Open questions on energy loss and nuclear PDF effects on heavy flavour production in pA collisions

François Arleo

Subatech, Nantes

GDR QCD workshop – Prospectives in QCD beyond 2030

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Two for tea

Hadron production in pA collisions affected by 2 nuclear effects

- **Fully coherent energy loss** (FCEL)
  - predicted from first principles in pQCD, leading to small uncertainty
- **Nuclear parton distribution functions** (nPDF)
  - not calculable, extracted from **global fits to data**
- Strength of FCEL/nPDF effects depend on x_{F}, x_2, Q, $\sqrt{s}$...

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☞ No single effect is able to reproduce all data available, both are needed

FCEL

- **Medium-induced gluon radiation** due to multiple scattering in nuclei
- FCEL spectrum computed perturbatively **in various frameworks**
- Average energy loss

$$\Delta E_{\text{FCEL}} \propto \alpha_s \, \frac{Q_s}{M_\perp} \, E$$

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

FCEL

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$$\Delta E_{\mathrm{FCEL}} \propto \alpha_s \, \frac{Q_s}{M_\perp} \, E$$

- **Important at all collision energies**, especially at large x_{F} (or y)
- 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
- Mass dependence
  - weaker effects on Υ and jets

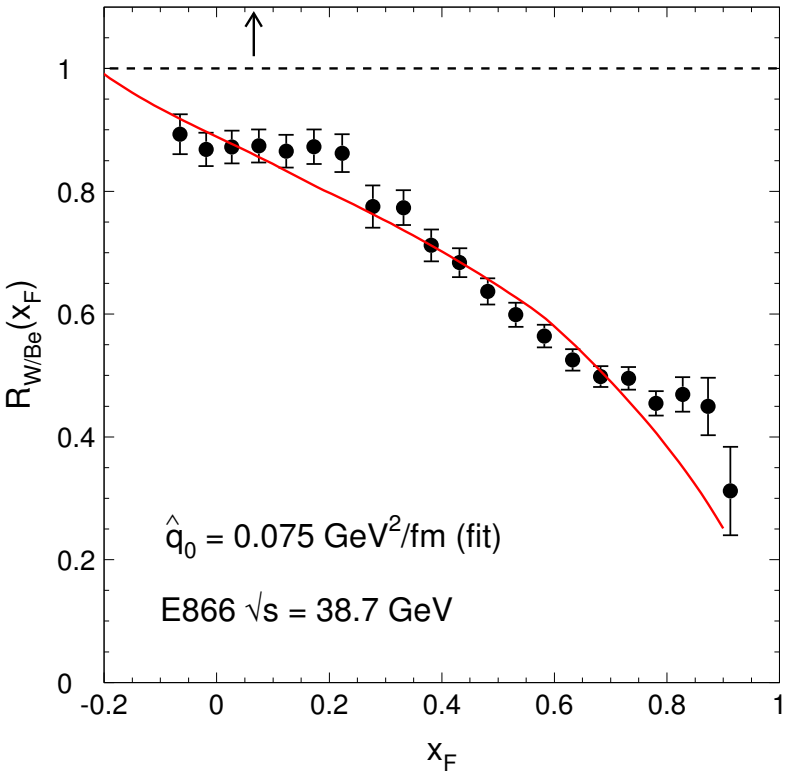
FCEL phenomenology

- FCEL effects modelled using the least number of assumptions
  - depends on one physical parameter: transport coefficient $\hat{q}$
- Applied to a **variety of processes** in pA collisions
  - quarkonia (2012-2014)
  - light hadrons (2020)
  - open heavy-flavour hadrons (2021)
  - atmospheric neutrinos from D decays (2021)
- Small uncertainties
  - typically $\lesssim 10\%$ relative uncertainty on R_{pA}
- Naturally explain forward J/ψ suppression at all energies

