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

François Arleo

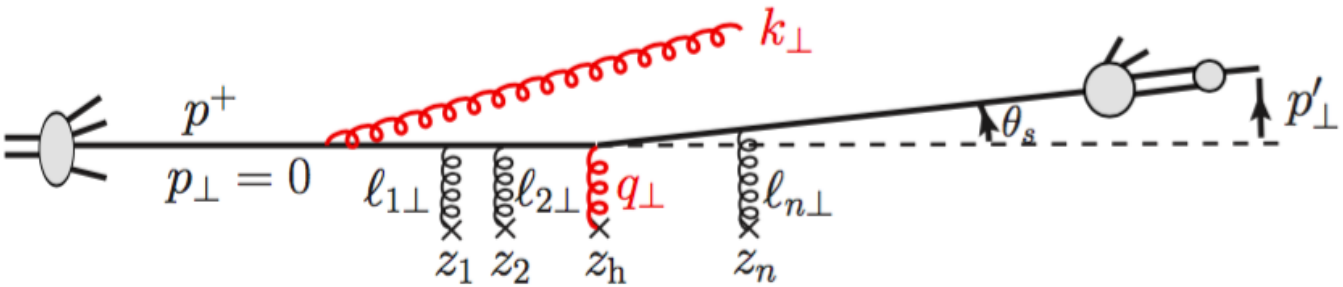
LLR, Palaiseau & Subatech, Nantes

Implications of LHCb measurements and future prospects

CERN, October 2021

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 $\Delta E \propto (Q_s/Q) \times \boldsymbol{E}$
- Important consequences for the phenomenology of pA collisions
  - How to extract nPDF given FCEL ?



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 $\Delta E \propto (Q_s/Q) \times \boldsymbol{E}$
- 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, S. Peigné, 2003.01987, FA, F. Cougoulic, S. Peigné, 2003.06337
- FA, G. Jackson, S. Peigné, 2107.05871
- FA, G. Jackson, S. Peigné, K. Watanabe, in preparation

