Fully coherent energy loss effects on light hadron production in pA collisions

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Hard Probes 2020

Austin, TX, USA and everywhere – June 2020
Energy loss in nuclear matter revisited: **fully coherent regime** (FCEL)

- Predicted from first principles
- Leads to $\Delta E \propto (Q_s/Q) \times E$
- Important consequences for the phenomenology of pA collisions
- FCEL affects the production of **all hadron species** in pA collisions
  - quarkonia
  - light hadrons (**this talk**)
  - open-heavy flavour hadrons
Outline

- **Fully Coherent Energy Loss (FCEL) regime**
  - Parametric dependence
  - Phenomenology of $J/\psi$ suppression in pA collisions

- **FCEL effects on light hadron production**
  - Setup and main assumptions
  - Predictions at the LHC

- **Discussion**

References

- FA, S. Peigné, 2003.01987
- FA, F. Cougoulic, S. Peigné, 2003.06337
Radiative energy loss regimes (1/2) : LPM

LPM regime, small formation time $\lambda \ll t_f \lesssim L$

\[ \Delta E_{\text{LPM}} \propto \alpha_s \hat{q} L^2 \]

- Best probed in:
  - Hadron production in nuclear semi-inclusive DIS
  - Drell-Yan in pA collisions at low energy
  - Hadron quenching in AA collisions

- Should be negligible in pA at the LHC
  - Fractional energy loss $\Delta E_{\text{LPM}}/E \sim 1/E \ll 1$
  - Could play a role in fixed target experiments

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Interference between initial and final state, large formation time $t_f \gg L$

$$\Delta E_{\text{FCEL}} \propto \alpha_s \left( \frac{\sqrt{qL}}{M_\perp} \right) E \quad (\gg \Delta E_{\text{LPM}})$$

FA Peigné Sami, 1006.0818, FA Peigné, 1204.4609, 1212.0434
Armesto et al. 1207.0984
FA Kolevatov Peigné, 1402.1671, Peigné Kolevatov 1405.4241
Liou Mueller 1402.1647, Munier Peigné Petreska 1603.01028
Interference between initial and final state, large formation time $t_f \gg L$

$$\Delta E_{\text{FCEL}} \propto \alpha_s \frac{\sqrt{qL}}{M_\perp} E \quad (\gg \Delta E_{\text{LPM}})$$

- Important at all collision energies, especially at large rapidity
- Needs color in both initial & final state
  - no effect on W/Z nor Drell-Yan, no effect in DIS
- $M_\perp^{-1}$ dependence
  - weaker effects on $\Upsilon$, let alone on high-$p_\perp$ jets
- Hadron production in pA collisions
  - applied to quarkonia
  - light hadrons currently investigated
- Moderate effects at $y = 0$, larger above $y \gtrsim 2 - 3$
- Smaller suppression expected in the $\Upsilon$ channel
- Excellent agreement with collider data (PHENIX, ALICE, LHCb)
- ... and fixed-target experiments (NA3, E866, HERA-B)
From quarkonium to light hadron production

Which differences from quarkonium to single light hadron production?

Partons c,d produced with opposite and large transverse momenta

\[ K_1 \approx K_2 \gg \sqrt{qL} \]

energy fractions \( \xi \) and \( 1 - \xi \)

Final state made of two partons at leading order

- Use medium-induced gluon spectrum associated to \( 2 \rightarrow 2 \) scattering
- Final state in different color representations \( R \) with probability \( \rho_R(\xi) \)

Hadronization: \( z \neq 1 \)
Energy loss model for a specific dijet configuration

- Consider a dijet with given color state $R$ and momentum fraction $\xi$

\[
\frac{1}{A} \frac{d\sigma_{pA}^R(y)}{dy \, d\xi} = \int_0^{x_{\text{max}}} dx \left\{ \frac{\hat{P}_R(x)}{1 + x} \frac{d\sigma_{pp}^R(y + \delta, \xi)}{dy \, d\xi} \right\}; \quad \delta \equiv \ln(1 + x)
\]