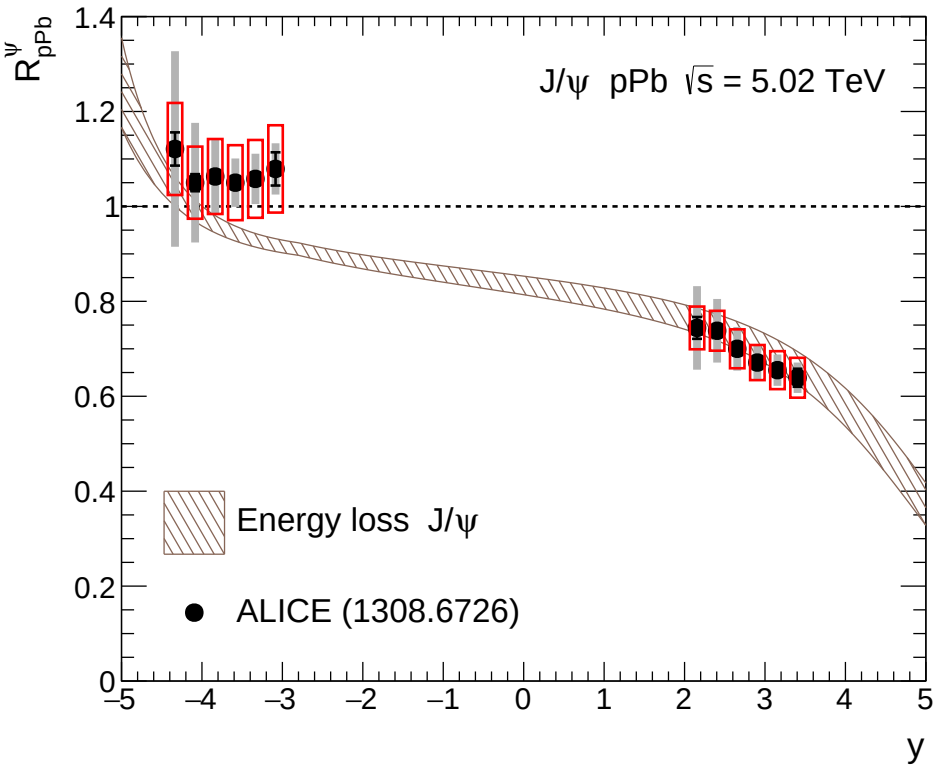
Selected FCEL results

- J/ψ from fixed-target to LHC

FA Peigné, 1212.0434



$\sqrt{s} = 38.7$ GeV

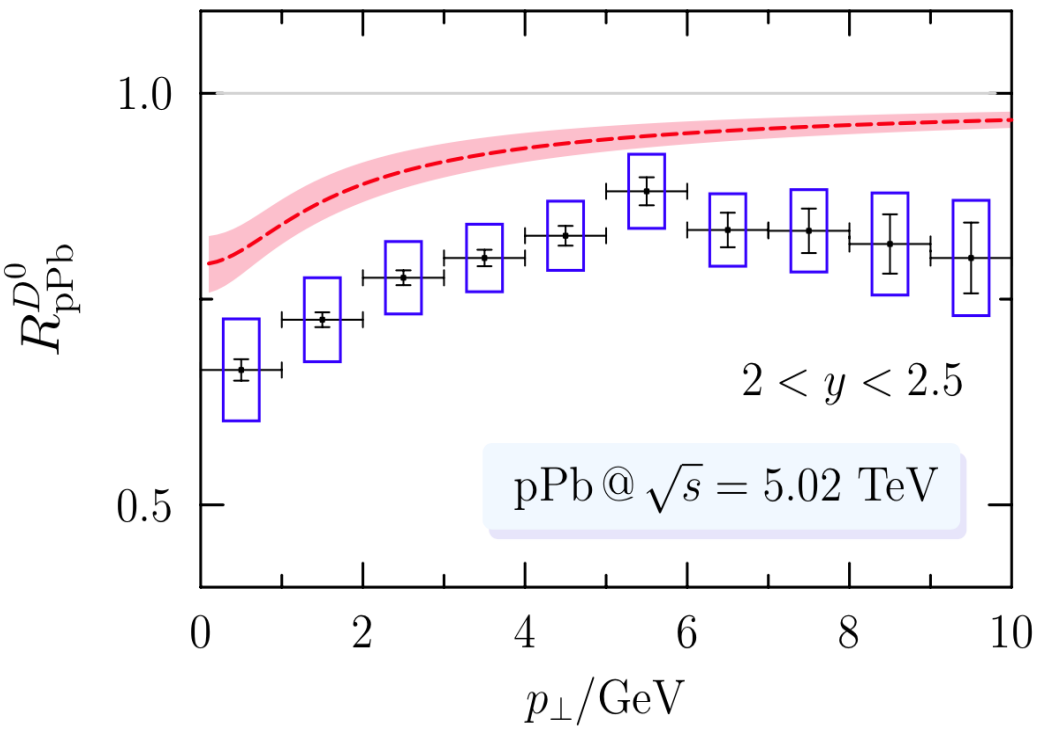


$\sqrt{s} = 5.02$ TeV

Selected FCEL results

