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

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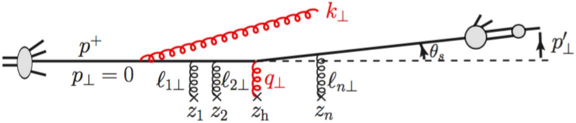
Context

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: natural explanation of J/ψ data from SPS to LHC
  - light hadrons (this talk)
  - open-heavy flavour hadrons

Outline

- Past results
  - Fully Coherent Energy loss (FCEL) regime
  - FCEL effects on single massive particle production
  - Phenomenology of J/ψ suppression data in pA collisions
- FCEL effects on light hadron production
  - Setup and main assumptions
  - Predictions at the LHC
  - Discussion

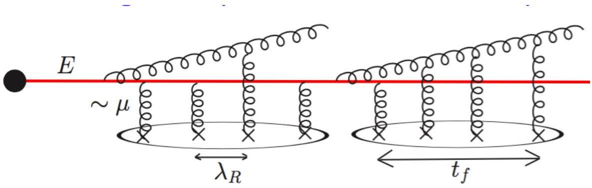
References

- FA, F. Cougoulic, S. Peigné, work in progress

Radiative energy loss regimes

Radiating gluons off the propagating parton takes a typical **formation time**, $t_{\rm f} \sim \omega/k_\perp^2$, to be compared to the two other length scales:

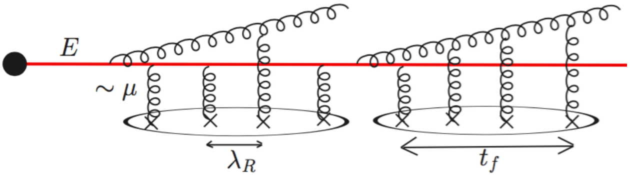
- λ: parton mean free path
- L: medium length



Radiative energy loss regimes

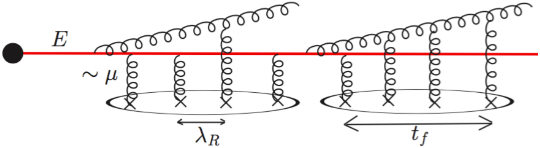
Three regimes

- $t_{\mathrm{f}} < \lambda$: **Bethe-Heitler**
  - Each scattering center acts as an independent source of radiation
  - $\omega < \mu^2 \lambda$
- $\lambda < t_{\mathrm{f}} < L$: **Landau-Pomeranchuk-Migdal** (LPM)
  - A group of (t_{f}/λ) scattering centers acts as a single radiator
  - $\mu^2 \lambda < \omega < \mu^2 L^2/\lambda \equiv \hat{q} L^2$
- $t_{\mathrm{f}} > L$: **Fully coherent**
  - All scattering centers act coherently as a source of radiation
  - $\omega > \hat{q} L^2$



Initial/final state energy loss

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



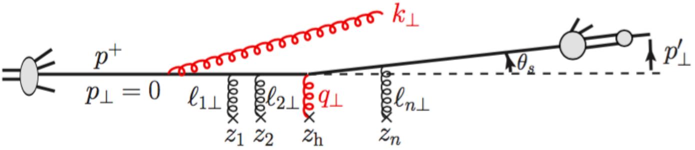
$$\Delta E_{\text{LPM}} \propto \alpha_s \; \hat{q} \; L^2 \; \log(E)$$

- Energy dependence at most logarithmic
  - $\hat{q}$ could receive large logarithmic corrections without changing the leading parametric dependence [Blaizot, Mehtar-Tani 1403.2323]
- Best probed in
  - Hadron production in nuclear semi-inclusive DIS
  - Drell-Yan in pA collisions at low energy
- 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

Fully coherent energy loss

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]

[FA Kolevatov Peigné, 1402.1671, Peigné Kolevatov 1405.4241]

[Liou Mueller 1402.1647, Munier Peigné Petreska 1603.01028]

Fully coherent energy loss

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

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

- 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
- Hadron production in pA collisions
  - applied to quarkonia
  - light hadrons currently investigated
- $M_\perp^{-1}$ dependence
  - weaker effects on Υ, let alone on high-$p_\perp$ jets

