Inconsistencies in Radiative Energy Loss

Coleridge Faraday

Supervised by A/Prof. W. A. Horowitz

Based on CF, A. Grindrod, and W. A. Horowitz *EPJ C* **83**, 1060 (2023)

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Energy loss in Small Systems: Theory Challenges

Theoretical energy loss models conventionally assume

- Thermalized medium
- No pre-thermalization time effects
- Many scatterings (in BDMPS-Z and related models)
- Central limit theorem in elastic energy loss
- Explicit dropping of $\mathcal{O}(e^{-L\mu})$ terms (in all models based on Gyulassy-Wang potential)

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- Explicit dropping of $\mathcal{O}(e^{-L\mu})$ terms (in all models based on Gyulassy-Wang potential)
  - These terms included in new **small system correction** to radiative energy loss
    Kolbé & Horowitz, PRC 100, 024913 (2019)

Short Path Length (SPL) Corr. to Rad. E-loss

- SPL corr. from missed poles $\sim e^{-\mu L}$ Kolbé & Horowitz, PRC 100, 024913 (2019)

$$
\begin{aligned}
x\frac{\mathrm{d}N}{\mathrm{d}x} &= \frac{C_R\alpha_s L}{\pi\lambda_g}\int\frac{\mathrm{d}^2\mathbf{q}_1}{\pi}\frac{\mu^2}{\left(\mu^2+\mathbf{q}_1^2\right)^2}\int\frac{\mathrm{d}^2\mathbf{k}}{\pi}\int\mathrm{d}\Delta z\,\bar{\rho}(\Delta z) \\
&\times\left[-\frac{2\left\{1-\cos\left[\left(\omega_1+\tilde{\omega}_m\right)\Delta z\right]\right\}}{\left(\mathbf{k}-\mathbf{q}_1\right)^2+\chi}\left[\frac{\left(\mathbf{k}-\mathbf{q}_1\right)\cdot\mathbf{k}}{\mathbf{k}^2+\chi}-\frac{\left(\mathbf{k}-\mathbf{q}_1\right)^2}{\left(\mathbf{k}-\mathbf{q}_1\right)^2+\chi}\right]\right. \\
&+\frac{1}{2}e^{-\mu_1\Delta z}\left(\left(\frac{\mathbf{k}}{\mathbf{k}^2+\chi}\right)^2\left(1-\frac{2C_R}{C_A}\right)\left\{1-\cos\left[\left(\omega_0+\tilde{\omega}_m\right)\Delta z\right]\right\}\right. \\
&\left.\left.+\frac{\mathbf{k}\cdot\left(\mathbf{k}-\mathbf{q}_1\right)}{\left(\mathbf{k}^2+\chi\right)\left(\left(\mathbf{k}-\mathbf{q}_1\right)^2+\chi\right)}\left\{\cos\left[\left(\omega_0+\tilde{\omega}_m\right)\Delta z\right]-\cos\left[\left(\omega_0-\omega_1\right)\Delta z\right]\right\}\right)\right] \qquad (1)
\end{aligned}
$$

- Breaking of **color triviality**
  $\Rightarrow$ increased corr. for gluons
- Possibility of **energy gain**
- Nonzero correction for **all path lengths**