- D-meson in pPb collisions at LHC

FA Jackson Peigné, 2107.05871

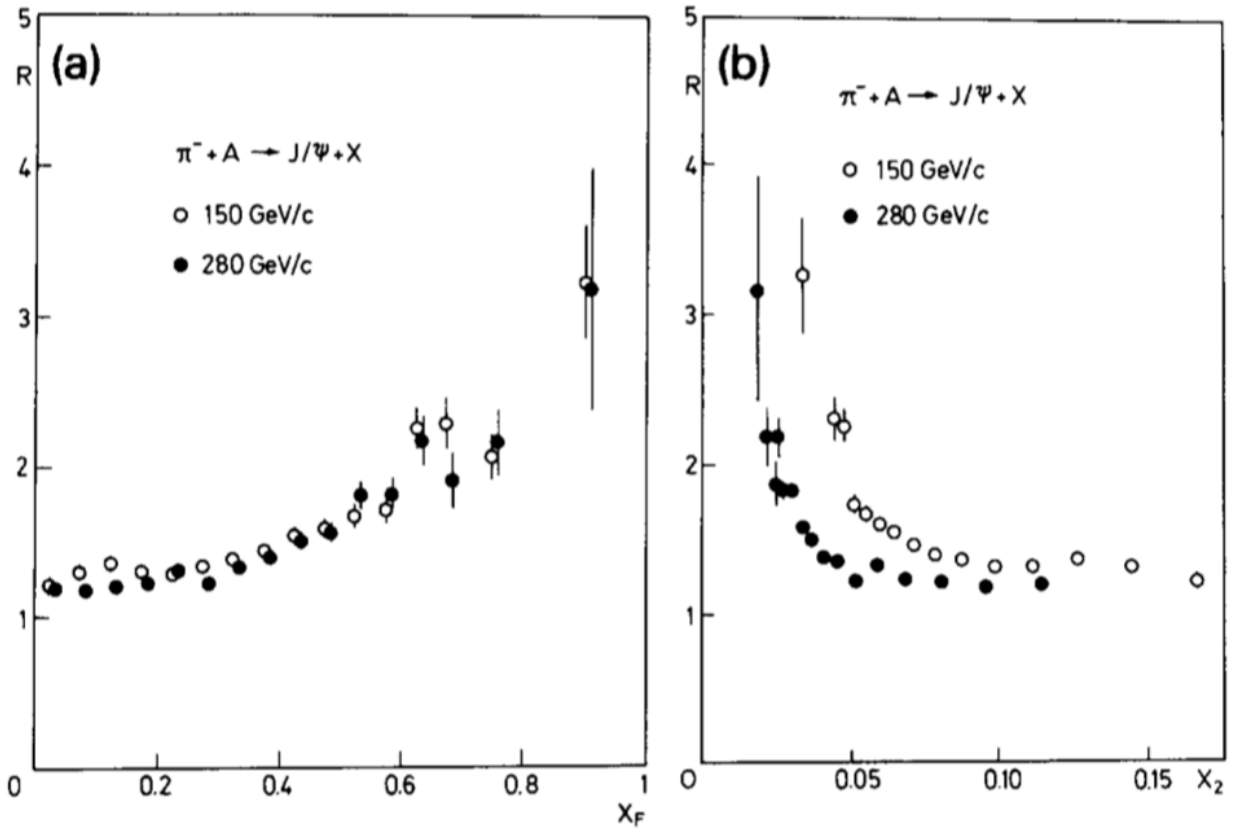


- Accounts for typically half of the observed suppression
- Small relative uncertainty ($\lesssim 10\%$)

