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

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Implications of LHCb measurements and future prospects

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**Fully coherent energy loss (FCEL)**

- **Fully coherent energy loss** affects the production of all hadron species in pA collisions
- Predicted from first principles
- Leads to $\Delta E \propto (Q_s/Q) \times E$
- Important consequences for the phenomenology of pA collisions
  - How to extract nPDF given FCEL?
**Fully coherent energy loss (FCEL)**

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- Important consequences for the phenomenology of pA collisions
  - How to extract nPDF given FCEL?
- **This talk**: light hadrons and open heavy-flavour hadrons

**References**

- FA, G. Jackson, S. Peigné, [2107.05871](https://arxiv.org/abs/2107.05871)
- FA, G. Jackson, S. Peigné, K. Watanabe, in preparation
Parametric dependence of FCEL

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

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

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
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Parametric dependence of FCEL

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

- Important at all collision energies, especially at large rapidity
  - Typically in LHCb acceptance :)

- Needs color in both initial & final state
  - Affects hadron production in pA collisions
  - 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
Past result: FCEL on quarkonia at RHIC and LHC

- 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 di-hadron production

Which differences from quarkonium to hadron production?

- Partons produced with opposite and large transverse momenta
- 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 $\rho_R(\xi)$
  - Massive partons in the case of open heavy-flavour hadrons
- Hadronization: $z \neq 1$
Nuclear production ratio

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

\[ R_{pA}^R (y, p_\perp) = \int d\delta \, \mathcal{P}_R (\epsilon (\delta)) \, \frac{d\sigma_{pp}^h (y + \delta, p_\perp)}{dy \, dp_\perp} \bigg/ \frac{d\sigma_{pp}^h (y, p_\perp)}{dy \, dp_\perp} \]

- Quenching weight \( \mathcal{P}_R \) related to the medium-induced gluon spectrum

\[ \mathcal{P}_R (\epsilon) \simeq \left. \frac{dI (\epsilon)}{d\epsilon} \right|_R \exp \left\{ - \int_{\epsilon}^{\infty} d\omega \, \left. \frac{dI (\omega)}{d\omega} \right|_R \right\} \]

- Gluon spectrum \( dI / d\epsilon \big|_R \) for \( ab \rightarrow (cd)_R \) hard process computed perturbatively

- pp cross section fitted from data

- Application to light and heavy-flavour hadrons
Color dependence

- 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 for light hadrons at LHC

- Significant effects
  - More pronounced at larger $y$
  - 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
- Need to compare to LHCb data
Predictions for light hadrons at LHC

- High precision
- Wide kinematic range in $y$ and $p_T$

[Diagram]

☞ Ideal to probe cold nuclear matter effects!
Similar shape than LHCb data in $y$ and $p_\perp$

Account for typically half of the reported suppression
Predictions for D mesons at LHC

- Similar shape than LHCb data in $y$ and $p_\perp$
- Account for typically half of the reported suppression

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FCEL effects on hadron production in pA collisions
LHCb workshop 2021 9 / 12
Discussion

Several nuclear effects can play a role:

- **FCEL**
  - Affects hadron production in pA collisions
  - Predicted from first principles to pQCD
  - Rather small theoretical uncertainty

- **nPDF**
  - Fitted from DIS and hadron collision data
  - Global fits assume that leading twist nPDF are responsible for all nuclear effects seen in data

☞ Which strategy to follow given LHCb new charged hadron and D-meson pPb data?
Reweighting nPDF, w/ and w/o FCEL

Given a new data set, **PDF can be conveniently reweighted**

- **Ignore FCEL**
  
  \[ \mathcal{P}(f_A | \text{pQCD } \cap \text{world data}) \]

  ▶ Good fits can be obtained including LHCb data
  ▶ Significantly shrinks theoretical uncertainty
  ▶ ...but is \( f_A \) reliable?

- **Include FCEL**
  
  \[ \mathcal{P}(f'_A | \text{pQCD } \cap \text{FCEL } \cap \text{world data}) \]

  ▶ Part of the nuclear dependence cannot be attributed to nPDF
  ▶ Different physical processes with different scaling properties
  ▶ Resulting nPDF extracted from data **will not be the same**: \( f'_A \neq f_A \)

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Reweighting nPDF, w/ and w/o FCEL

Given a new data set, **PDF can be conveniently reweighted**

$$P(f'_A | \text{FCEL } \cap \text{LHCb data})$$

$$P(f_A | \text{no FCEL } \cap \text{LHCb data})$$

$$f'_A \neq f_A$$
Summary

- FCEL predicted from first principles with small uncertainty
- Affects significantly hadron production in pA collisions
- LHCb measurement of charged hadrons and D mesons sensitive probe of gluon nPDF at small $x$
- ... but the reweighted nPDF depends strongly on the theoretical assumptions (ignoring v. including FCEL)
- FCEL-free probe of nPDF = color singlet final state
  ▶ Drell-Yan
  ▶ Prompt photons
  ▶ Weak bosons (yet small nPDF effects due to large mass)