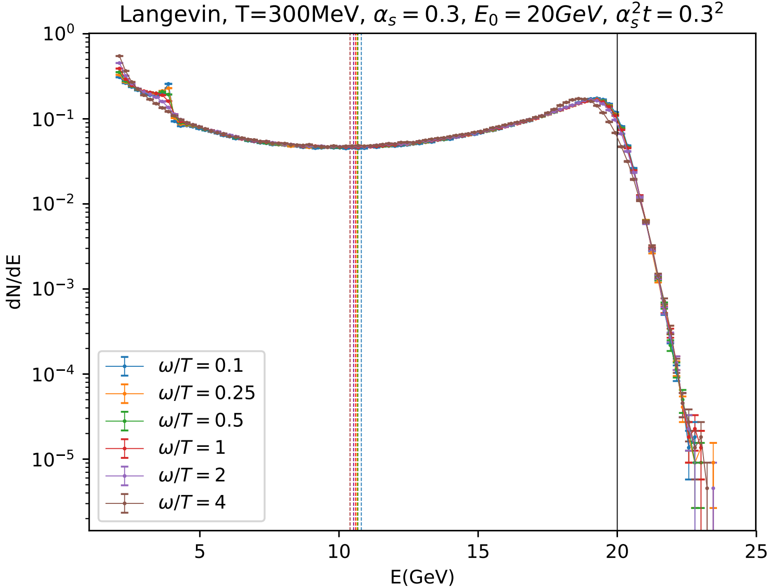
$$\hat{q}_L^{elas} = \frac{g^2 C_R T M_\infty^2}{4\pi} \ln(1 + (\frac{\mu_{\tilde{q}_\perp}}{M_\infty})^2)$$

$$\hat{q}_L^{inel} = \frac{(2-\ln 2) g^4 C_R C_A T^2 \mu_\omega}{4\pi^3}$$

$$\eta_D(p) = \frac{\hat{q}_L}{2Tp} + \frac{1}{2p^2}(\hat{q} - 2\hat{q}_L)$$

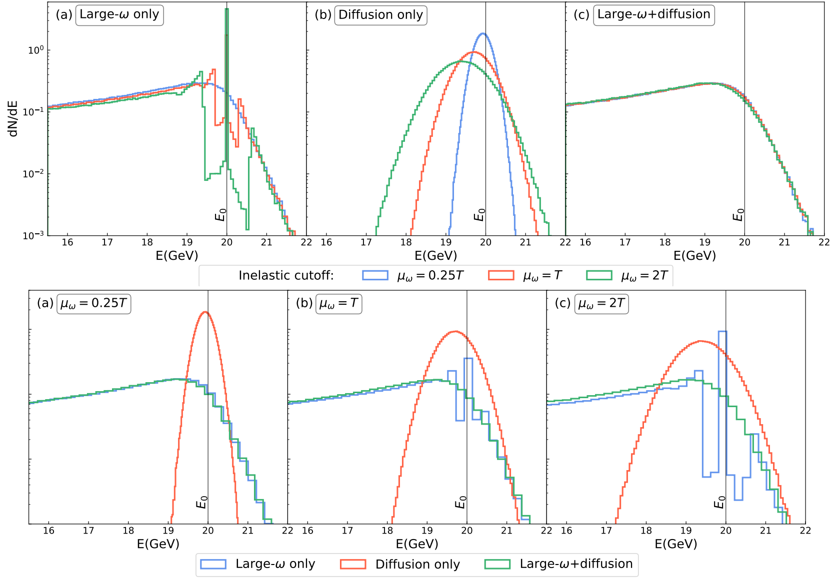
Back Up - Inelastic Cutoff Independence - Inelastic Interactions Only