nPDF

- Parton distribution functions are modified in nuclei
  - evidence at large x from EMC/NMC measurements in DIS
- Cannot be calculated, extracted from data global fits
  - nuclear DIS: structure functions F_2
  - pA collisions: DY, W/Z, jets, hadrons (π at RHIC, D at LHC)
  - latest releases include nCTEQ15, EPPS21, nNNPDF3.0
- Expected shadowing at small x_2
  - leads to hadron suppression at high $\sqrt{s}$ and large y
  - strength of shadowing unknown due to poor constraints from data
- Leads to x_2 **scaling** for hadron suppression: $R_{\mathrm{pA}}(x_2, \sqrt{s}) = R_{\mathrm{pA}}(x_2)$
  - known to be strongly violated in the case of forward hadron suppression

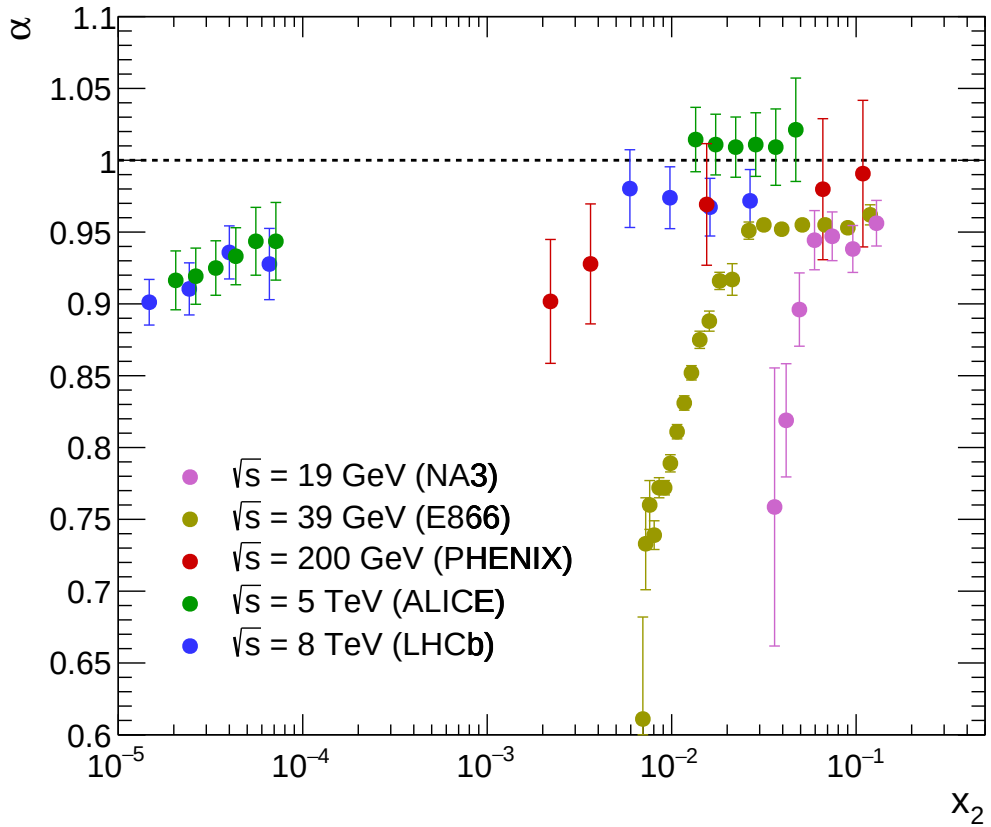
nPDF



Hoyer Vänttinen Sukhatme 1990

- J/ψ suppression is **not** a scaling function of x_2
- Evidence for nuclear effects beyond nPDF