- Quenching weight $\hat{P}_R$ related to the medium-induced gluon spectrum

\[
\hat{P}_R(\epsilon) \simeq \left. \frac{dI(\epsilon)}{d\epsilon} \right|_R \exp \left\{ - \int_\epsilon^{\infty} d\omega \left. \frac{dI(\omega)}{d\omega} \right|_R \right\}
\]
Induced gluon spectrum for dijet final state

Gluon spectrum $dI/d\omega$ for $ab \to (cd)_R$ hard process

$$\omega \left. \frac{dI}{d\omega} \right|_{ab \to (cd)_R} = (C_a + C_R - C_b) \frac{\alpha_s}{\pi} \ln \left( 1 + \frac{\hat{q} L E^2}{M^2_\xi \omega^2} \right) - \text{pp}$$

- Derived in the GLV opacity expansion and saturation formalism
- $M_\xi = K_\perp / \sqrt{\xi(1 - \xi)}$: dijet invariant mass
- Valid in the pointlike dijet approximation
  - gluon radiation does not probe the dijet
    $$\lambda_\perp \sim \frac{1}{k_\perp} \gg v_\perp \times t_f \to \frac{\omega}{E} K_\perp \ll \sqrt{qL}$$
  - condition equivalent to the leading logarithmic accuracy
    $$\ln \left( \frac{\hat{q} L E^2}{K^2_\perp \omega^2} \right) \gg 1$$
Induced gluon spectrum for dijet final state

Gluon spectrum $dI/d\omega$ for $ab \rightarrow (cd)_R$ hard process

$$\omega \frac{dI}{d\omega}igg|_{ab \rightarrow (cd)_R} = (C_a + C_R - C_b) \frac{\alpha_s}{\pi} \left[ \ln \left( 1 + \frac{\hat{q} L E^2}{M^2_\xi \omega^2} \right) - \text{pp} \right]$$

- Derived in the GLV opacity expansion and saturation formalism
- $M_\xi = K_\perp/\sqrt{\xi(1 - \xi)}$: dijet invariant mass
- Valid in the pointlike dijet approximation
- Transport coefficient

$$\hat{q}(x) = 4\pi^2 \alpha_s C_R \frac{N_c^2 - 1}{N_c^2} \rho \chi G(x) = \hat{q}_0 \left( \frac{10^{-2}}{x} \right)^{0.3}; \hat{q}_0 = 0.05–0.09 \text{ GeV}^2/\text{fm}$$

- $\hat{q}_0$ range in agreement with LPM energy loss and nuclear broadening studies, corresponds to $Q_s \simeq 1.3–1.8$ GeV at LHC at mid-rapidity
Color state probabilities ($gg \rightarrow gg$ case)

- Color representations: $R = 1, 8, 27$ ($P_{10} = 0$ for $N_c = 3$) with Casimir
  
  \[ C_1 = 0, \quad C_8 = N_c, \quad C_{27} = 2(N_c + 1) \]

- Probabilities depend solely on $\xi$ and obtained from color algebra

\[
\mathcal{M}_{\text{hard}} \propto \frac{K}{K^2} + \frac{K - q}{(K - q)^2} - \frac{K - \xi q}{(K - \xi q)^2} \\
\propto \left[ \frac{K - q}{(K - q)^2} - \frac{K - \xi q}{(K - \xi q)^2} \right] + \left[ \frac{K}{K^2} - \frac{K - q}{(K - q)^2} \right]
\]
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- Probabilities depend solely on \(\xi\) and obtained from color algebra
From dijet to single hadron production

Needs to sum/integrate

- Recoiling jet: \[ \int_0^1 d\xi \]
- Final-state color probabilities: \( \sum_R \rho_R(\xi) \)
- Fragmentation variable: \( \int_0^1 dz D_i^h(z) \)

\[
\frac{1}{A} \frac{d\sigma_{pA}^h(y)}{dy} = \sum_R \int d\xi \rho_R(\xi) \int_0^{x_{\text{max}}} dx \frac{\hat{P}_R(x)}{1 + x} \frac{d\sigma_{pp}^h(y + \delta, \xi)}{dy d\xi}
\]

