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

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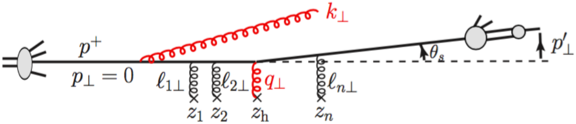
Hard Probes 2020

Austin, TX, USA and everywhere – June 2020

Context

Energy loss in nuclear matter revisited: **fully coherent regime** (FCEL)

[FA Peigné Sami 2010, FA Peigné 2012]



- Predicted from first principles
- Leads to $\Delta E \propto (Q_s/Q) \times \boldsymbol{E}$
- 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

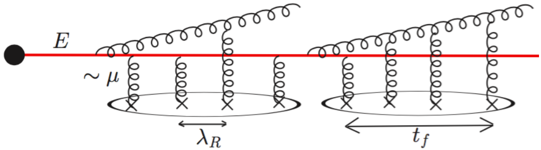
- Fully Coherent Energy Loss (FCEL) regime
  - Parametric dependence
  - Phenomenology of J/ψ suppression in pA collisions
- FCEL effects on light hadron production
  - Setup and main assumptions
  - Predictions at the LHC
- Discussion

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

Radiative energy loss regimes (2/2) : FCEL

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

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

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

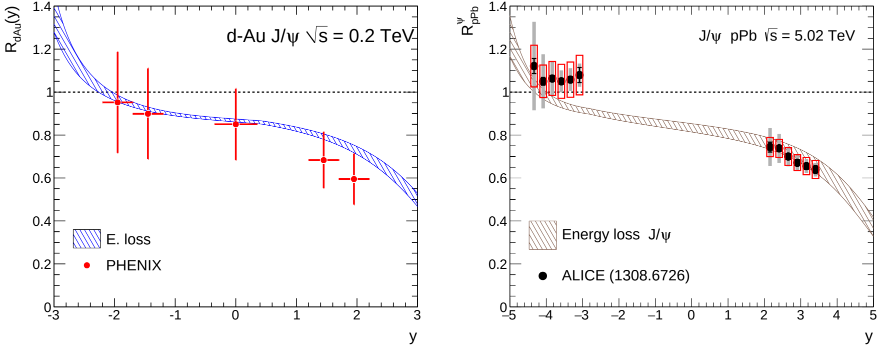
Radiative energy loss regimes (2/2) : FCEL

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

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

- 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 Υ, let alone on high-$p_\perp$ jets
- Hadron production in pA collisions
  - applied to quarkonia
  - light hadrons currently investigated

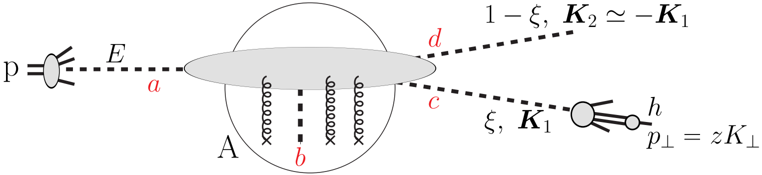
Past result: FCEL on quarkonia at RHIC and LHC



- Moderate effects at $y = 0$, larger above $y \gtrsim 2 - 3$
- Smaller suppression expected in the Υ 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
  - $K_1 \simeq K_2 \gg \sqrt{\hat{q}L}$
  - energy fractions ξ and $1-\xi$
- Final state made of two partons at leading order
  - Use medium-induced gluon spectrum associated to $2 \to 2$ scattering
  - Final state in different color representations R with probability $\rho_{\text{R}}(\xi)$
- Hadronization: $z \neq 1$

Energy loss model for a specific dijet configuration

- Consider a dijet with given color state R and momentum fraction ξ

$$\frac{1}{A}\,\frac{\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{pA}}(y)}{\mathrm{d}y\,\mathrm{d}\xi} = \int_0^{x_{\max}} \mathrm{d}x\;\frac{\hat{\mathcal{P}}_{\mathrm{R}}(x)}{1+x}\,\frac{\mathrm{d}\sigma^{\mathrm{R}}_{\mathrm{pp}}(y+\delta,\xi)}{\mathrm{d}y\,\mathrm{d}\xi}\;;\;\delta \equiv \ln(1+x)$$

- Quenching weight $\hat{\mathcal{P}}_{\mathrm{R}}$ related to the medium-induced gluon spectrum

$$\hat{\mathcal{P}}_{\mathrm{R}}(\epsilon) \simeq \left.\frac{\mathrm{d}I(\epsilon)}{\mathrm{d}\epsilon}\right|_{\mathrm{R}} \exp\left\{-\int_{\epsilon}^{\infty}\mathrm{d}\omega\;\left.\frac{\mathrm{d}I(\omega)}{\mathrm{d}\omega}\right|_{\mathrm{R}}\right\}$$