nPDF



FA Naïm Platchkov 2019

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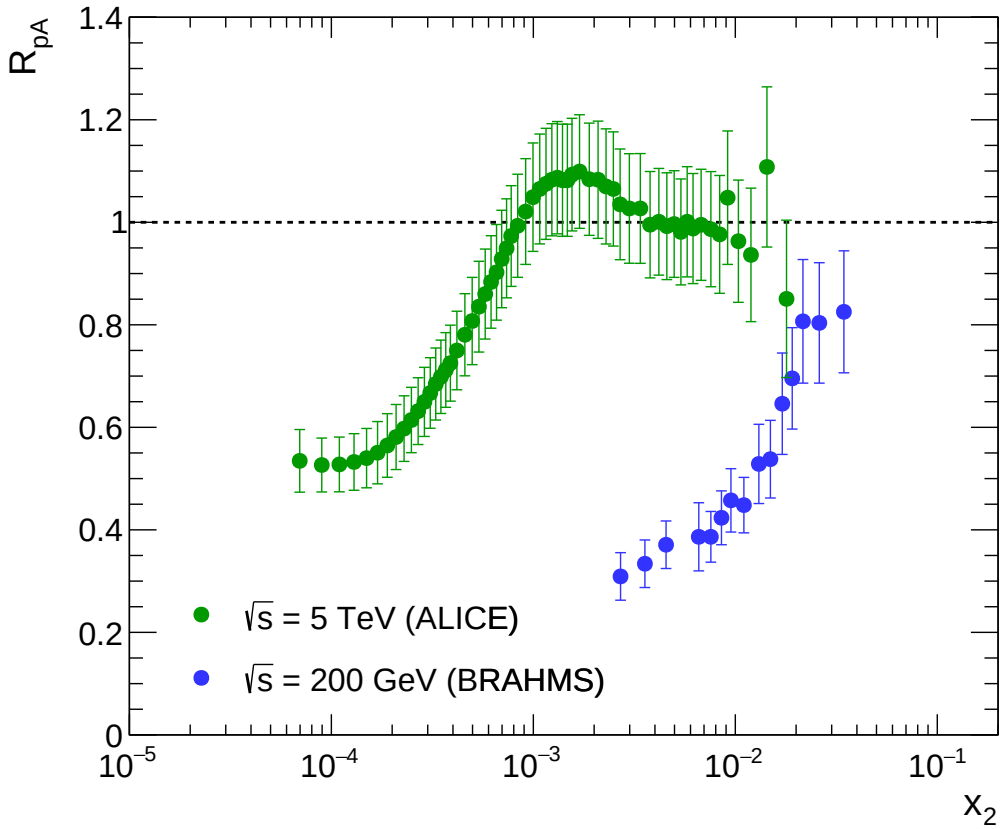
nPDF



- Strong x_2 violation in light hadron production
- BRAHMS forward data discarded in global fit analyses after EPS08
  - without reason a priori, except tension with other data sets

Which nPDF global fit strategy

- FCEL uncertainties $\ll$ nPDF uncertainties
- **Given the FCEL effects on hadron production**, how should nPDF be extracted from data ?