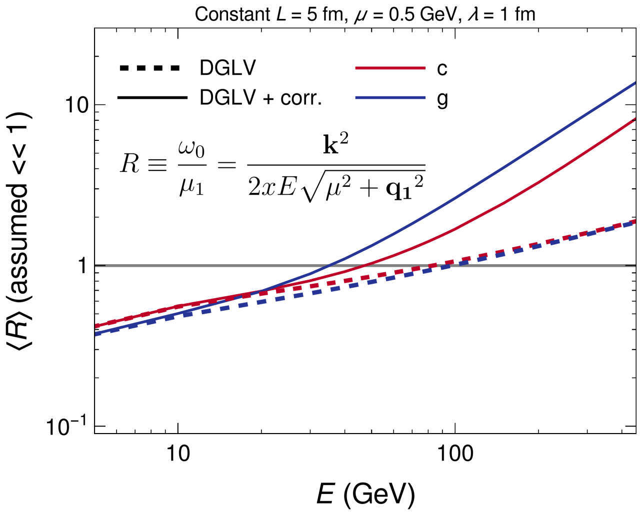
Large Pathlength Assumption

figures/diagram_100.png

Assumptions in GLV

- The *large pathlength assumption*, that $L \gg \mu^{-1}$.
- The *well separated scattering centers assumption*, that $\lambda_g \gg \mu^{-1}$.
- The *eikonal assumption*, that $P^+ = E^+ \simeq 2E$ is the largest scale in the problem.
- The *soft radiation assumption*, that $x \ll 1$.
- The *collinear radiation assumption*, that $k^+ \gg k^-$.
- The *large formation time assumption*, that $\mathbf{k}^2/xE^+ \ll \mu$ and $\left(\mathbf{k} - \mathbf{q}_1\right)^2/xE^+ \ll \sqrt{\mu^2 + \mathbf{q}_1^2}$.

Consistency of Large Formation Time Assumption



Disaster!

$$\langle R \rangle \equiv \frac{\int \mathrm{d}\{X_i\}\ R(\{X_i\}) \left|\frac{\mathrm{d}E}{\mathrm{d}\{X_i\}}\right|}{\int \mathrm{d}\{X_i\} \left|\frac{\mathrm{d}E}{\mathrm{d}\{X_i\}}\right|}$$

- Large Formation Time assumption **not** valid at high-p_T
- Plays a crucial role in derivation of (most) energy loss models

Energy-weighted expectation of **large formation time** assumption

A Band-Aid Fix

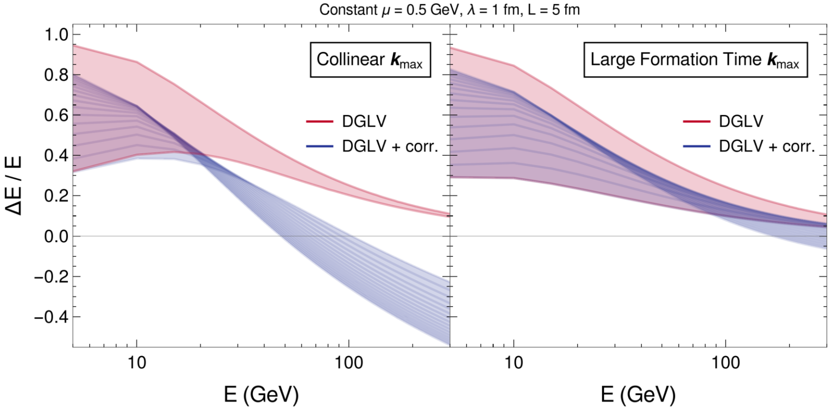


Figure 1: Comparison of collinear $k_{\max}$ and collinear + large formation time $k_{\max}$ (CF, Horowitz 2309.06246)

Collinear: $|\mathbf{k}| < 2xE(1-x)$

Collinear + LFT:

$$|\mathbf{k}| < \operatorname{Min}\left[2xE(1-x), \sqrt{2xE\sqrt{\mu^2+\mathbf{q}^2}}\right]$$

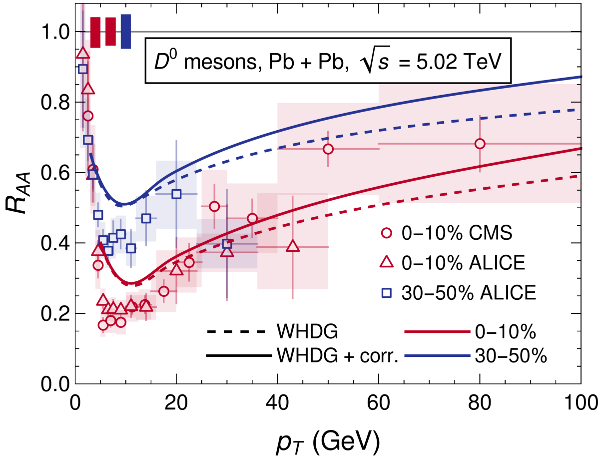
- Dramatically reduces SPL corr.
- Results in increased uncertainty