Induced gluon spectrum for single massive particle

Gluon spectrum $\mathrm{d}I/\mathrm{d}\omega$ for $1 \to 1$ hard forward process

$$\omega \frac{\mathrm{d}I}{\mathrm{d}\omega}\bigg|_{1\to 1} = \frac{F_c\ \alpha_s}{\pi}\ \ln\left(1 + \frac{\hat{q}L\ E^2}{M_\perp^2\ \omega^2}\right)$$

- First determined in the simple model, later confirmed rigorously in the GLV opacity expansion and saturation formalism
- Color factor F_c follows from simple color algebra

$$\begin{aligned} 2\,T_1^a \cdot T_2^a &= (T_1^a)^2 + (T_2^a)^2 - (T_1^a - T_2^a)^2 \\ F_c &= C_{\rm in} + C_R - C_t \quad (R = \text{color of the final particle}) \end{aligned}$$

$$\begin{aligned} g \to g &: \quad F_c = N_c + N_c - N_c = N_c \\ q \to g &: \quad F_c = C_F + N_c - C_F = N_c \\ q \to q &: \quad F_c = C_F + C_F - N_c = -1/N_c \quad (< 0\ !) \end{aligned}$$

Phenomenology

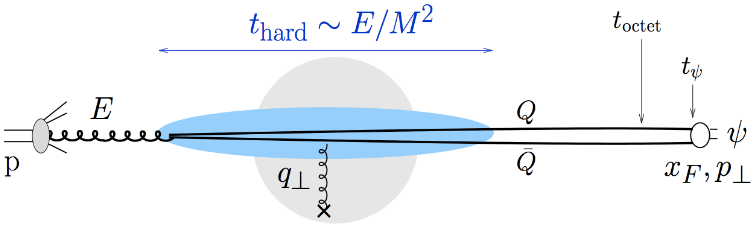
Goal

- Explore phenomenological consequences of coherent energy loss
- Approach as simple as possible with the least number of assumptions
- Observables
  - Quarkonium suppression in pA and AA collisions
  - Light hadron production in pA collisions (new!)

Model for quarkonium suppression

Physical picture and assumptions

[FA Peigné, 1204.4609, 1212.0434]



- Color neutralization happens on long time scales: $t_{\rm octet} \gg t_{\rm hard}$
- In-medium rescatterings do not resolve the octet $Q\bar{Q}$ pair

Model for quarkonium suppression

Energy shift

$$\frac{1}{A}\frac{\mathrm{d}\sigma_{\mathrm{pA}}^{\psi}}{\mathrm{d}E}\left(E,\sqrt{s}\right)=\int_0^{\varepsilon_{\max}}\mathrm{d}\varepsilon\,\mathcal{P}(\varepsilon,E)\,\frac{\mathrm{d}\sigma_{\mathrm{pp}}^{\psi}}{\mathrm{d}E}\left(E+\varepsilon,\sqrt{s}\right)$$

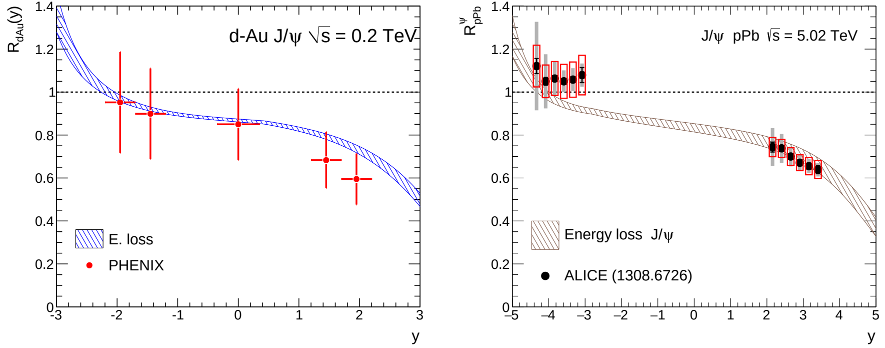
- pp cross section fitted from experimental data
- $\mathcal{P}(\epsilon)$: quenching weight related to the induced gluon spectrum

$$\mathcal{P}(\epsilon)\simeq\frac{\mathrm{d}I(\epsilon)}{\mathrm{d}\omega}\,\exp\left\{-\int_{\epsilon}^{\infty}\mathrm{d}\omega\frac{\mathrm{d}I}{\mathrm{d}\omega}\right\}$$