Parametric dependence of FCEL

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

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

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

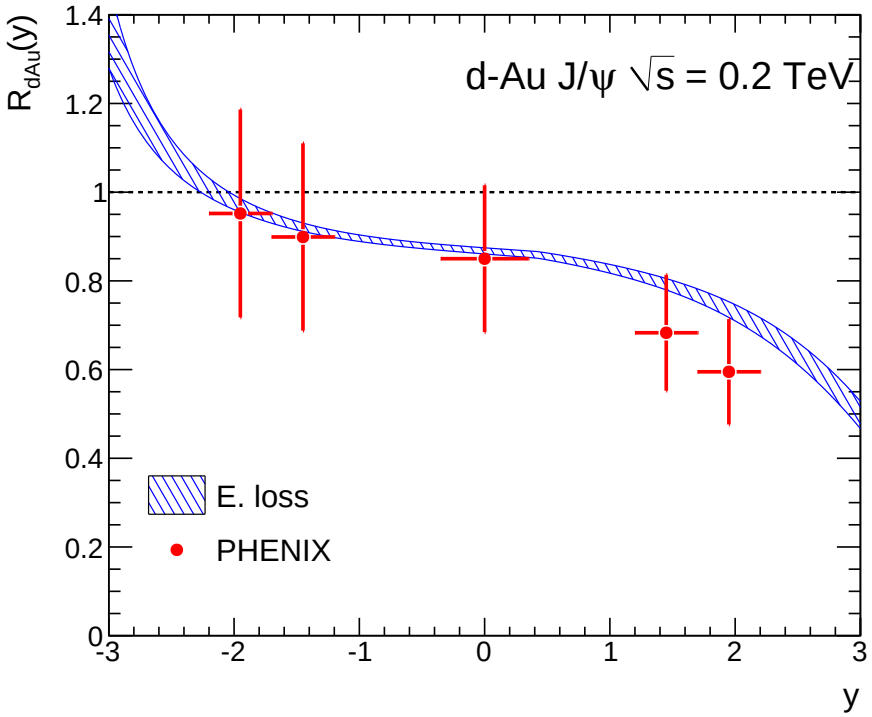
Parametric dependence of FCEL

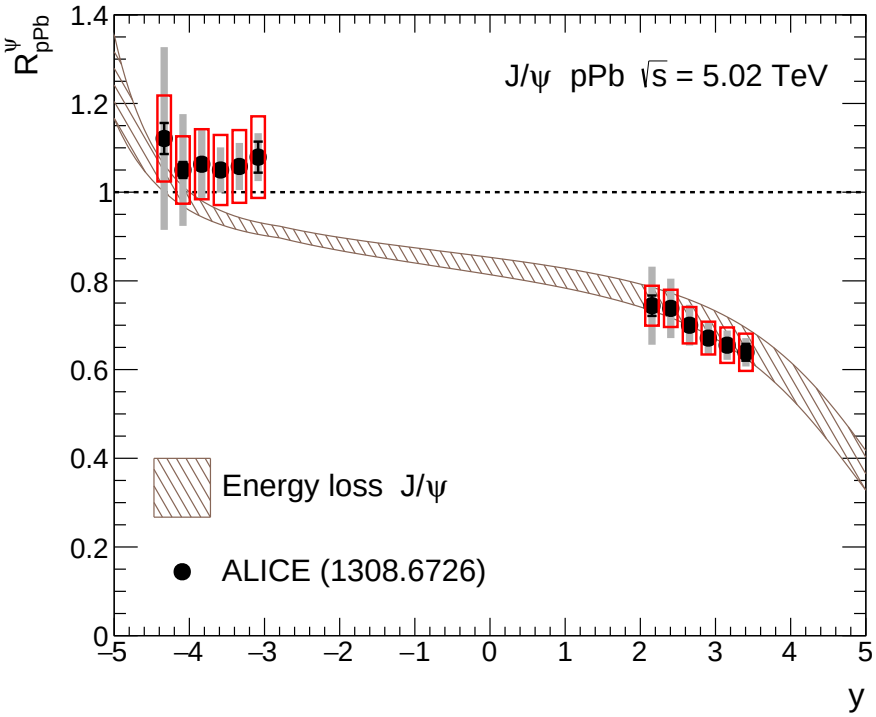
Interference between initial and final state, large formation time $t_f \gg L$

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

- 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 Υ, let alone on high-$p_\perp$ jets

Past result: FCEL on quarkonia at RHIC and LHC



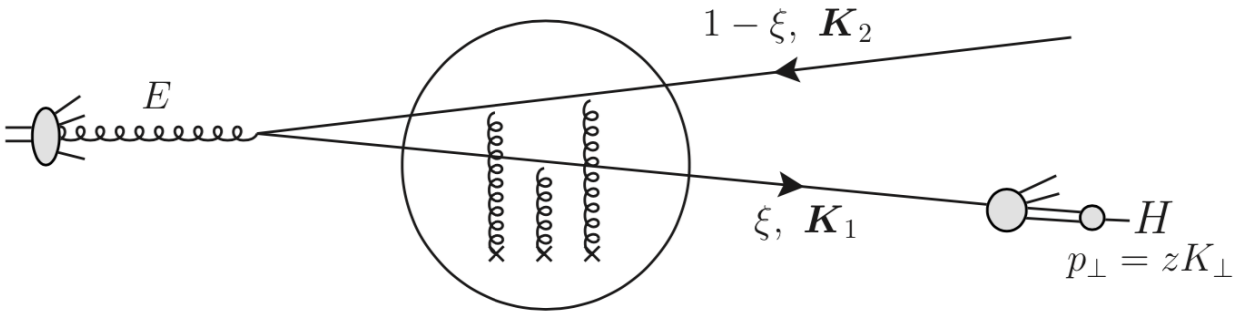


- Moderate effects at $y = 0$, larger above $y \gtrsim 2 - 3$
- Smaller suppression expected in the Υ channel
- Excellent agreement with collider data (PHENIX, ALICE, LHCb)
- . . . and fixed-target experiments (NA3, E866, HERA-B)

From quarkonium to di-hadron production

Which differences from quarkonium to hadron production?