Future work

- Rederivation of DGLV which removes the LFT assumption
- Theoretical control over HTL vs vacuum propagators
- Implementation of LFT + collinear kinematic bound & resulting uncertainty bands
    - Sensitivity of various observables to this uncertainty
- Simultaneous description of R_{AA} in small and large collision systems (one parameter fit in α_s)

Bonus slides!

Heavy flavour A+A



Pb + Pb suppression

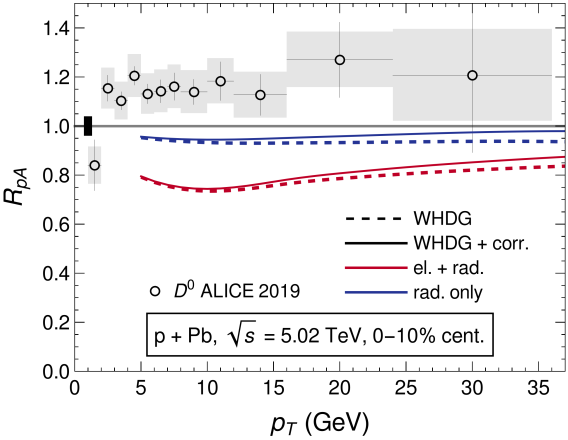
CF, Grindrod, Horowitz 2305.13182

Data: CMS 1708.04962 + ALICE 1804.09083

✓ Small system correction should be small in $A + A$

Heavy flavour p+A

- Is small system correction important in $p + A$?
- Large predicted suppression?
  - $\rightarrow$ Only $\mathcal{O}(1)$ scatter in $p + A$
  - $\rightarrow$ Central Limit Theorem (CLT) in elastic E-loss breakdown?



p + Pb suppression

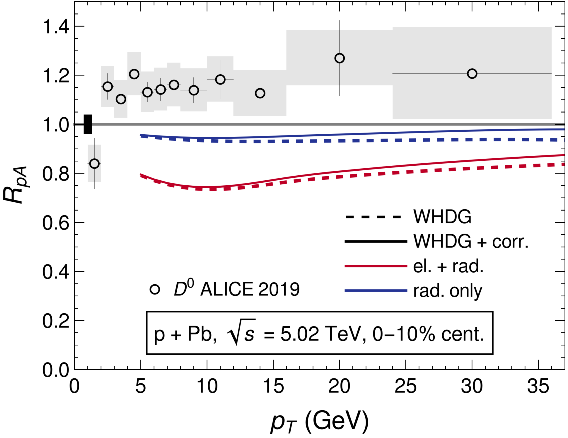
CF, Grindrod, Horowitz 2305.13182

Data: ALICE 1906.03425

Heavy flavour p+A

- Is small system correction important in $p + A$?
- Large predicted suppression?
  - → Only $\mathcal{O}(1)$ scatter in $p + A$
  - → Central Limit Theorem (CLT) in elastic E-loss breakdown?