- Transport coefficient

$$\hat{q}(x)=\frac{4\pi^2\alpha_s C_R}{N_c^2-1}\,\rho\,xG(x)=\hat{q}_0\left(\frac{10^{-2}}{x}\right)^{0.3}\quad;\ \hat{q}_0=0.075\ \mathrm{GeV}^2/\mathrm{fm}$$

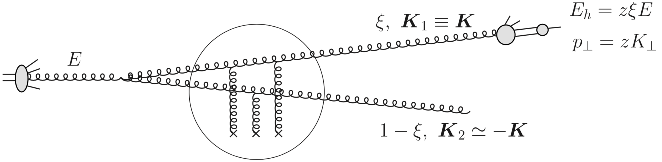
Effects at RHIC and LHC



- 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 1 & 2 produced with opposite and large transverse momenta
  - $K_1 \simeq K_2 \gg \ell_\perp = \sqrt{\hat{q}L}$
- Final state made of two partons at leading order
  - Use $1 \to 2$ medium-induced gluon spectrum
  - Final state in different color representations
  - Recoil particle not measured
- Hadronization
  - $z = 1$ was assumed for quarkonium production: $D_{c\bar{c}}^{J/\psi}(z) = \delta(1-z)$

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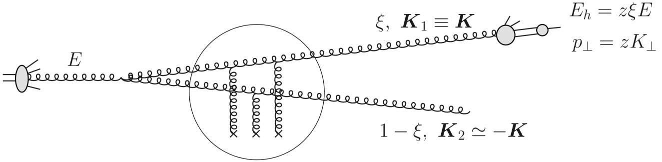


- Partons 1 & 2 carry momentum fractions ξ and $1-\xi$
- Detected hadron carries momentum fraction z of parton 1
- 2-parton final state in color representation R with probability $\rho_R(\xi)$
- At LHC we consider only $g \to gg$ channel

Energy loss model for a specific dijet configuration

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

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

- As before, $\hat{\mathcal{P}}_R$ related to the medium-induced gluon radiation

$$x\frac{\mathrm{d}I_R}{\mathrm{d}x}\bigg|_{1\to 2} = F_c\,\frac{\alpha_s}{\pi}\left[\ln\left(1+\frac{\ell^2_{\perp\mathrm{A}}}{x^2 M^2_{\mathrm{jj}}}\right) - \mathrm{pp}\right]\ ;\ F_c = C_{\mathrm{in}} + C_R - C_{\mathrm{t}}$$

$$M^2_{\mathrm{jj}} = \frac{K^2_\perp}{\xi\,(1-\xi)}$$

- Gluon radiation does not probe the dijet: pointlike dijet approximation

Pointlike dijet approximation

Condition for not resolving the transverse size of the dijet

- Time of emission: $t_{\rm f} \sim \omega/k_\perp^2$
- Transverse velocity of dijet constituents: $v_\perp \sim K_\perp/E$

$$\lambda_\perp \sim \frac{1}{k_\perp} \gg v_\perp \times t_{\rm f} \to x\,K_\perp \ll k_\perp \lesssim \ell_{\perp \rm A}$$

Leading logarithmic accuracy requires

$$\ln\left(\frac{\ell^2_{\perp \rm A}}{x^2 K_\perp^2}\right) \gg 1$$

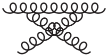
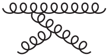
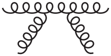
- Pointlike dijet approximation valid at this accuracy

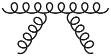
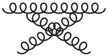
Color state probabilities (gg case)

- 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

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

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

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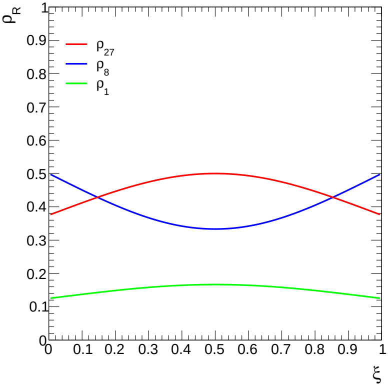