[FA Cougoulic Peigné (2020)]



- Partons produced with opposite and large transverse momenta
- Final state made of two partons at leading order
  - Use medium-induced gluon spectrum associated to $2 \to 2$ scattering
  - Final state in different color representations R with probability $\rho_{\mathrm{R}}(\xi)$
  - Massive partons in the case of open heavy-flavour hadrons
- Hadronization: $z \neq 1$

Nuclear production ratio

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

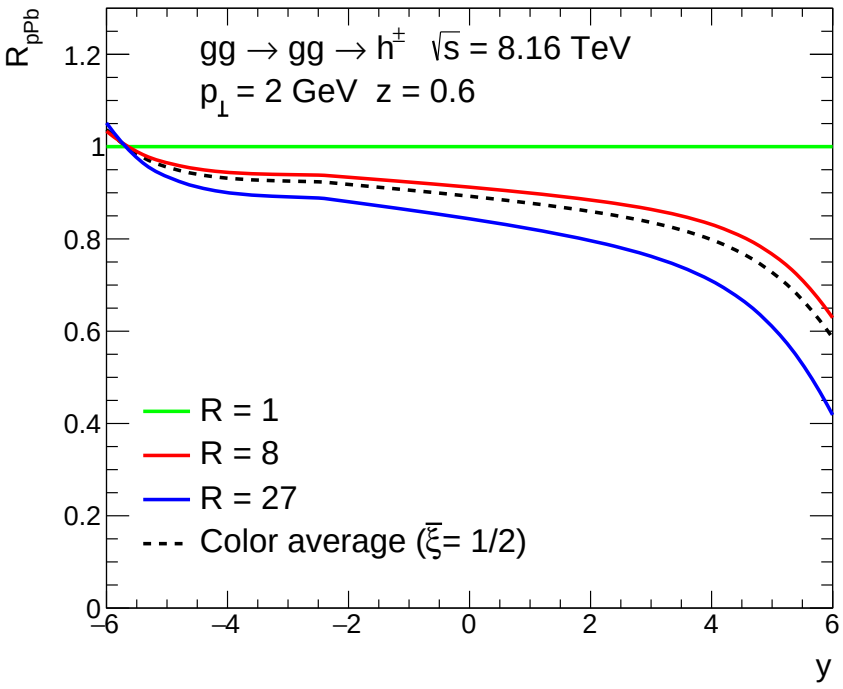
$$R^R_{\mathrm{pA}}(y,p_\perp) = \int \mathrm{d}\delta \; \mathcal{P}_R\left(\epsilon(\delta)\right) \frac{\mathrm{d}\sigma^{\mathrm{h}}_{\mathrm{pp}}(y+\delta,p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp} \Big/ \frac{\mathrm{d}\sigma^{\mathrm{h}}_{\mathrm{pp}}(y,p_\perp)}{\mathrm{d}y\,\mathrm{d}p_\perp}$$

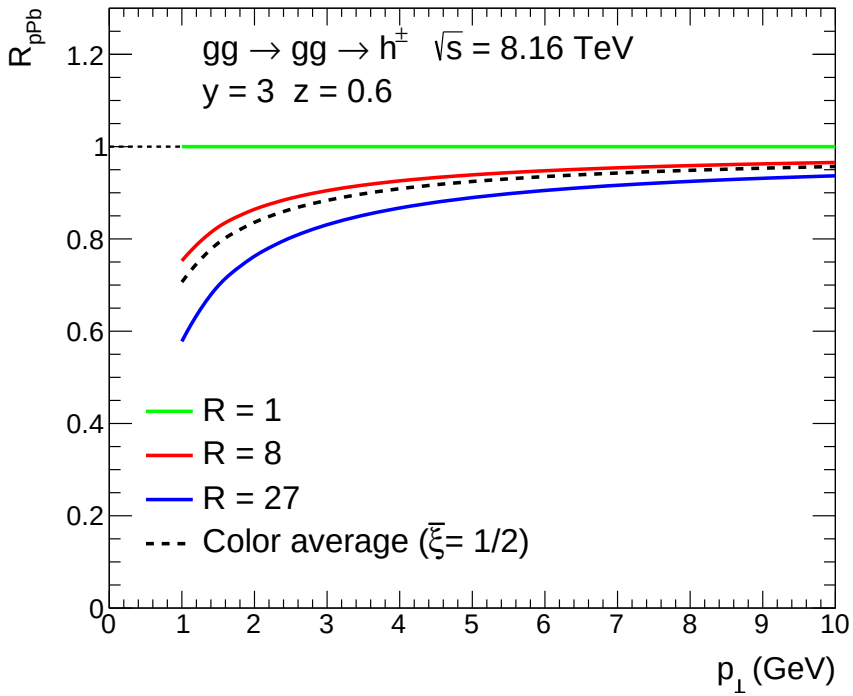
- Quenching weight $\mathcal{P}_{\mathrm{R}}$ related to the medium-induced gluon spectrum