→ Implement different, **Poissonian** HTL elastic E-loss to make realistic small system predictions



p + Pb suppression

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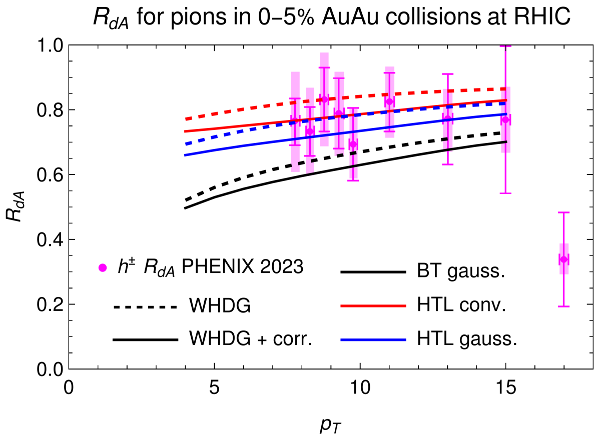
Data: ALICE 1906.03425

Poissonian elastic E-loss

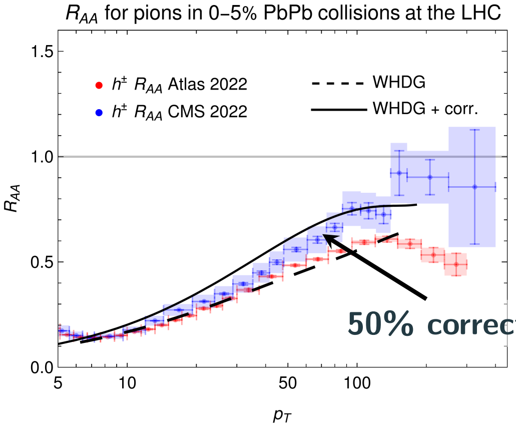


dAu suppression (preliminary)

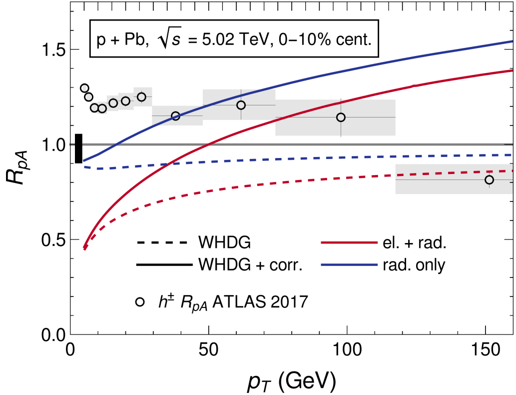
CF, Horowitz, in preparation
Data: PHENIX 2303.12899

- ✓ Implemented Poissonian HTL elastic energy loss (Wicks PhD Thesis, 2008)
- Gaussian vs Poisson has little impact
- Elastic energy loss still dominant in small systems
- Large uncertainty in vacuum vs HTL propagators

Light flavour predictions



50% correction!



- Huge "correction" at high-p_T!
- Potential explanation for leveling of R_{AA} at high-p_T?

- Large suppression at low–mid p_T

* pPb curves will likely change at high-p_T due to bug in hadronization

How physical are these results?

Is anything breaking?

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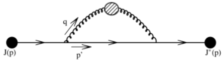
Is anything breaking?

$\longrightarrow$ **Investigate <u>all assumptions</u> in the model**

The Energy Loss Model



Elastic E-loss
$P_{\text{el.}}(\epsilon) \sim$ Gaussian

Braaten & Thoma PRD 44 R2625
$\frac{\Delta E}{E} \sim \alpha_s^2 T^2 L \log ET/m_g$

Collision geometry

Static "bricks" with L_{eff} & T_{eff}

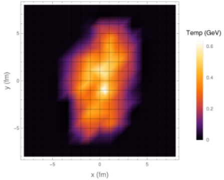
Total E-loss
$P_{\text{tot}}(\epsilon) = P_{\text{rad}}(\epsilon) \otimes P_{\text{el.}}(\epsilon)$

Partonic R_{AA} / R_{pA}
$\simeq \int \mathrm{d}x (1-x)^{n(p_T)} P_{\text{tot}}(x)$