Induced gluon spectrum for dijet final state

Gluon spectrum $\mathrm{d}I/\mathrm{d}\omega$ for ab $\rightarrow (\mathrm{cd})_{\mathrm{R}}$ hard process

$$\omega \left.\frac{\mathrm{d}I}{\mathrm{d}\omega}\right|_{\mathrm{ab}\to(\mathrm{cd})_{\mathrm{R}}} = (C_{\mathrm{a}} + C_{\mathrm{R}} - C_{\mathrm{b}}) \frac{\alpha_s}{\pi} \left[\ln\left(1 + \frac{\hat{q}L}{M_\xi^2}\frac{E^2}{\omega^2}\right) - \mathrm{pp}\right]$$

- 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
  - gluon radiation does not probe the dijet

$$\lambda_\perp \sim \frac{1}{k_\perp} \gg v_\perp \times t_{\mathrm{f}} \rightarrow \frac{\omega}{E} K_\perp \ll \sqrt{\hat{q}L}$$

  - condition equivalent to the leading logarithmic accuracy

$$\ln\left(\frac{\hat{q}L}{K_\perp^2}\frac{E^2}{\omega^2}\right) \gg 1$$

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- 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

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

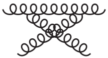
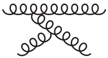
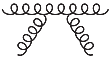
  - $\hat{q}_0$ range in agreement with LPM energy loss and nuclear broadening studies, corresponds to $Q_s \simeq 1.3$–1.8 GeV at LHC at mid-rapidity

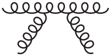
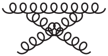
Color state probabilities ($gg \to gg$ case)

- Color representations: $R = \mathbf{1}, \mathbf{8}, \mathbf{27}$ ($P_{\mathbf{10}} = 0$ 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 ξ and obtained from color algebra

$\mathcal{M}_{\text{hard}} \propto \frac{\boldsymbol{K}}{\boldsymbol{K}^2}$  $+ \frac{\boldsymbol{K} - \boldsymbol{q}}{(\boldsymbol{K} - \boldsymbol{q})^2}$  $- \frac{\boldsymbol{K} - \xi \boldsymbol{q}}{(\boldsymbol{K} - \xi \boldsymbol{q})^2}$ 

$\propto \left[\frac{\boldsymbol{K} - \boldsymbol{q}}{(\boldsymbol{K} - \boldsymbol{q})^2} - \frac{\boldsymbol{K} - \xi \boldsymbol{q}}{(\boldsymbol{K} - \xi \boldsymbol{q})^2} \right]$  $+ \left[\frac{\boldsymbol{K}}{\boldsymbol{K}^2} - \frac{\boldsymbol{K} - \boldsymbol{q}}{(\boldsymbol{K} - \boldsymbol{q})^2} \right]$ 

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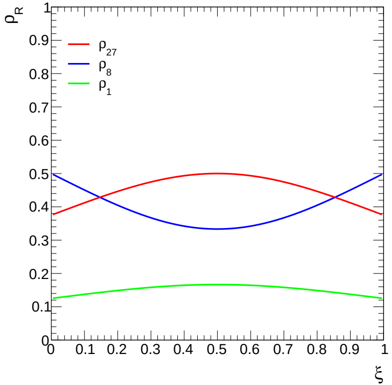

From dijet to single hadron production

Needs to sum/integrate

- Recoiling jet: $\int_0^1 \mathrm{d}\xi$
- Final-state color probabilities: $\sum_{\mathrm{R}} \rho_{\mathrm{R}}(\xi)$
- Fragmentation variable: $\int_0^1 \mathrm{d}z\, D_i^{\mathrm{h}}(z)$

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}^{\mathrm{h}}(y)}{\mathrm{d}y} = \sum_{\mathrm{R}} \int \mathrm{d}\xi\, \rho_{\mathrm{R}}(\xi) \int_0^{x_{\max}} \mathrm{d}x\, \frac{\hat{\mathcal{P}}_{\mathrm{R}}(x)}{1+x}\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\mathrm{h}}(y+\delta,\xi)}{\mathrm{d}y\,\mathrm{d}\xi}$$

Nuclear modification of inclusive hadron production

- Assuming a smooth variation of ρ and $R_{\mathrm{pA}}^{\mathrm{h}}$ with ξ

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

$$R_{\mathrm{pA}}^{R}(y,p_\perp) = \int_0^{\delta_{\max}} \mathrm{d}\delta\ \hat{\mathcal{P}}_R\left(x, \frac{\sqrt{\hat{q}L}\,\langle z\rangle}{M_\xi}\right)\, \frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\mathrm{h}}(y+\delta,p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp} \Bigg/ \frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\mathrm{h}}(y,p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp}$$

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

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

- Use realistic values for parameters:
  - $\xi = 0.5 \pm 0.25$, $\langle z \rangle = 0.6 \pm 0.2$, $\hat{q}_0 = 0.07 \pm 0.02$ GeV^2/fm
- Theoretical uncertainty coming from the variation of ξ, $\langle z \rangle$, n, $\hat{q}_0$
  - The product $\hat{q}_0\, \xi\, (1-\xi) \langle z \rangle^2$ enters the log in $\mathrm{d}I/\mathrm{d}\omega$ leading to narrow uncertainty at logarithmic accuracy