Which nPDF global fit strategy

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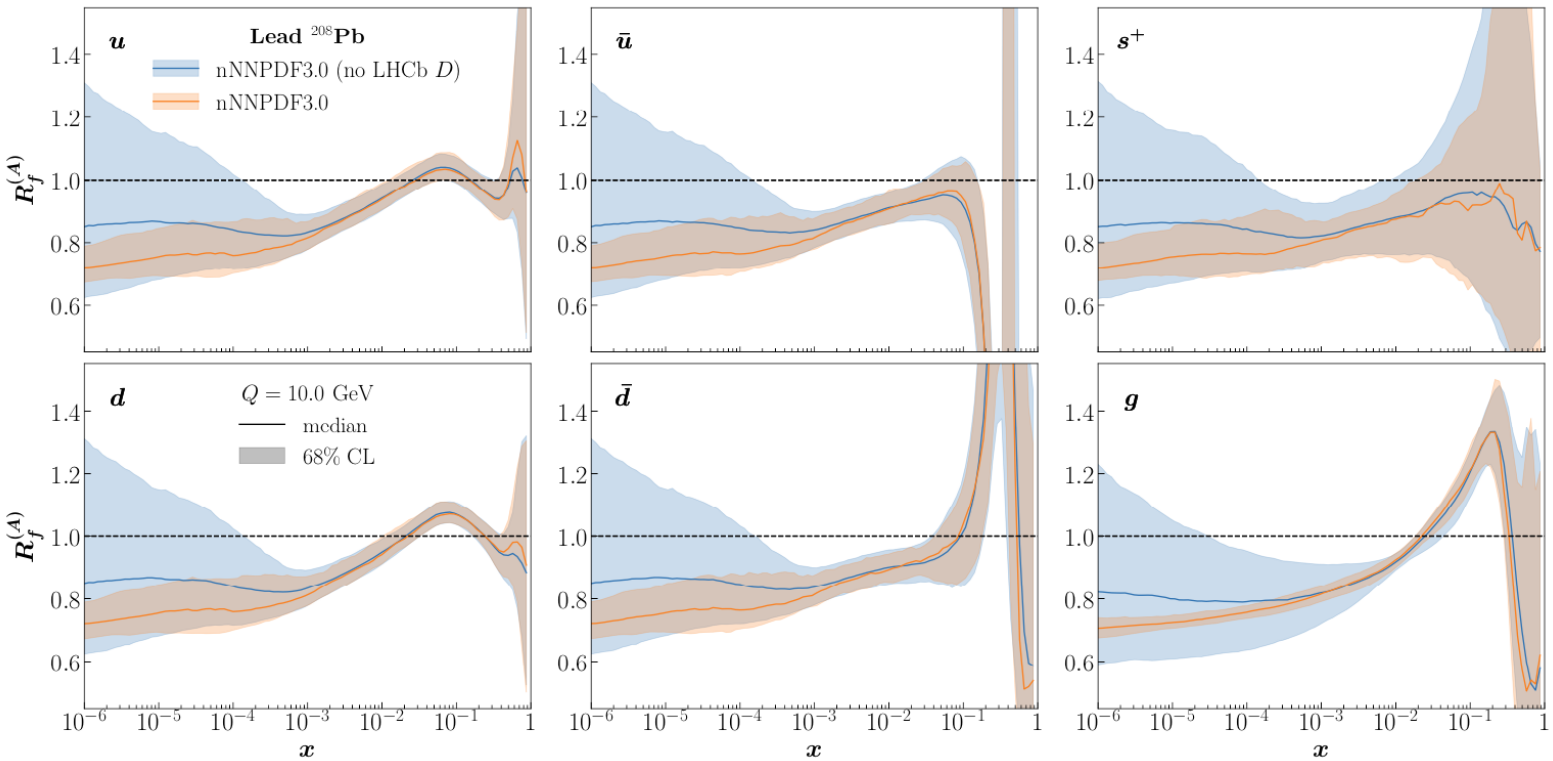
- **Given the FCEL effects on hadron production**, how should nPDF be extracted from data ?

✓ Focus on observables **insensitive to FCEL**
  - F_2 in DIS, weak bosons, Drell-Yan (and jets) in pA collisions
  - Lacks constraints at small x (until EIC)

✓ **Include FCEL** in the pQCD calculation and then fit data
  - Reliable nPDF estimate
  - Strong constraints from all data available
  - Challenging

FA Jackson Peigné Watanabe, work in progress

nNNPDF3.0 (w/ and w/o LHCb D meson data)



- Huge uncertainty on gluon shadowing nNNPDF, 2201.12363
- Strong constraints given by forward D-meson data
  - key measurements. . . but affected by FCEL
- Several other attempts Kusina Lansberg Schienbein Shao 2012.11462

  Eskola Paakkinen Paukkunen Salgado 2112.12462

Reweighting nPDF, w/ and w/o FCEL

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

✗ **Ignore FCEL** :

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

- 'Statistically good' fits can be obtained, including LHCb data
- Strong constraints. . . but unreliable result