From dijet to single hadron production

Needs to sum/integrate

- Recoiling jet: $\int_0^1 \, \mathrm{d}\xi$
- Final-state color probabilities: $\sum_R \, \rho_R(\xi)$
- Fragmentation variable: $\int_0^1 \, \mathrm{d}z \, D^h_{p1}(z)$

$$\frac{1}{A}\,\frac{\mathrm{d}\sigma^{\mathrm{h}}_{\mathrm{pA}}(y)}{\mathrm{d}y} = \sum_R \int \mathrm{d}\xi \, \rho_R(\xi) \int_0^{x_{\mathrm{max}}} \mathrm{d}x \; \frac{\hat{\mathcal{P}}_R(x)}{1+x} \, \frac{\mathrm{d}\sigma^{\mathrm{h}}_{\mathrm{pp}}(y+\delta,\xi)}{\mathrm{d}y\,\mathrm{d}\xi}$$

Nuclear modification of inclusive hadron production

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

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

$$R^R_{\mathrm{pA}}(y, p_\perp) = \int_0^{\delta_{\mathrm{max}}} \mathrm{d}\delta \; \hat{\mathcal{P}}_R \left(x, \frac{\ell_{\perp \mathrm{A}} \, \langle z \rangle}{M_{\mathrm{jj}}} \right) \, \frac{\mathrm{d}\sigma^{\mathrm{h}}_{\mathrm{pp}}(y+\delta, p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp} \Bigg/ \frac{\mathrm{d}\sigma^{\mathrm{h}}_{\mathrm{pp}}(y, p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp}$$

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

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

- Use realistic values for parameters:
  - $\xi = 0.5 \pm 0.25$, $\langle z \rangle = 0.7 \pm 0.2$
- Transport coefficient identical to the model for quarkonia
- 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 $dI/d\omega$ leading to narrow uncertainty at logarithmic accuracy

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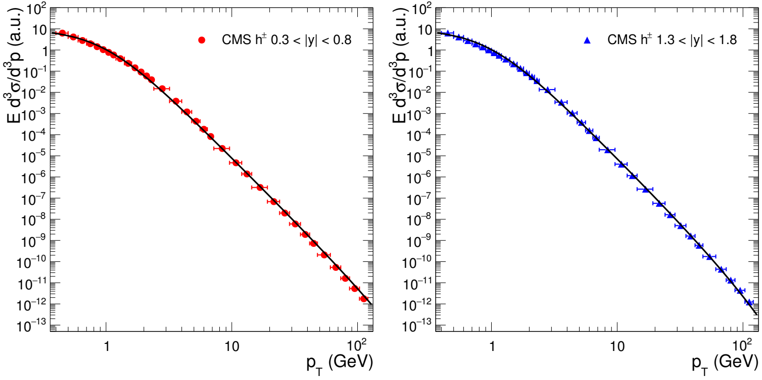

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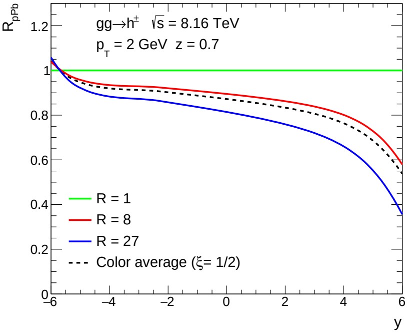
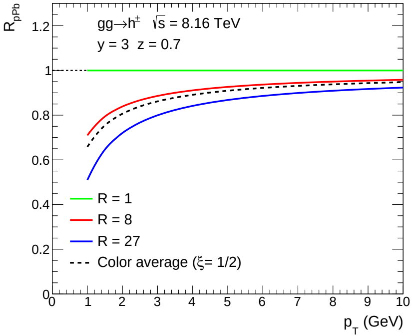
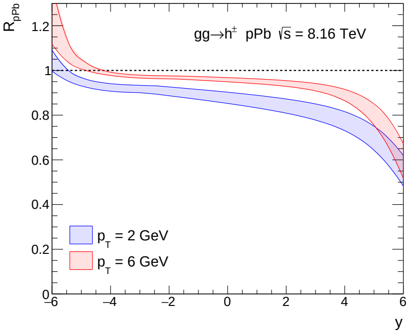
Color dependence