pure gluon
$\alpha_s = 0.3$
T $=$ 300 MeV
infinite medium
τ $=$ 1fm/c

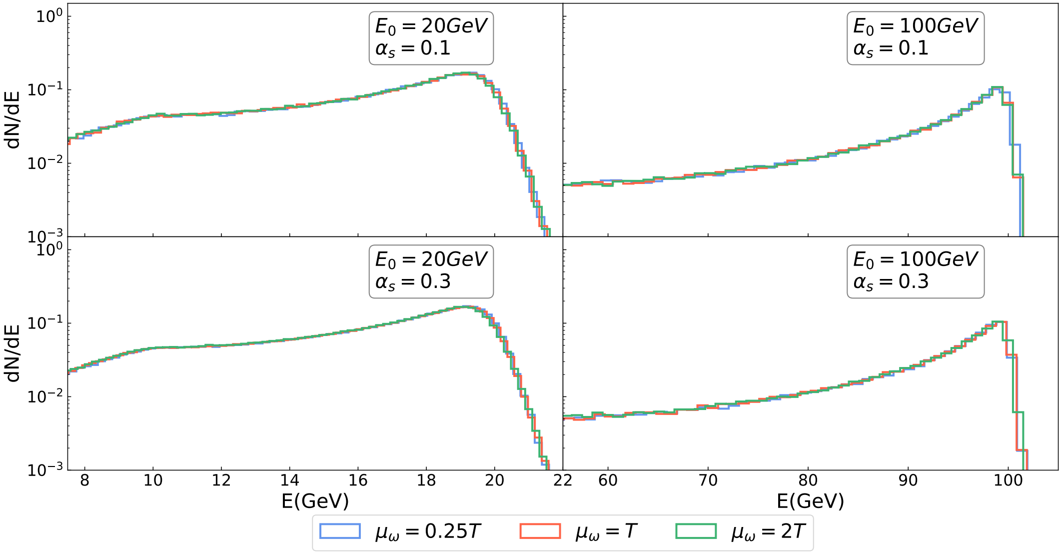


Back Up - Inelastic Cutoff Independence - Inelastic Interactions Only

20 GeV gluon
$\alpha_s = 0.3$
T $=$ 300 MeV
infinite medium
$\tau = 1\text{fm}/\text{c}$

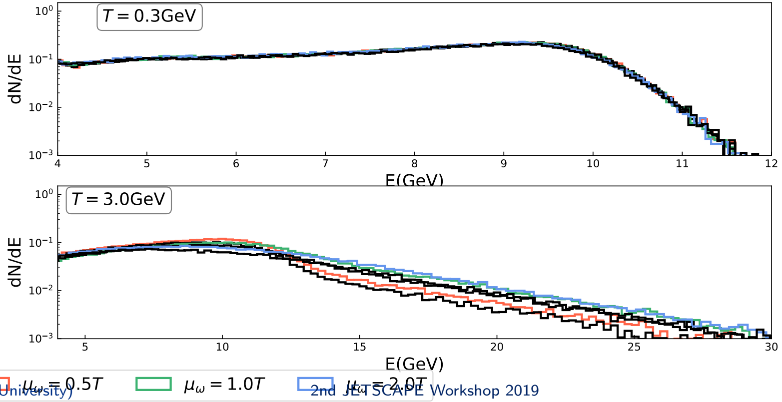


Back Up - Inelastic Cutoff Independence - Inelastic Interactions Only

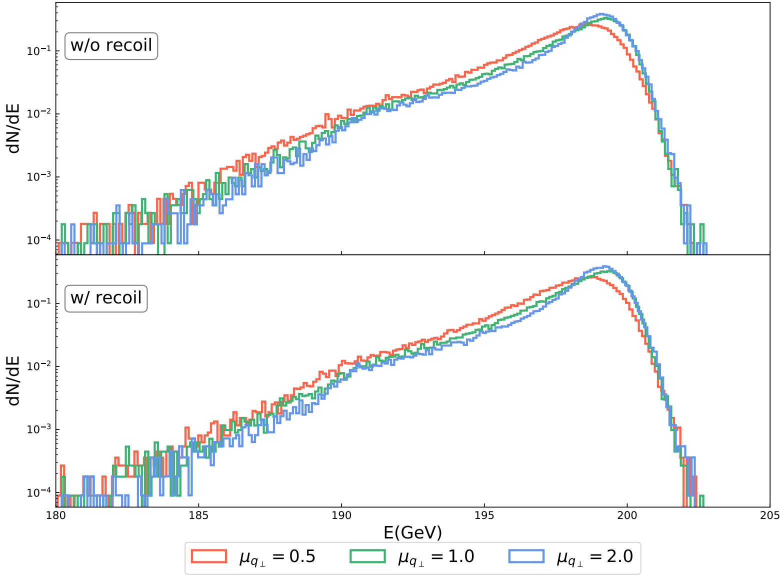


Back Up - Effects of Inelastic Conversion Processes - Inelastic Interactions Only

- Gluon, initial energy $E_0 = 10 GeV$, infinite medium, $\tau = 1$fm/c
- T/p: small in the upper plot and large in the lower plot
- Black curves: w/ inelstic conversion
- Colorful curves: w/o ineastic conversion

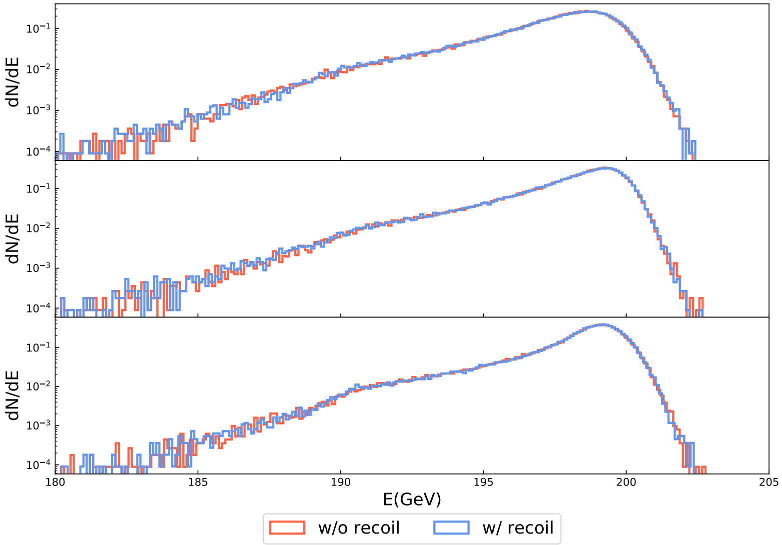


Back Up - Effects of Recoil Particles - Elastic Interactions Only



200 GeV gluon
$\alpha_s = 0.3$
T = 300 MeV
infinite medium
τ = 1fm/c

Back Up - Effects of Recoil Particles - Elastic Interactions Only



200 GeV gluon
$\alpha_s = 0.3$
$T = 300$ MeV
infinite medium
$\tau = 1\text{fm}/c$

Back Up - Test with Realistic Hydrodynamic Medium

Realistic hydrodynamic event is used, $\alpha_s = 0.3$.

Both elastic and inelastic interactions are allowed