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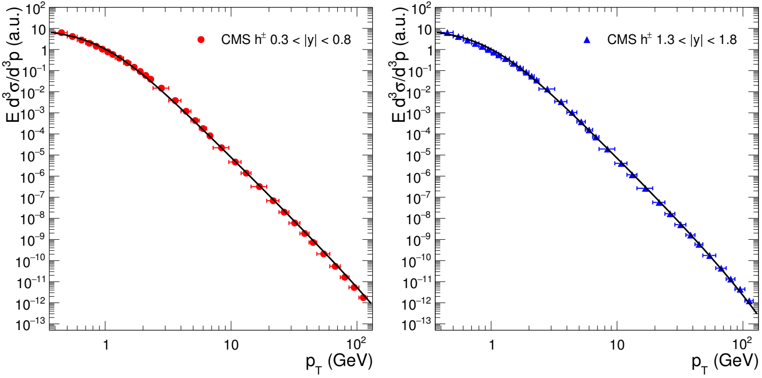

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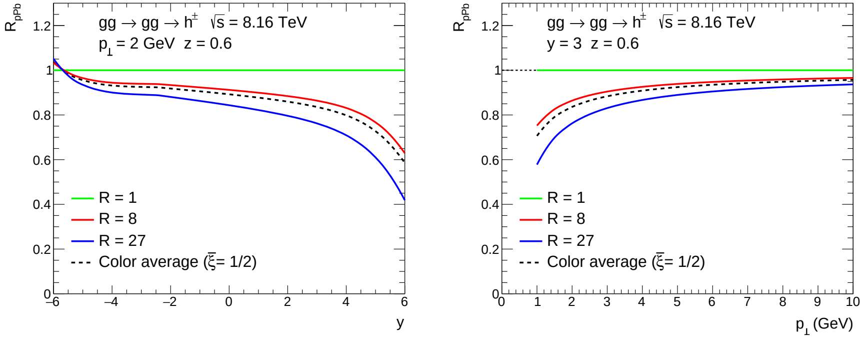
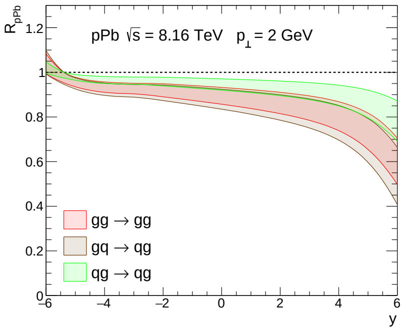
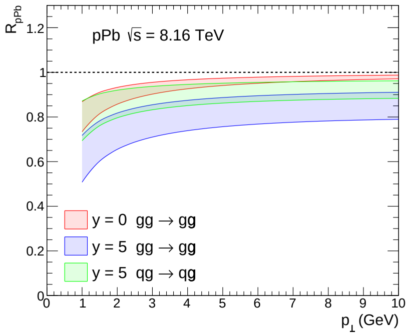
Color dependence



- 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 $p_\perp$

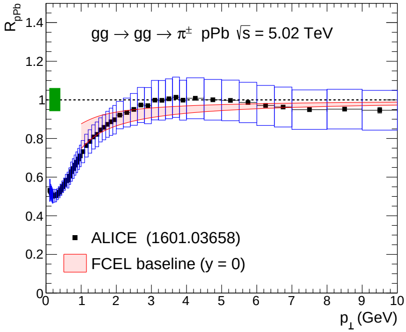
Predictions at LHC

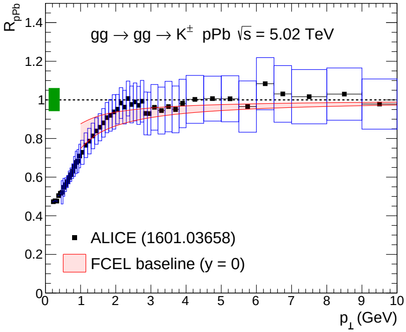




- Significant effects
  - More pronounced at larger y (measurable e.g. by LHCb)
  - Persists up to $p_\perp \simeq 10$ GeV
- All scattering processes can be computed (here most important ones)
- Similar in magnitude to saturation/nPDF effects

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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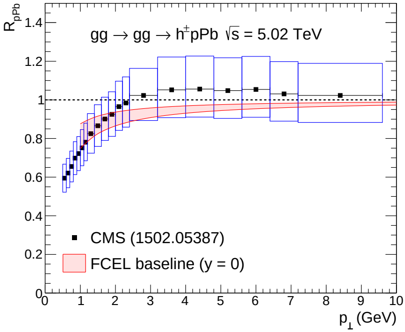

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Discussion

- 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