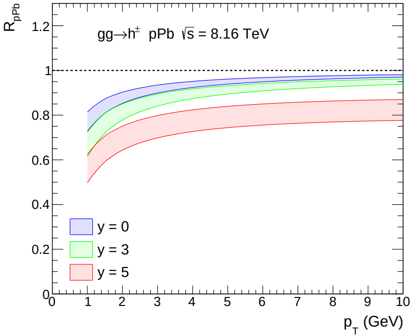




- Rapidity dependence reminiscent of quarkonium suppression
- Significant suppression, especially in the **27** color state
- Color-averaged suppression similar to that of an octet
- Effects weaken at large $p_\perp$

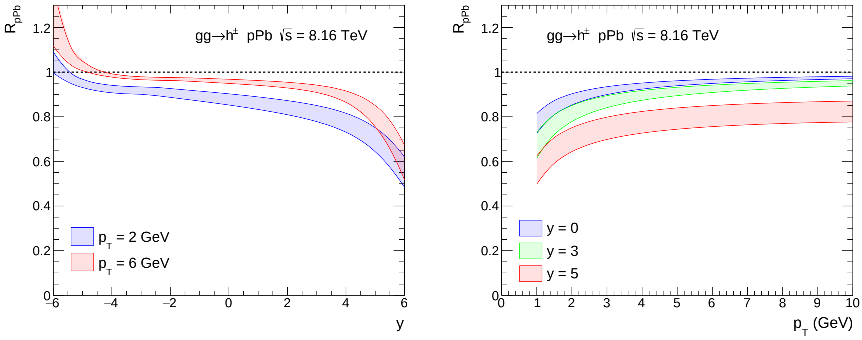
Predictions at LHC





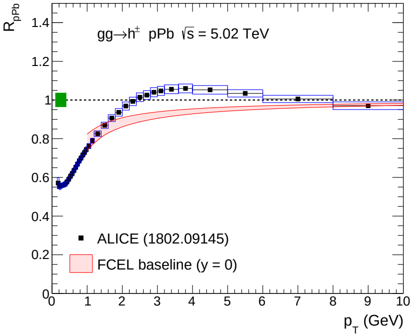
- Significant effects at all rapidity !
  - Most spectacular at large y (measurable by LHCb)
- Similar in magnitude to saturation/nPDF effects
- Persists up to $p_\perp \simeq 10$ GeV

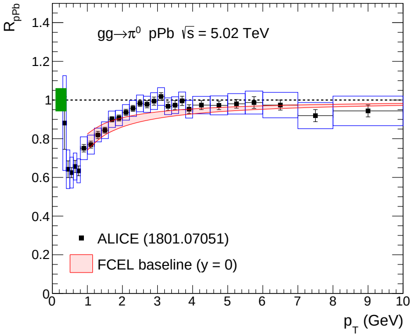
Predictions at LHC



- Light hadron suppression not only caused by saturation/nPDF
- FCEL should be taken into account for a proper interpretation
- Hadron production in pA collisions cannot be used to extract nPDF
  - Quarkonia, light hadrons, heavy hadrons all sensitive to FCEL
  - Unless FCEL included in nPDF global fits (challenging)

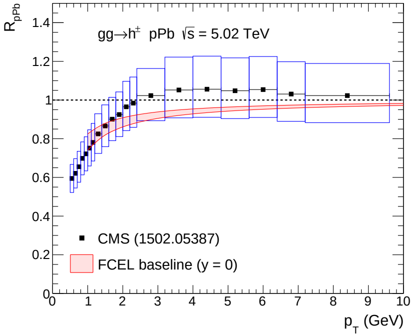
Comparison to data





- Hint for Cronin effect on top of FCEL effects in ALICE h$^{\pm}$ data
- Good agreement with ALICE π^0 & CMS h$^{\pm}$ data
- Precise baseline following first principles FCEL spectrum

Comparison to data



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- Good agreement with ALICE π^0 & CMS $h^{\pm}$ data
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Summary

- FCEL predicted from first principles
- Affects the production of all hadron species in pA collisions
- Successful quarkonium phenomenology at all collision energies

- Approach of predicting FCEL effects on pA from pp collisions 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