Leading hadron R_{AA} / R_{pA}

Radiative E-loss
$P_{\text{rad.}}(\epsilon) \sim$ Poissonian

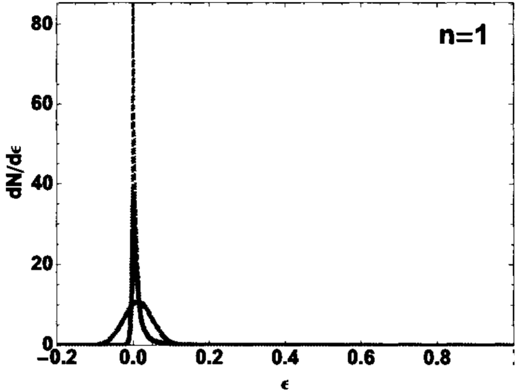
IP-Glasma

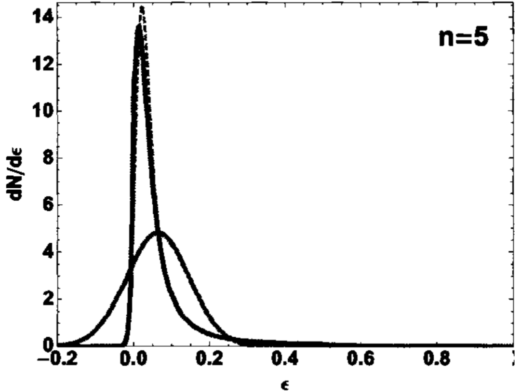


Debye screened scatt. centers

DGLV nucl-th/0310076

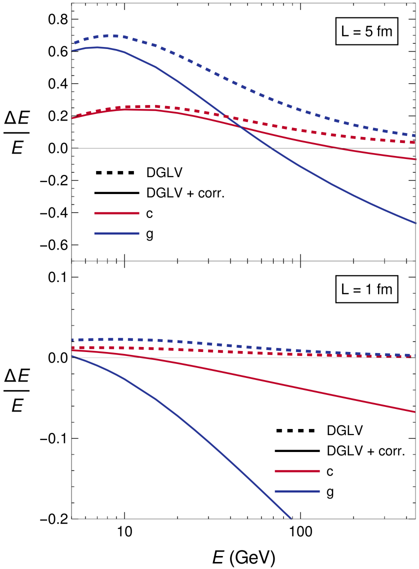
Elastic E-loss: Central limit theorem





Fractional collisional elastic energy loss distribution where ε is the momentum fraction lost.
(Wicks 2008, PhD thesis)

Implementation of SPL corr.



Asymptotically:

$$\frac{\Delta E_{\text{DGLV}}}{E} \sim C_R \, L^2 \, \frac{\log E/\mu}{E}. \tag{2}$$

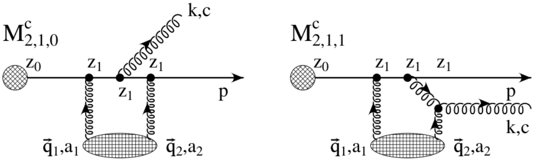
$$\frac{\Delta E_{\text{SPL}}}{E} \sim -C_R \left(\frac{C_R}{C_A}\right) L \, \log(EL) \tag{3}$$

We see that the SPL correction is

- Nonzero even for $L = 5\ \text{fm}$
- Exceedingly large for gluons
- Dominates at high E
- Leads to energy gain at high E

Large Formation Time Assumption: Who cares?

- DGLV **neglects entire class of diagrams** based on large formation time assumption
  - → and used heavily in simplification of matrix elements



$$\sim \frac{\mathbf{k}_\perp^2+m_g^2+x^2M^2}{2\omega}\frac{1}{\mu_1} \to 0$$

- SPL corr. **neglects 16/18 new corr. terms** based based on large formation time assumption
- Currently **impossible** to estimate the magnitude of corrections resulting from relaxing the large formation time assumption
- Calculation is **completely uncontrolled for** $p_T \gtrsim 30\ \mathrm{GeV}$