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

- Gluon spectrum $\mathrm{d}I/\mathrm{d}\epsilon|_{\mathrm{R}}$ for $\mathrm{ab} \to (\mathrm{cd})_{\mathrm{R}}$ hard process computed perturbatively
- pp cross section fitted from data
- Application to light and heavy-flavour hadrons

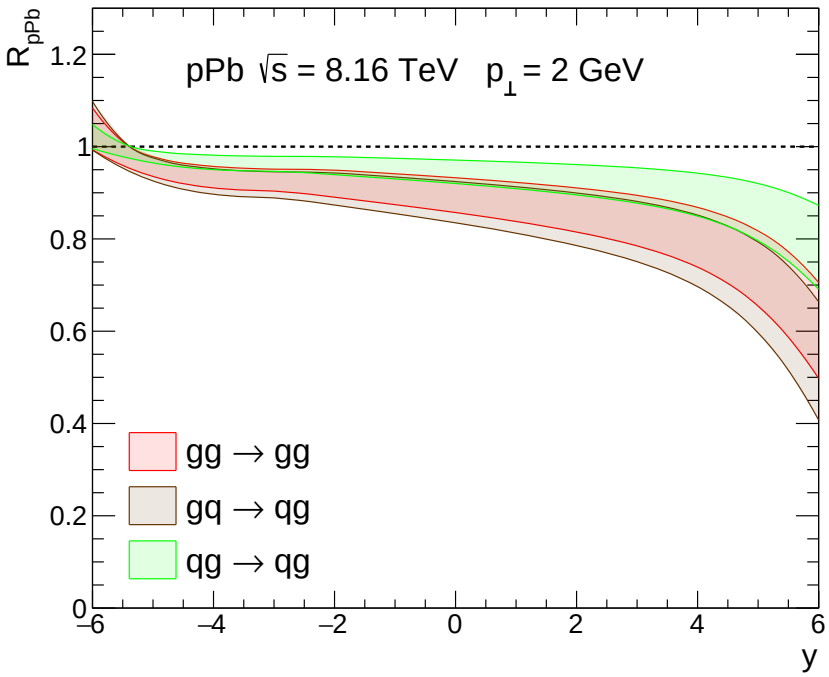
Color dependence

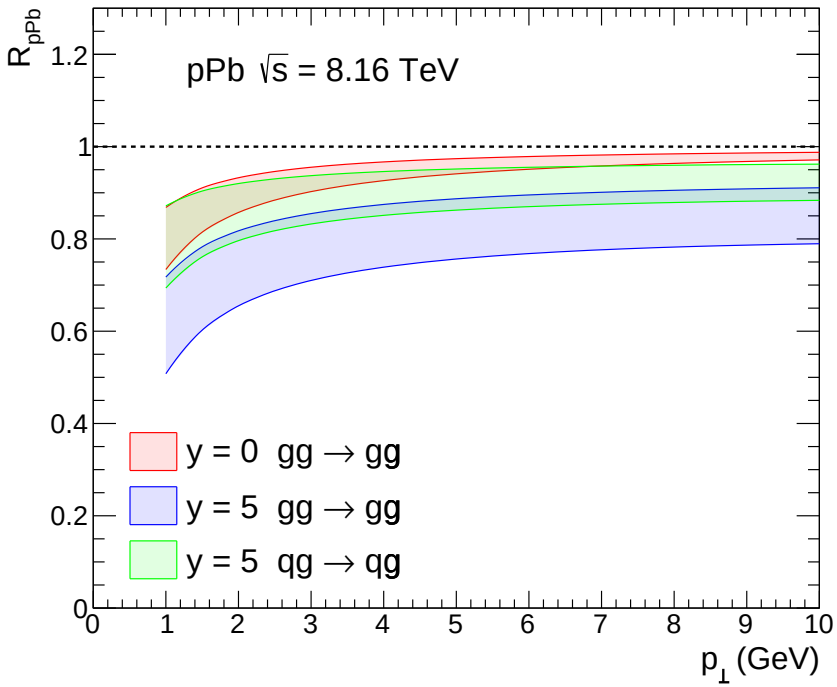




- Rapidity dependence reminiscent of quarkonium suppression
- Significant suppression, especially in the **27** color state
- Color-averaged suppression similar to that of an octet
- Effects weaken at large $p_\perp$