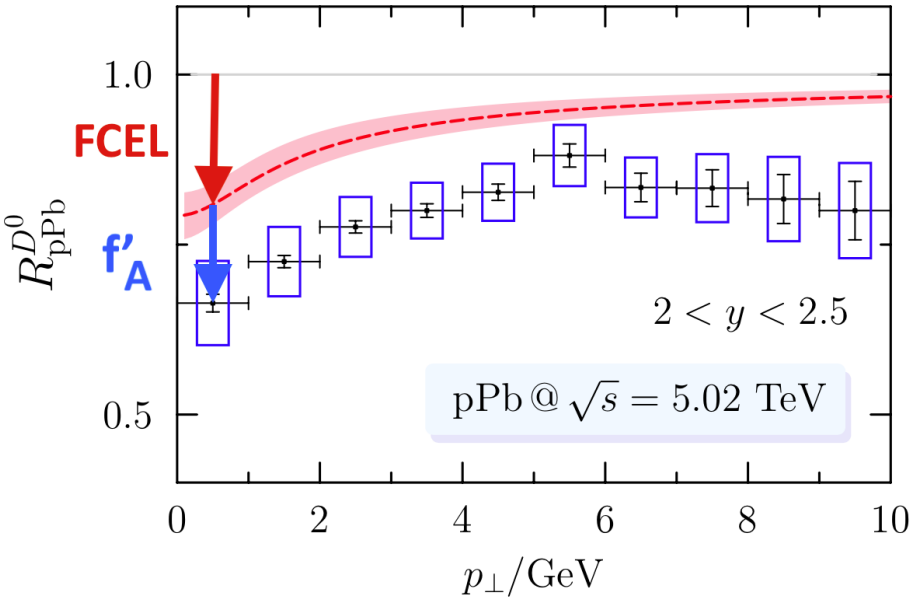
✓ **Include FCEL**

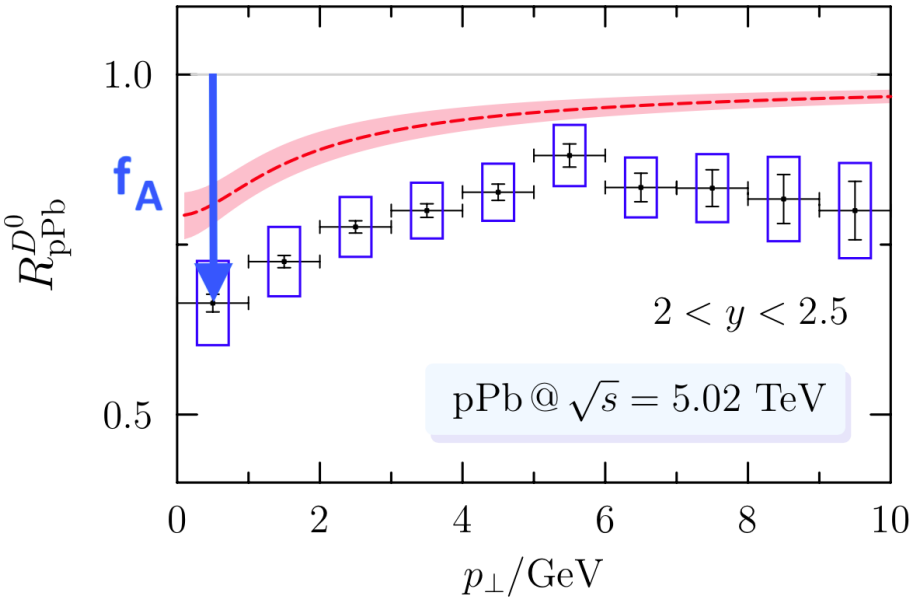
$$\mathcal{P}(f'_A | \text{ pQCD} \cap \text{FCEL} \cap \text{world data})$$

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

Reweighting nPDF, w/ and w/o FCEL

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





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

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

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

FCEL and nPDF in 2030 (and beyond)

It is difficult to make predictions, especially about the future.
– Karl Kristian Steincke

Pre-EIC

- FCEL will be included in the extraction of nPDF
- Precise ($\sim 10\%$?) and reliable extraction of nPDF at small x
  - using forward hadron production, prompt photons, Drell-Yan

LHC + EIC

- Evidence for physics beyond nPDF from the raw comparison of forward hadron production in pA collisions and in SIDIS
- Consistency of the nPDF+FCEL framework between LHC and EIC

Summary

- FCEL predicted from first principles **with small uncertainty**
- **Affects significantly hadron production** in pA collisions
- Ignoring FCEL in nPDF global fits leads to **wrong nPDF extractions**
- nPDF global fit strategy should either
  - **exclude measurements** of hadron production in pA collisions
  - **include FCEL** in the theoretical framework
- EIC will be crucial to compare to LHC pA data