Nuclear modification of inclusive hadron production

- Assuming a smooth variation of \( \rho \) and \( R_{pA}^h \) with \( \xi \)

\[
R_{pA}^h(y, p_\perp) \simeq \sum_R \rho_R(\xi) R_{pA}^R(y, p_\perp)
\]

\[
R_{pA}^R(y, p_\perp) = \int_0^{\delta_{\text{max}}} d\delta \hat{P}_R \left( x, \frac{\sqrt{qL} \langle z \rangle}{M_\xi} \right) \frac{d\sigma_{pp}^h(y + \delta, p_\perp)}{dy dp_\perp} \frac{d\sigma_{pp}^h(y, p_\perp)}{dy dp_\perp}
\]
Making predictions

General strategy

- Provide baseline calculations assuming FCEL effects only
  - Other effects e.g. saturation/nPDF or Cronin effect can be added
- Use data instead of perturbative calculations for pp cross sections

\[
\frac{d\sigma^{\psi}_{pp}}{2\pi p_\perp dp_\perp dy} = N \times \left( \frac{p_0^2}{p_0^2 + p_\perp^2} \right)^m \times \left( 1 - \frac{2 p_\perp}{\sqrt{s}} \cosh y \right)^n
\]

- Use realistic values for parameters:
  - \( \xi = 0.5 \pm 0.25, \langle z \rangle = 0.6 \pm 0.2, \hat{q}_0 = 0.07 \pm 0.02 \text{ GeV}^2/\text{fm} \)
- Theoretical uncertainty coming from the variation of \( \xi, \langle z \rangle, n, \hat{q}_0 \)
  - The product \( \hat{q}_0 \xi (1 - \xi)\langle z \rangle^2 \) enters the log in \( dI/d\omega \) leading to narrow uncertainty at logarithmic accuracy
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\frac{d\sigma_{\psi}}{2\pi p_\perp dp_\perp dy} = \mathcal{N} \times \left( \frac{p_0^2}{p_0^2 + p_\perp^2} \right)^m \times \left( 1 - \frac{2 p_\perp}{\sqrt{s} \cosh y} \right)^n
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Rapidity dependence reminiscent of quarkonium suppression

Significant suppression, especially in the 27 color state

Color-averaged suppression similar to that of an octet

Effects weaken at large $p_{\perp}$
Predictions at LHC

- Significant effects
  - More pronounced at larger $y$ (measurable e.g. by LHCb)
  - Persists up to $p_{\perp} \approx 10$ GeV

- All scattering processes can be computed (here most important ones)

- Similar in magnitude to saturation/nPDF effects
Comparison to data

- Precise baseline in agreement with ALICE $\pi^\pm/K^\pm$ & CMS $h^\pm$ data
  - brings constraints on other physical effects
  - disagreement with $p/\bar{p}$ data
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  - disagreement with $p/\bar{p}$ data
Discussion

- Light hadron suppression not only caused by saturation/nPDF
- FCEL should be taken into account for a proper interpretation
- How to extract nPDF reliably, given FCEL?
  - Use color neutral probes in pA collisions: DY, W/Z
  - Use large-$Q^2$ measurements: jets, top quarks
  - Use DIS data
  - ... or include FCEL in nPDF global fits

First DY measurement in pPb at LHC: É. Chapon Tue 7:30 & A. Baty Wed 11:50
Summary

- FCEL predicted from first principles
- Affects the production of all hadron species in pA collisions
- Successful quarkonium phenomenology at all collision energies
- FCEL effects generalized to light hadron production
  - Rich color structure: suppression sensitive to the color state of the parent dijet
  - Predictions at LHC, significant effects on a wide range in $y$ and $p_{\perp}$
  - First comparison to ALICE and CMS data