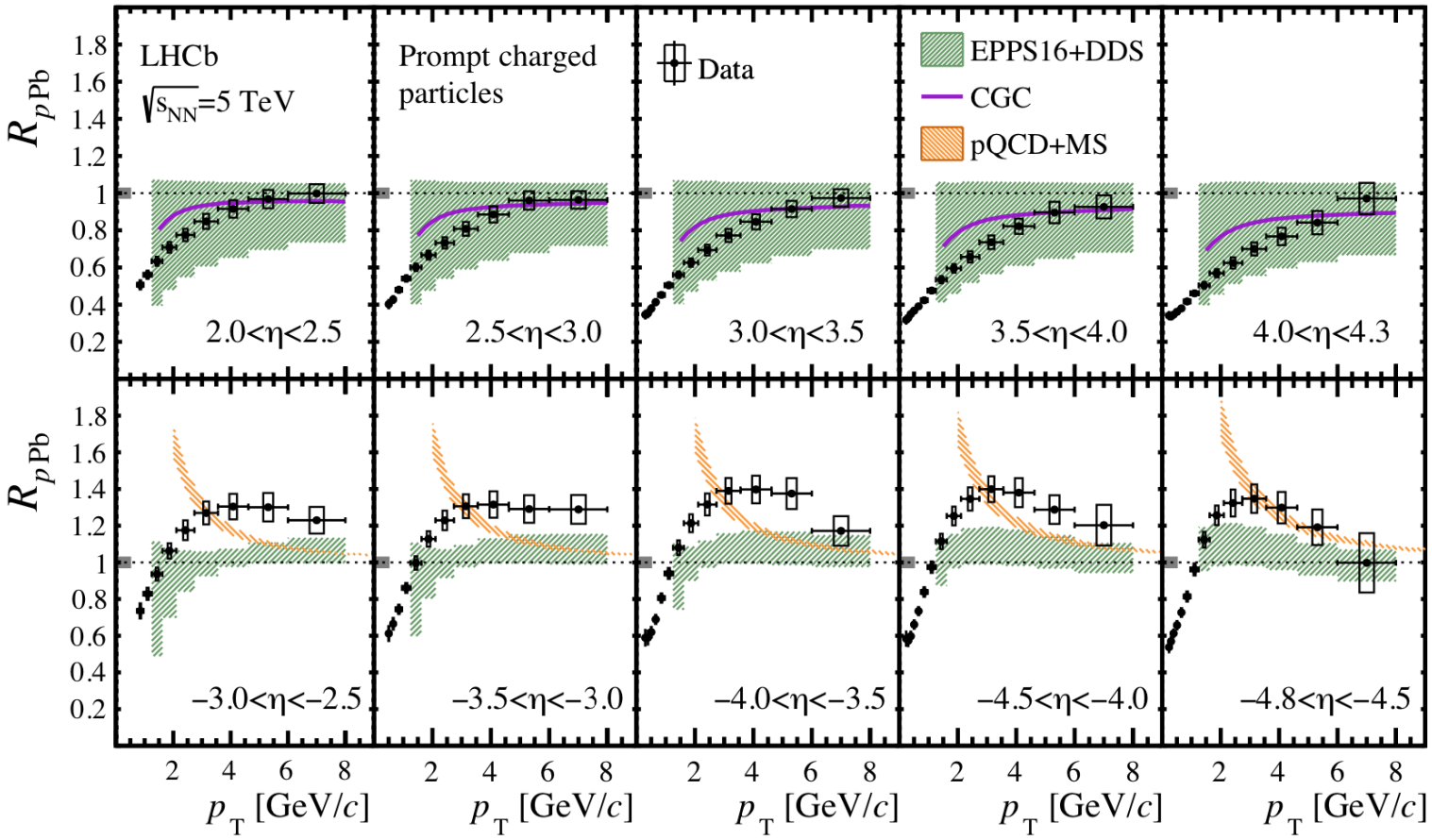
Predictions for light hadrons at LHC





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

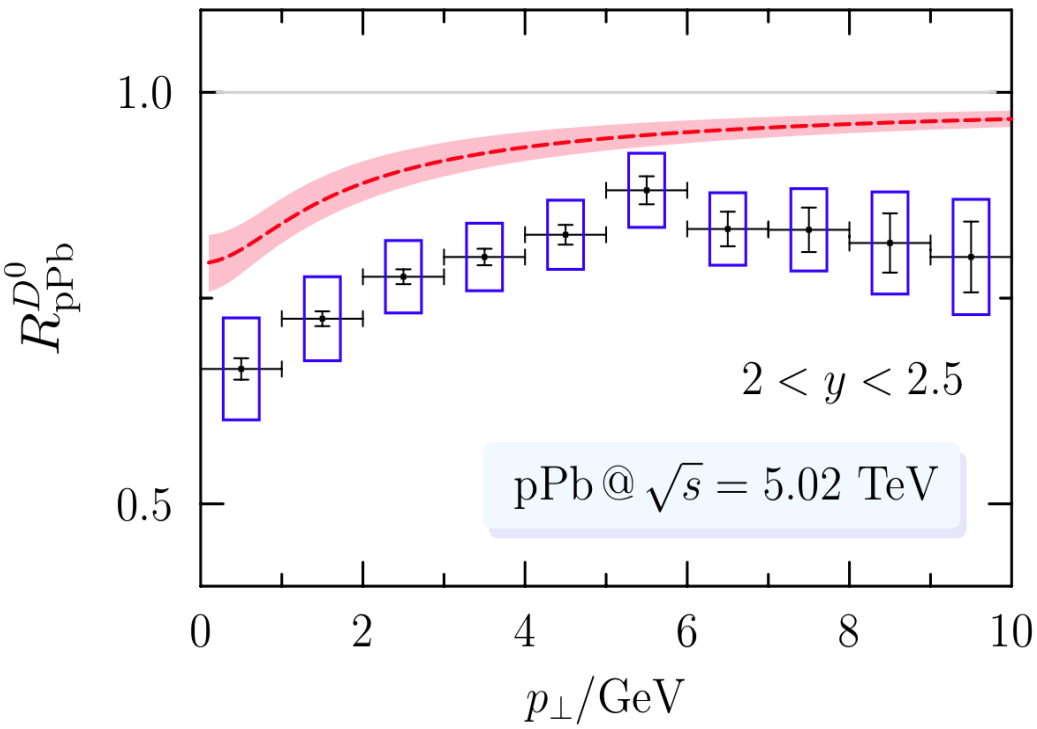
Predictions for light hadrons at LHC



- High precision
- Wide kinematic range in y and $p_\perp$

☞ Ideal to probe cold nuclear matter effects !

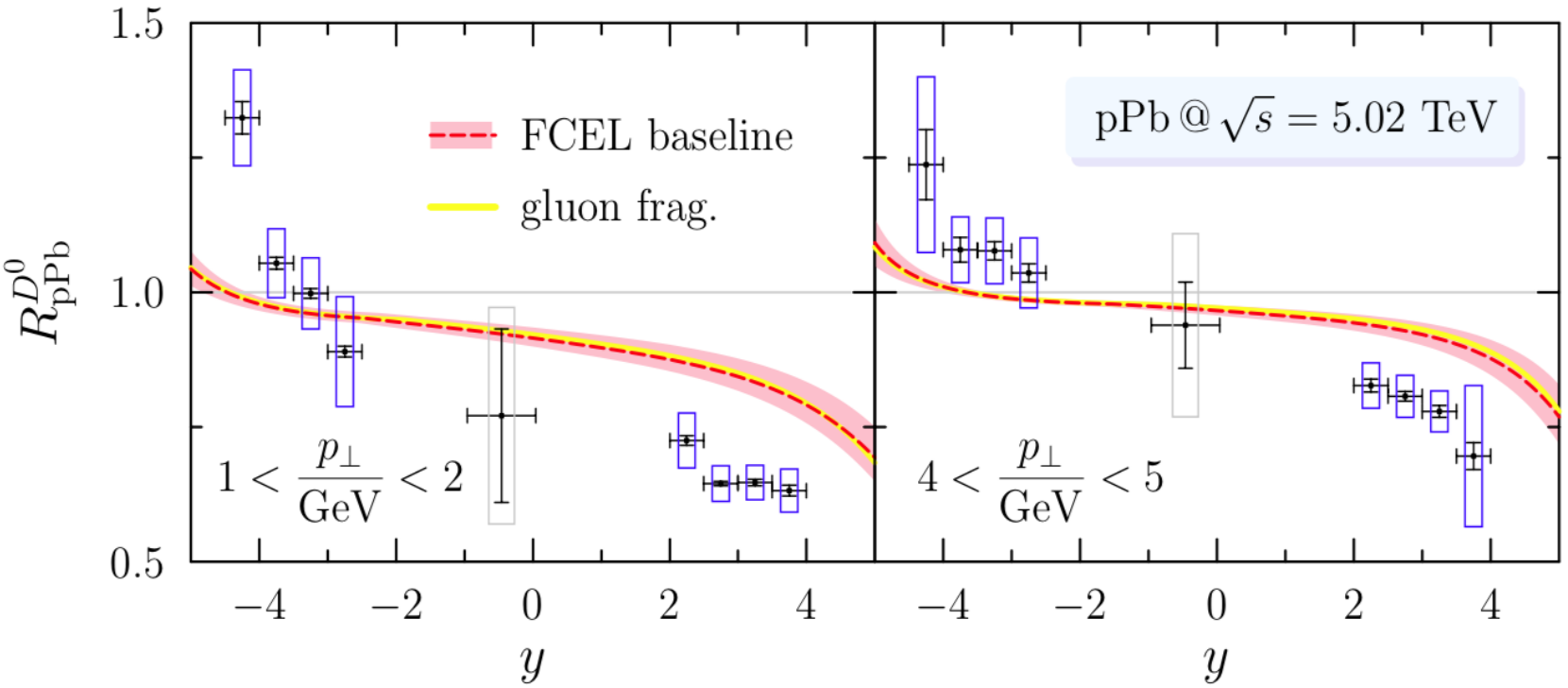
Predictions for D mesons at LHC



[FA Jackson Peigné (2021)]

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

Predictions for D mesons at LHC



[FA Jackson Peigné (2021)]

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

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** [Eskola Helenius Paakkinen Paukkunen (2020)] :

$$\mathcal{P}(f_A | \text{ pQCD} \cap \text{world data})$$

  - Good fits can be obtained including LHCb data
  - Significantly shrinkens theoretical uncertainty
  - . . . but is f^A reliable ?

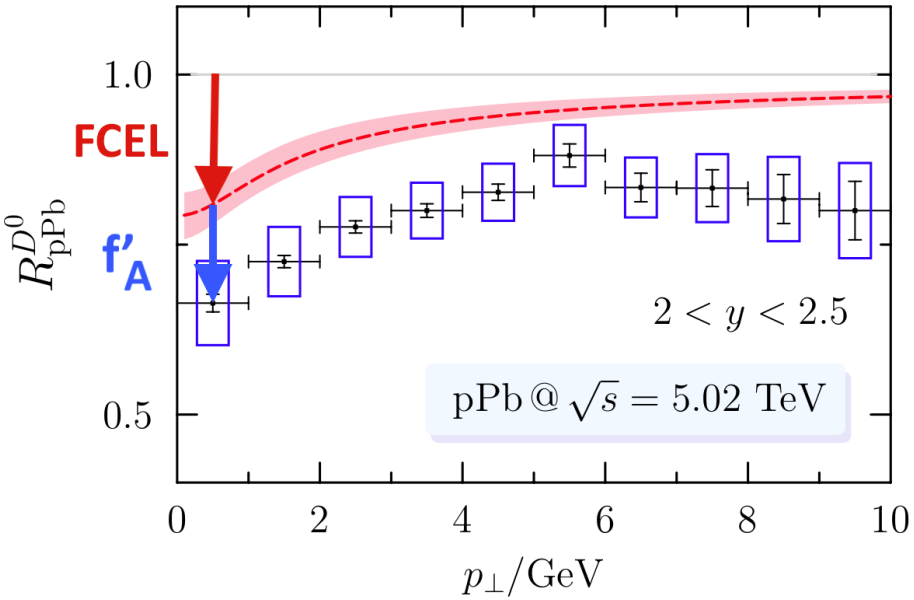
- **Include FCEL** [FA Jackson Peigné Watanabe, in progress]

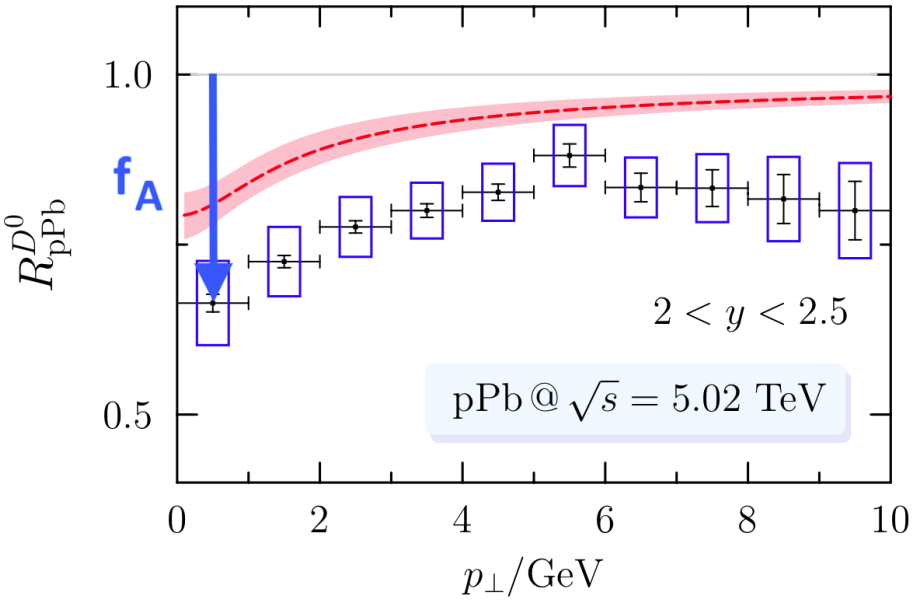
$$\mathcal{P}(f'_A | \text{ pQCD} \cap \text{FCEL} \cap \text{world data})$$

  - 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**: $f'_A \neq f_A$

Reweighting nPDF, w/ and w/o FCEL

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





$\mathcal{P}(f'_{\rm A} \,|\, \text{FCEL} \cap \text{LHCb data})$

$\mathcal{P}(f_{\rm A} \,|\, \text{no FCEL} \cap \text{LHCb data})$

$$f'_{\rm A} \neq f_{\rm A}$$

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)